Sensing Techniques For Opening And Closing Of Prosthetic Hand In Upper Limb Amputation

By

MAJ ALI SALMAN

2010-NUST-MS PhD–Mts-23

Submitted to the Department of Mechatronics Engineering

In Partial Fulfillment of the requirements for the Degree of

Masters of Science

in

Mechatronics Engineering

Thesis Advisor

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بسم الله الرحمن الرحيم

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Abstract

Human hand is an indispensible organ of human structure, function and expression. Without human hand, it would have been almost impossible for this world to be in the same way as it is today, as human beings would have not been able to make and make use of the tools which have brought them into the huge technological advancement of today. Upper limb prosthetics are devices designed to replace as much as possible the function or appearance of a missing upper limb. Upper limb prosthesis are devices designed to support, supplement, or augment the function of a missing upper limb.

Current state of the art prosthesis can be considered to be a tool rather than a limb replacement. Due to the reason, the prosthetic components and interface techniques are still a long way from realizing the goal to develop a hand replacement, which can produce the same speeds of response and strength as that of a physiological hand. It is therefore; felt that the sensing techniques may further be researched to develop a system which is analogous to real hand. Different available sensing techniques to operate a prosthetic hand will be analyzed, aiming removal of existing bottlenecks. Furthermore improvements will be suggested.

Thesis Supervisor: Dr Umar Shahbaz Khan

Title: Associate Professor

Dedicated To My Beloved Mother

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CHAPTER 1: UPPER EXTREMITY PROSTHETIC DEVICE

1.1 Introduction

Human hand is an indispensable organ of human structure, function, and expression. Without human hand, it would have been almost impossible for this world to be in the same way it is today as human beings would have not been able to make and make use of the tools which have brought them into the huge technological advancements of today. The significance of this part is really crucial for us to survive. It is capable of producing complex and expressive articulation. Due to its complex neurophysiology it is a daunting challenge for robotic hand designers to emulate human hand in the applications of prosthetics, robot planning and human computer interaction. In many common applications, such as activities of dialing living (ADL) like, eating, drinking, typing, playing a musical instrument and many sports or writing a research paper, extremely fine motor control of the human hand is required to carry out multiple tasks. An adult human learn these fine motor skills required for these applications over a period of time.

Over the past few decades enormous efforts have been made in the development of prosthetic hands and terminal devices on the basis of the latest advancements in the technology, thereby developing more dexterous and more homomorphous hand devices. Designing a fully functioning artificial arm and hand that can be used by an amputee, which provides same or even better strength and speed-of-response as that of the original arm and hand, and at the same time it's control is also accomplished almost without thought (as in case of human arms) has remained the aim of scientists and engineers while researching in the field of below elbow prosthetics. However, it is still a long way from achieving this goal and there is a great difference between the actual human hand and the present state of the art hand devices, which are highly functional, cosmetic, durable, and yet inexpensive.

In this research an endeavor is to carry out a detailed review of different types of prosthetic arms (below elbow only) and study the developments in this field with a special focus on sensing techniques, i.e. how the control inputs are being provided to the artificial arms in order to get the terminal device at a specific location. Detailed study of the technical advancements in each technique has been conducted in order to recommend possible improvements in the existing technology. Moreover a survey has been conducted as to what is the requirement of user, as the challenges being faced by amputees and their needs carry the prime importance in the design process whether functionality, cosmesis, weight or ease of usage, what gets the top priority for the user. Design specifications of commercially available prosthetic terminal devices have also been compared.

1.2 Research Approach

Below elbow prosthetic devices have been researched from the very beginning that is from its historic advent and the latest trends in the following fields have been studied:

a. Equipment and Material

b. Design Considerations

c. Sensing Techniques

1.3 Diversity of Problem

The movement of hand is possible due to the anatomical structure of the combined effect of bones and muscles of hand as well as arm. Compound contractions of muscles cause flexion of some joints, and extension of others, and at the same time holds others in a bolted position. At the same time, the importance of neural control systems cannot be denied, as they provide a pathway for the nervous signal through the integrative and system of the brain and spinal cord. Designing an artificial hand, which can cause the same movements as that of a physiological hand using mechanical linkages and electric wires carrying the signals is certainly a divergent problem. It can therefore be claimed that it is a multifaceted issue and requires that the designer of prosthetics possesses a thorough knowledge of following fields [1]:

a. Muscloskeletal Anatomy

b. Muscular- as well as Neurophysiology

c. Mechanics of Mechanisms

d. Electromechanical Design

1.3.1 Muscloskeletal Anatomy

The organ system that ensures the movement of animals (as well as humans) with the help of their muscles and skeleton (bones) is called Musculoskeletal system. It provides structure, base, firmness, stability, and movement to the body as well as body parts. This system comprises of muscles, bones, tendons, cartilage, joints, ligaments and so many connective tissue that are responsible for binding both organs and tissues together. Main functions of musculoskeletal system are [2]:

a. Provide supporting to the body

b. Moving the body and body parts

c. Protection of vital organs

The connection of bones with other bones and muscle fibers through tissues like, tendons and ligaments, is described by this system. Muscles ensure that the bones remain at their place and also assist in their movement. All the bones are connected to each other by joints, this allows motion. Movement of the bone is completed by contraction or extension of muscles. In order to design an artificial arm it is necessary to have an introductory knowledge of muscloskeletal anatomy, as different movement are caused by different muscles.

1.3.2 Muscular Physiology and Neurophysiology

The muscular system in a human body is a biological system which causes motion of body and different body parts. Muscle is tissue which has the capability to contract and expand. Production of force and to cause motion is its two main functions. Motion can be of any type, locomotion or internal organ movement. Movement of body is caused by the voluntary muscle contraction, which can be controlled finely. Its examples can be, motion of fingers or the motion of biceps and triceps. In order to cause a specified movement of index finger it is mandatory to know the muscle, contraction of which causes index finger to move. Therefore the study of muscular physiology is essential before going into the designing of prosthetic hand.

The nervous system of a human being is an organ system which consists of a network of specialized cells. These specialized cells are called neurons. Main function of neurons is to coordinate the actions of different body parts in an animal. This is accomplished by the transmission of signals between different parts in a body. Nervous system of most of the animals is comprised of two parts:

a. Central nervous system. The central nervous system of humans is composed of the brain, spinal cord, and retina.

b. Peripheral nervous system. In animals (including human beings) the peripheral nervous system is composed of sensory neurons, clusters of neurons called ganglia, and inter connecting nerves which are connecting them to one another and to the central nervous system.

The signal for movement of hand in a specified direction and at a specific location is forwarded by the brain but is transmitted to the muscles after being decoded as to contract or extend through these neurons.

1.3.3 Mechanics of Mechanisms

A mechanism can be any combination of mechanical linkages, which is utilized to produce desired mechanical transformations. This transformation can be of any one or a combination of conversion from the following [3]:

a. Conversion of one type of speed into another type of speed (lower to higher or higher to lower)

b. Conversion of one kind of force into another kind of force (reducing or enhancing the end effect of force or changing the direction of application of force)

c. Conversion of one torque into another torque

d. Conversion of force into torque or vice versa

e. Conversion of angular motion to another angular motion (clock wise to anti clock wise or may be from anti clock wise to clock wise)

f. Conversion of angular motion into linear motion or vice versa

With the help of a good designed linkages combination we can not only take the end effecter to a specified location in space but also calculate its velocities and accelerations. It is therefore necessary to have an understanding of this branch of science in order to start the designing process of an artificial arm.

1.3.4 Electromechanical Design

Electromechanical engineering deals with analyzing, designing, manufacturing and maintaining, products and equipment with a combined application of electrical instruments, electronic circuitry and mechanical systems. Hence it can be said that it is a combination of it is a combination of electrical / electronic and mechanical engineering. Electronics deals with the systems that incorporate electrical circuits along with items such as resistors, transistors, diodes and integrated circuits. Understanding of both mechanical and electronics is required before making or even designing an artificial arm.

1.4 Arm (Below Elbow) Anatomy

The study of an organism's structures is called Anatomy of that organism. As we discover the architecture of human body, we learn how the uniqueness in size, shape, and other features constitute their function, or physiology. In anatomy, the complete arm constitutes of two regions. The portion between shoulder and elbow is called the upper arm and the portion below the elbow is called forearm. Muscle tissues are made up of muscle cells, which enclose contractile protein structures which are called myofibrils. Nervous system stir these myofibrils, resultantly they contract or shorten, creating movement in human body [4].

Combined elbow, forearm, wrist, and hand can produce various articulations to accomplish several important functions of ADL. Some produce power, such as grasping and lifting. Some require precision and delicacy, such as twisting and plucking. Some are complex, which involve simultaneous function of more joints of this region. Wrist and hand are multifunctional due to the presence of multiple joints and small muscles in them.

Figure 1-1: Anatomy of our arm

1.4.1 Forearm

1.4.1.1 Forearm Bones

Above forearm is only one bone and its name is Humerus. Forearm consists of two bones, named Radius and Ulna:

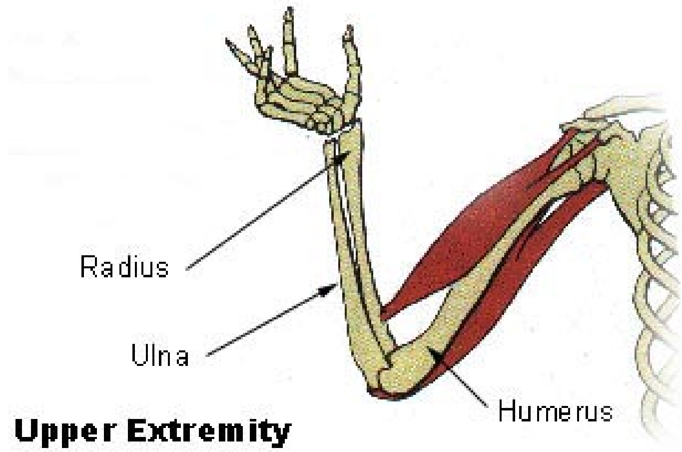


Figure 1-2: Bones of Upper Extremity

Radius. It is the bone of the forearm, which starts at the elbow and goes uptil wrist. It is comparatively long and curved, and is parallel to ulna. Its main function is to support the arm and ensure its motion. It connects to many muscles, such as biceps, supinator, flexor digitorum superficialis, flexor pollicis longus muscles, extensor ossis metacarpi pollicis, extensor primi internodii pollicis, and the pronator teres muscles.

Ulna. It is the second bone of the forearm. It is also starts from the elbow and goes uptil wrist, and it is parallel to the radius. It is the longest forearm bone and is slightly curved. Its main function is also allowing motion and supporting the arm. The ulna connects to many muscles and ligaments, such as the triceps brachii muscle, supinator muscle, pronator teres muscle, pronator quadratus muscle, and the flexor digitorum superficialis muscle.

1.4.1.2 Forearm Muscles

The muscles, which are responsible for the movement of the forearm are located along the humerus. These are the triceps brachii, biceps brachii, brachialis, and brachioradialis. There are more than 20 muscles, which cause most wrist, hand, and finger movements and these are located along the forearm [5].

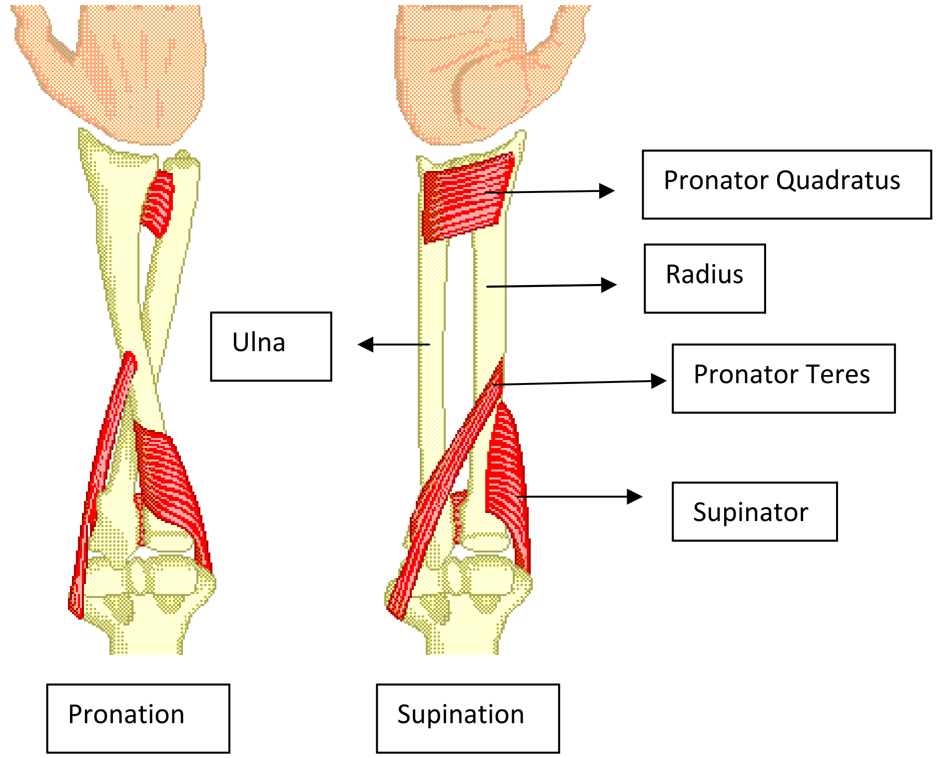


Figure 1-3: Forearm muscles causing Supination and Pronation

a. Pronator Quadratus. This is the muscle, which is at the wrist end of forearm and it is joind outer side of the ulna with the outer side of radius. The prontator quadrus is located along the distal quarter of forearm, and it extends down in between the ulna and the radius. It helps Pronator Teres while rotating the arm towards inside, i.e. rotating the palm from facing upward to downward.

b. Pronator Teres. It is a short muscle and it connects ends of Humerus and Ulna to the Radius. Its function is to turn the hand inside. It resides in the upper medial region of forearm.

c. Supinator Muscle. It is also a short muscle, which runs from Ulna and joins the lateral end of Humerus with the Radius, it is found swirling around upper posterior region of the radius. It helps Biceps Brachii (muscle above elbow) in rotation the forearm such that the palm is facing upward.

The muscles of the forearm are subdivided into two groups:

a. Flexor / Pronator Group

b. Extensor / supinator Group

Frontal / anterior portion of the forearm is occupied by the flexor / pronator group. The muscle of this group arises from the medial portion of humerus. Whereas the rear / posterior portion of the forearm is filled by the extensor / supinator group. The muscle of this group arises from lateral portion of the humerus.

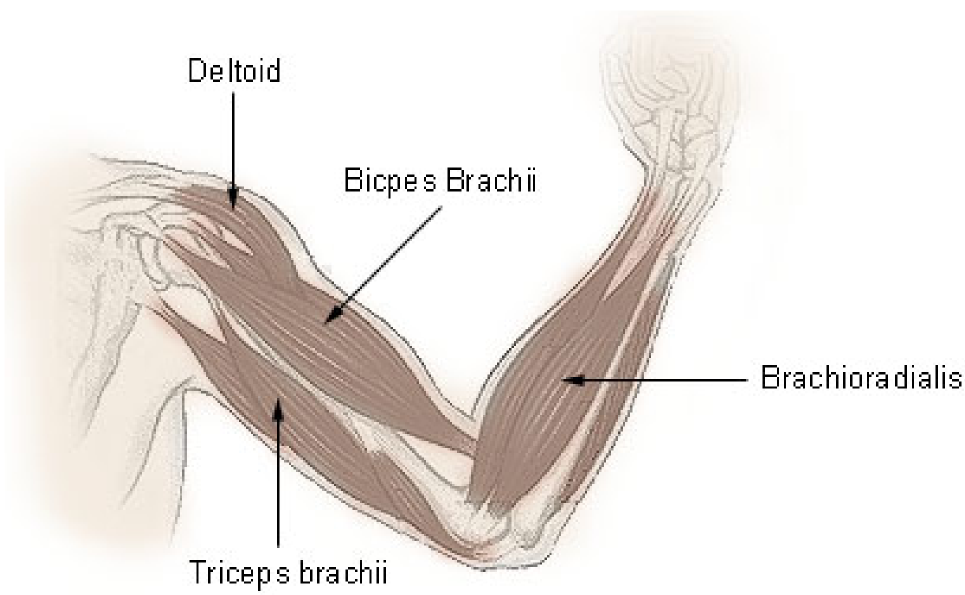


Figure 1-4: Muscles of **Forearm**

1.4.1.3 Forearm Movement

Movement of forearm is primarily due to the elbow or in medical terms due to radioulnar joint. Radius and Ulna are the two bones which are parallel to each other and make meet at two places. They meet at the elbow and at the wrist. At the elbow the joint in called Proximal radioulnar joint and at the wrist it is known as distal radioulnar joint. At both the places it makes a pivot joint. The specific movement caused by the combined effect of these joints is rotation of the forearm.

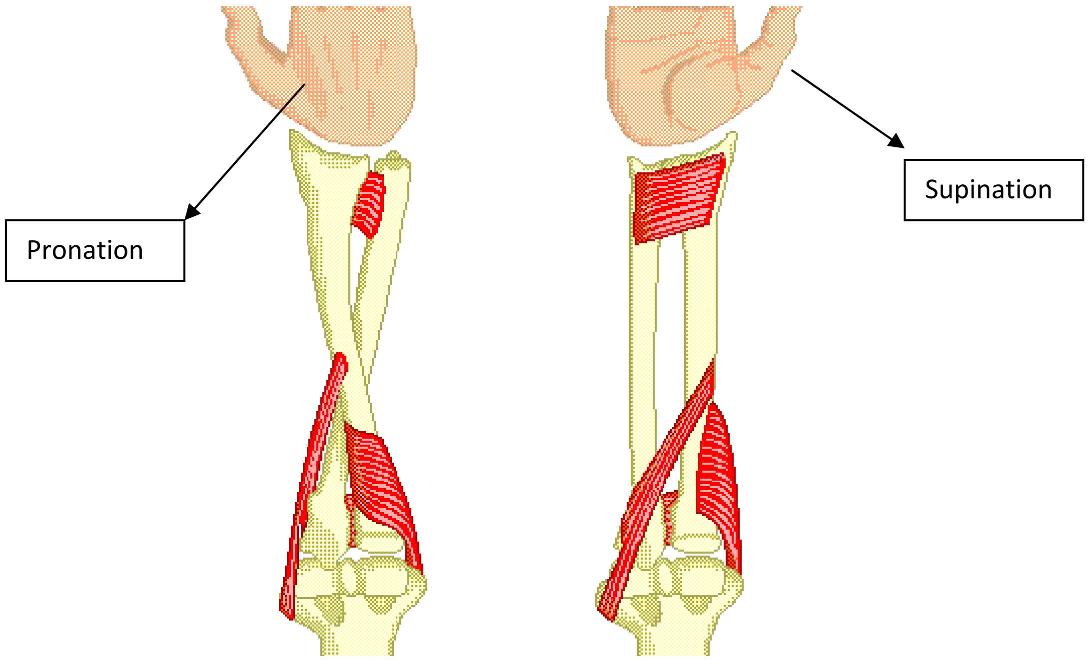


Figure 1-5: Movements caused by Forearm

a. <u>Pronation</u>. It is the position of the forearm, when the palm is facing downward, i.e. towards the earth. Cohesive synergetic contraction of pronator teres and the pronator quadrus leads to pronation.

b. <u>Supination</u>. It is the position of the forearm, when the palm is facing upward, i.e. towards the sky. Supinator muscle is responsible for the supination of human hand and this muscle is situated swirling around upper posterior region of the radius.

1.4.2 Hand

Human hand represents one of the most intricate and complex mechanisms, yet of great utility. It is very intimately linked with the brain. Hands are the main organs which are used for physically maneuvering the surroundings. Hands are utilized by humans for both gross motor skills (such as grasping a large object) and fine motor skills (such as picking up a small pebble). Hence it can be very safely said that to a certain degree we use our hands to "think" and "feel", resultantly our hands assist in our mental processes of thinking and feeling. One of the densest area of nerve endings in our body is at the fingertips, and this area is used to get the tactile feedback. All the organs in our body, which are given in pairs are dominantly controlled by the opposing brain hemisphere. Likewise each hand is controlled by the opposing brain hemisphere.

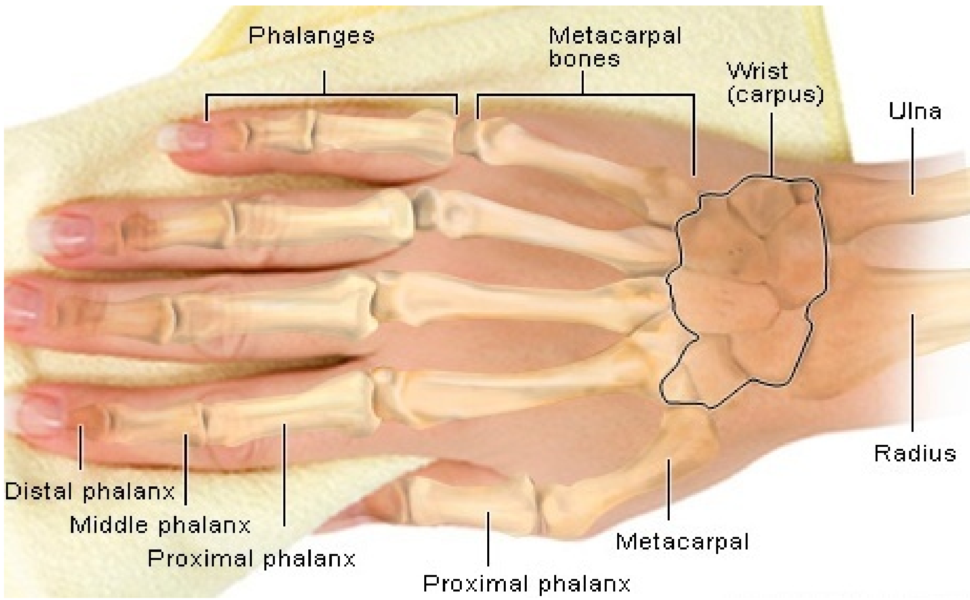


Figure 1-6: Anatomy of Hand (Bones)

In order to analyze human hand it is necessary to develop an understanding of both its sensory and mechanical features. Complete books have been written on hand anatomy, and it is not possible to go into the intricate details of hand anatomy. However, to have a basic understanding of hand anatomy the basic construction of bones, muscles, joint articulations and the system of producing motions have been studied.

Hand consists of twenty four muscle groups, which is controlled by the numerous motor and sensory nerves. Due to the central and wonderful connections of bones and muscles, hand acquires the capacity of innumerable patterns of actions.

1.4.2.1Hand Bones

There are a total of 27 bones in a human hand [4]. Human hand is subdivided into three main regions:

a. Phalanges. It consists of the bones, which are in the fingers and thumb, these are total 14 bones, 12 in the fingers and 2 in the thumb. Each finger contains three bones, while the thumb comprises of two bones. The bones which are at the tip of the finger are called Distal Phalanges, the middle ones are known as Medial Phalanges and the largest ones which are towards the wrist are called Proximal Phalanges.

b. Metacarpal Bones. These are the bones which connect fingers with the wrist. They are total 5 bones and are in the main hand of a human and they make up the palm. Metacarpals are named the first, second, third, fourth and fifth Metacarpal, in which the first starts from the thumb side.

c. Wrist Carpus. These are in the wrist region of the hand and they are total 8 bones. Carpal bones are arranged in two rows, each row contains four bones. The upper row, which is towards the fingers is called the distal row and the row towards the forearm is known as proximal row.

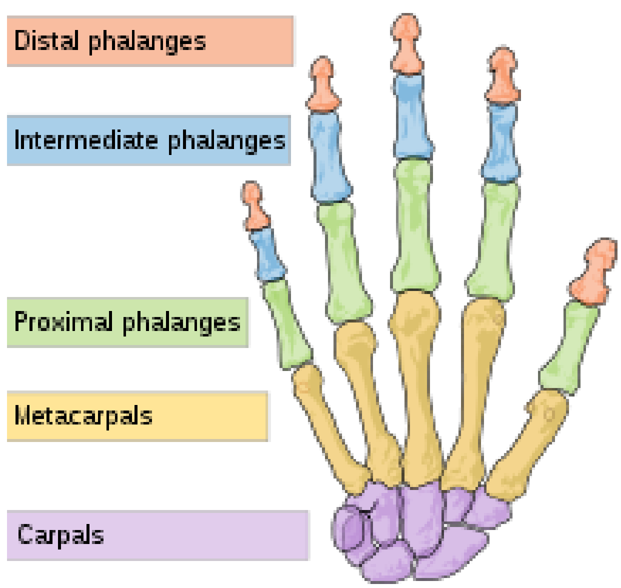


Figure 1-7: Anatomy of human hand

1.4.2.2Hand Muscles

There are twelve different muscles in the hand, which are subdivided into three groups:

a. Thenar Muscles. These are the short muscles of the thumb and are situated in the hand in the line of Radius. It contains five muscles, and their names are, the abductor pollicis brevis, flexor pollicis brevis, opponens pollicis, adductor pollicis, and the first palmar and dorsal interossei.

b. Hypothenar Muscles. These muscles are the short muscles of the little finger and are situated along the Ulna in the hand. These are three musclesa and teir names are, the abductor digiti minimi, flexor digiti minimi brevis, and opponens digiti minimi.

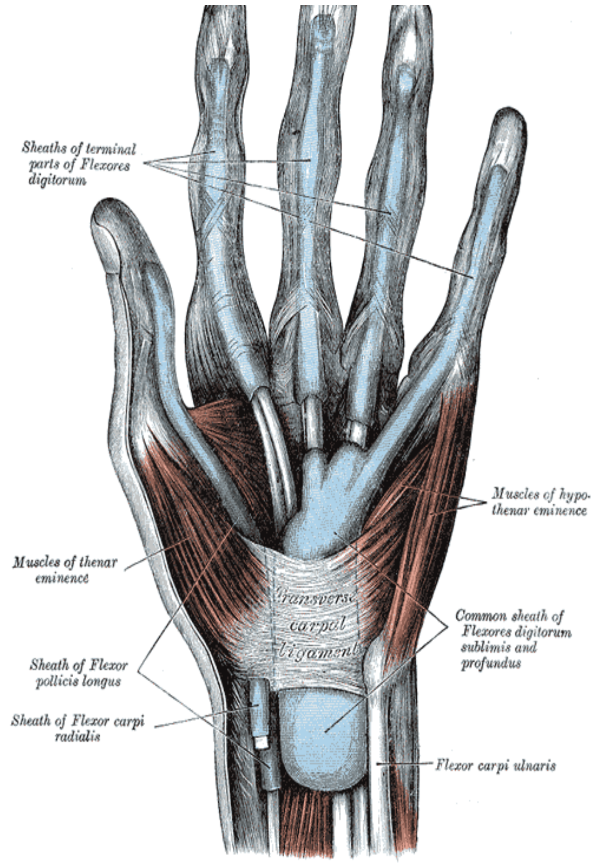


Figure 1-8: Anatomy of Hand (muscles/tendons)

c. Lumbricals and Interossei. These muscle are a dozen small muscles which are inserted mainly into the extensor expansion. The lumbricals are situated with the tendons of the flexor digitorum profundus in the palm. The palmar interossei reside on the palmar surfaces of the metacarpals, whereas the dorsal interossei are more truly interosseous, i.e., between the bones.

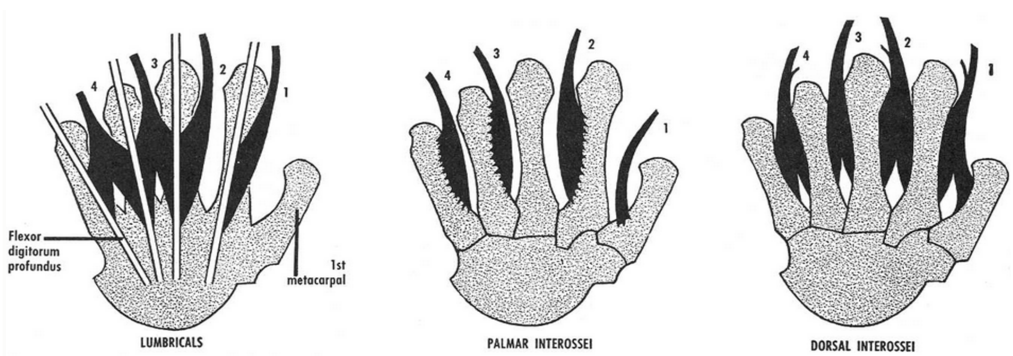


Figure 1-9: Muscles of fingers

1.4.2.3Hand Movements

a. <u>Flexion</u>. Any kind of bending movement which decreases the angle between two parts is called Flexion. Bending elbow upwards or curving a hand into a fist, are examples of flexion.

Figure 1-10: Flexion of Hand

b. <u>Extension</u>. It is the movement, which is opposite of flexion, i.e. a straightening movement which causes an increase in the angle between the parts. When the arm is fully open it can be the extension of elbow, similarly straightening the hand backward i.e. towards the back of forearm is an example of extension of wrist muscles and the fingers are fully extended in the handshake.

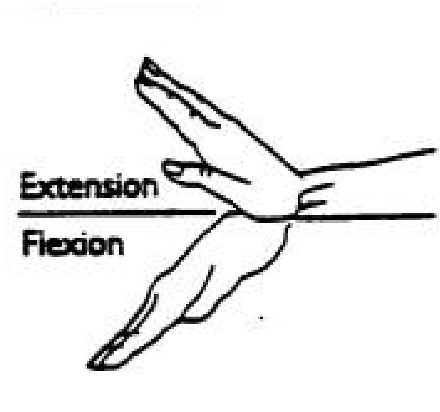


Figure 1-11: Flexion / extension of Hand

c. <u>Abduction</u>. Any kind of motion of any part of body, which pulls a structure or part away from the midline of the body, is called Abduction. Abduction of the wrist is known as radial deviation. Example of abduction, in case of arm is raising the arms laterally, to the sides.

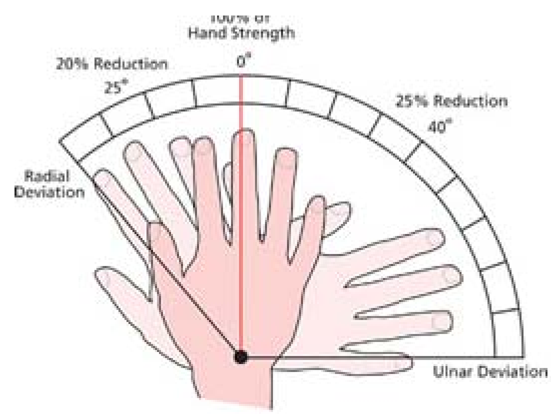


Figure 1-12: Adduction / abduction of Hand

d. Adduction. Similarly any kind of motion which pulls a structure or part towards the midline of the body, or towards the midline of a limb is called Adduction. Its example can be, dropping the arms to the sides. Closing the digits together, can be the example of adduction in case of the fingers. Adduction of the wrist is called ulnar deviation.

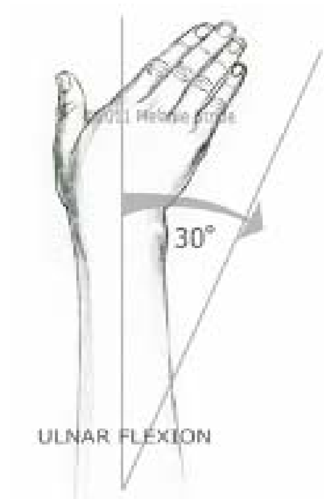


Figure 1-13: Adduction of Hand

1.5 Design Aspects

The most advanced prosthetic hand for upper limb amputee in today's era is the myoelectric prosthesis. Aspects which are critical in nature during the design phase of a prosthetic device are the structure's weight, volume, complication of control, its appearance and dexterity. Hence, in order to design a prosthesis which is comfortable, humanlike yet easy to control it must be kept in mind that it is not possible to replicate all the physiological joint movements of a hand and some are to be compromised, which limits the functionality and flexibility of the prosthesis.

In order to ensure the rehabilitation of an amputee, the designer must design suitable arm mechanism and control system, keeping in mind the amputee's level of amputation, age, size, musculature situation, activities of daily living, nature of job, requirement of appearance. The prosthesis structural design, i.e. the link mechanism and the cartography of the prosthesis, must be so selected that it suits the personal needs and potentials of the amputee. Preferably the prosthetic hand must be so designed, that it provides the patient with the artificial hand which best matches the specific requirements of a particular patient. However generally all the prosthetic designs must possess the following properties [6]:

a. Great mobility

b. Advanced control

c. Good "wearability"

i. Tolerable weight

ii. User friendliness

iii. Humanlike appearance

The basic concepts enumerated above are interlinked and there all the possibilities that ensuring one may compromise the other. Therefore the designer must make a trade off amongst all the above listed properties keeping in mind the priority demanded by the customer. Major design considerations are:

1.5.1 Form or Appearance

Anything, which has an unexpected appearance will always grasp attention and will not remain unnoticed. It is therefore always tried that the appearance of the prosthetic hand should be as similar to the physiological hand as possible, because people (observers) are comfortable with anything which is expected. Hence if the appearance and movement of the artificial hand of an amputee is in the expected manner, then the fact of artificial limb of that individual will often remain unnoticed by the casual observers.

In prosthetics the term used for the appearance of a particular device is **cosmesis,** so it describes that how a device looks like. If a device is so designed that it is aesthetically pleasing and its appearance resembles in both, shape and color with the limb for the replacement of which it is designed, then it is said to be cosmetic. Cosmesis can be of two types [3]:

a. Static Cosmesis. It refers to the term that how does the device look like when it is not in motion.

b. Dynamic Cosmesis. It refers to the term that how does the device look like while it is in motion.

There are possibilities that a device is statically "correct" in appearance (looks like the physiological limb when not in motion) but becomes "wrong" or lifeless when in motion. In this case, it would be said that the device has good static cosmesis but possesses poor dynamic cosmesis. On the contrary a prosthetic hand which has a hazy resemblance to the physiological hand but it can be moved in the same manner as that of a natural hand, it will remain unnoticed unless very closely and specially analyzed. This device posses poor static cosmesis but has a better dynamic cosmesis.

Out of the two types of cosmesis, dynamic cosmesis gets an obvious importance, but due to the fact that it is difficult to be achieved, it is frequently ignored. In order to raise the dynamic cosmesis, amputee's residual motion must be preserved and utilized as much as possible.

1.5.2 Cosmesis Versus Functionality

Achieving functionality of a prosthetic hand along with its cosmesis is a difficult ask. Obviously the importance of cosmesis and that of functionality are not the same. Functionality of any device evidently is more important than its appearance, yet in prosthetics the role of cosmesis, can never be overstated. Prehensile function of the fingers often becomes the reason for the design team to sacrifice the cosmesis. However, the importance of both the aspects is purely relative and switches from person to person.

There can be an amputee who is only interested in the visual presentation of the device and he may refuse a highly functional prosthetic device getting power from the body, being operated by the cable, only due to the undesirable appearance of harness being used to control the device, or due to the hook shaped end effecter. In contrast there can be an individual who accepts a prosthetic device with an unpleasing shape only due to its functionality as he might consider it sufficient to overshadow his apprehension about the appearance of the device.

Another possibility is (and is being practiced as well) that an amputee keeps two prostheses devices. One which is more mechanical in nature and it emphasizes on its functionality, he may use it at his work place, and another interchangeable one which is more similar to the physiological hand in its appearance and can be used in the social gatherings. This concept can be called specific tool for a specific job. In order to improve the cosmesis of the prosthetic hands cosmetic gloves are used. These gloves are made up of poly vinyl chloride (PVC) or silicone. It gives the artificial hand a more physiological appearance and enhances its static cosmesis. The other advantage of PVC is that, since it has an increased coefficient of friction hence these coverings increase the reflexive malleability of the artificial hand to the form of a clutched object.

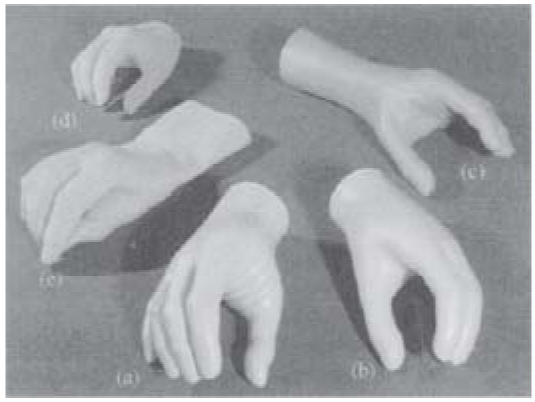


Figure 1-14: Cosmetic gloves

This enhanced cosmesis and grasping function is achieved at the cost of range of motion, which gets restricted and the performance which also is reduced. The reason of this reduced performance is the elastic force of glove which is to be overcome by the hand motors. Ideal would have been if the inclusion of glove would raised the cosmesis of the artificial hand without affecting its performance.

1.5.3 Weight

The weight of the prosthetic hand is critical as it will be taken by the amputee as if the same weight is being hung on the shoulder and the wearing time of the artificial hand may shuffle between 8 – 10 hours a day. Hence it can be said that the success of a prosthetic design very heavily depends on its final weight. This aspect becomes more critical in the case of upper limbs. The weight of an artificial limb must be much more less than the weight of the physiological limb, whose replacement it has to become. An adult male’s arm weighs approximately 10 kg (20 lb). If a prosthetic arm of the same weight is designed then it would not be possible for the amputee to use it. This can be very conveniently perceived that the artificial arm will be taken as an external device weighing 10 Kgs suspending from the shoulder and the amputee will not bear that for more than 10 – 15 minutes at a stretch. Moreover it will cause the patient fatigued within the first few hours of the day, so it will be a failure design. It has been proved after experimenting that it cannot be expected from an amputee to wear an arm replacements which exceed in weight from 3.5 kg (~7.5 lb) for a full day, owing to the discomfort which it will cause if this much weight is suspended with the body for this much time [3]. Therefore while designing it must be ensured that the prosthetic arm must be kept as light as possible. In the absence of a warm link in between the prosthetic arm and the amputee, the patient will perceive the artificial arm as an exterior load suspended with the shoulder and therefore will take it as something which is being carried.

1.5.4 Power Sources

In all portable devices the power source is a critical issue as the device is to be used in different locations and the power is limited and the requirements are that the power source must be available for longest time despite of being used continuously without being recharged. Power source actually describes the actuator.

One possibility can be that amputee's own musculature power is utilized to operate the prosthetic device, this is called body powered prosthetics. In this case the prosthesis should be so designed that it does not involve undue effort to be used. The mechanical mechanisms must be designed in a way that they are the most efficient and offer minimum frictional losses to ensure that the user is not tired after a use of say a complete day.

The other possibility can be that the artificial limb is given power externally, i.e., it uses an external power source and does not use body power. In most cases electric power is used as external power source. In case of an electric power source, it must be ensured that the limb gives its full performance for the entire day with the unchanged power source without being recharged or replaced. Moreover it should be so designed that it has the space to accommodate the power source within itself.

Modern externally powered portable devices utilize different energy sources, like electrochemical batteries, pneumatic gas cylinders (presently not very popular), electromechanical flywheel systems, miniature wankel rotary engines and ethanol- or methanol based fuel cells. Cellular phones are already using these devices, but the problem with these energy sources is that each one of these has more weight and they occupy unnecessary space. In the foreseeable future, it is perceived that dc electric motors will become the most popular actuators. Prosthesis arm is also a portable device and its problem of power source is analogous to the power concerns in cellular phone and laptops. In these portable equipments also power source takes the main share of weight and space, and at the moment this power source is a battery. The requirement of a prosthetic arm is a high power and energy density.

1.5.5 Body Powered Power Sources

In the Body powered Prosthetic arm, the amputee utilizes his / her own muscular power to give drive to the prosthetic arm with the help of a steel cable, which is called a Bowden cable. The Bowden cable is concealed in an outer housing, and it comprises of two parts one is the inner tension cable and the other one is the outer protection housing. Outer protection housing is tied from the two ends and serves as a free pathway for jerk less movement of the inner tension cable, thereby keeping a stable length of cable irrespective of any movement.

Bowden cable was first used by the Raleigh Bicycle Company as brake actuator in the braking system of the bicycle towards the end of nineteenth century. In early twentieth century this concept of Bowden cable was used by the fledgling aircraft industry. Most of the aircraft engineers, which were involved in aircraft designing, were given a task to improve / rather design a better prosthetic arm for the war victims on the conclusion of World War II. These engineers utilized this Bowden cable for the first time to operate an upper limb prosthetic arm.

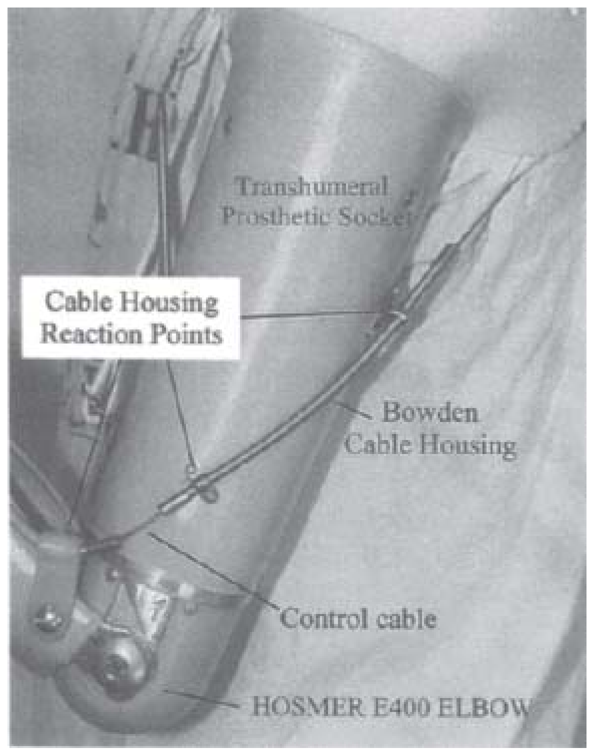


Figure 1-15: Prosthetic Hand driven by Bowden cable

1.5.6 Electric Power Sources (Batteries)

Most of the portable electronic equipment is dependent on battery technology, particularly rechargeable batteries. Prosthetics designers also work side by side with the other portable equipment designers and are ready to pick up anything which can prove to be useful. The main current consumer in the prosthetics operated by electrical power, is the dc motor(s), which is/are used to activate the device. Output torque of a dc motor is directly proportional current that it draws. In prosthesis arms the use of motor is intermittent and not continuous. It is therefore important to know that how fast and how much power a battery can provide. In order to understand the concept of power provision by a battery and power consumption by the motor certain terms are required to be understood first, these are [3]:

a. Stall Current. The maximum current drawn by the dc motor at any instant is known as the stall current.

b. Stall Torque. The maximum value of torque output generated by the dc motor at any instant is known as the stall torque.

c. Discharge Rate of a Battery. Discharge rate of a battery determines the rate at which the battery can deliver the energy to the load. Higher discharge rate is desirable, as it ensures that the battery can fulfill the energy demands faster.

d. Self Discharge Rate. The rate at which a battery gets discharged itself under no load condition is called its self-discharge rate.

When the motor is fully "ON" but unable to move further, is the instance when it is drawing stall current. This situation can happen in a hand when the fingers have grasped something and holding it and cannot close themselves further, when the fingers have to keep on exerting the same force on that object for an extended period of time. As a matter of fact the motor produces the stall torque at the same very moment. It can be dangerous for the dc motor, if it is run in "stall" situation for a longer period of time. Stall current is actually the upper limit of current requirements of that mechanism which is driven the motor, therefore it determines the specifications of the MOSFET's (field-effect transistor) and the bridges circuitry required by the motor.

The rechargeable batteries easily available off the shelf in the market today are nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion). These are the mostly used batteries in prosthetics arms as well. Li-ion gives the best capacity-to-size (weight) ratio and self-discharge characteristic, hence it is gaining popularity day by day.

Service life measure of a battery is the average number of times it can be charged and discharged. Prosthetic arm ought to have minimum one day of usage before it requires a recharged.

1.5.7 DC Electric Motors

Prosthetic arms, which are getting power from electric sources mostly use dc motors, which work on permanent magnet principle. Some arrangement for transmission of power is used in the form of gear ratios to get desired rpm. In prosthetic hands use of ironless or coreless dc motor along with some appropriate gear transmission is preferred. In order to actuate the arm mechanism, particularly for elbow joint

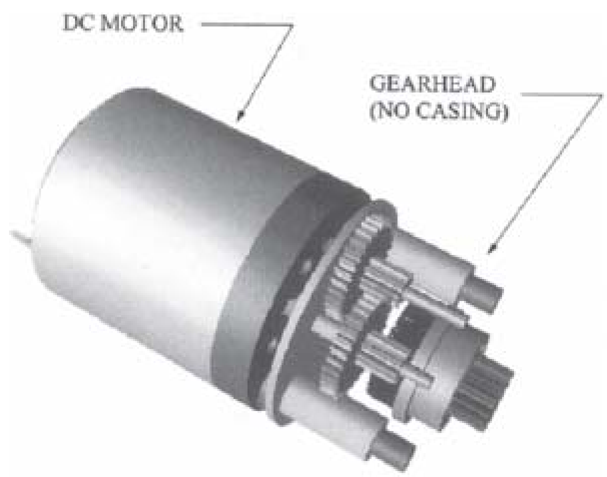


Figure 1-16: Gear arrangements of dc motor

coreless or brushless dc motors are used. Due to the small size of motor and its allied electronics, brushless dc motors can be very conveniently accommodated in the elbow joint. Due to this reason, it is gaining more popularity nowadays. Despite of its small size, still it is large enough that it cannot be used in the hands. The electronic circuitry required to control the brushless motors is a little complicated, still its use is preferred owing to its better performance as compared to coreless dc motors. With the advent of surface mounted IC technology, the complexity of electronic circuitry has further facilitated the designers in using brushless motors.

1.5.8 Synergetic Prehension

As per the definition Prehension is an act of taking hold, seizing or grasping. The process of prehension can be subdivided into two phases. The first phase is wneh the fingers are approaching the object which is to be grasped, in this phase no or very little force is being exerted and it is more of an excursion. The second phase starts when the fingers touch the object to be held and in this phase the fingers are exerting a force on the object which remains constant till it is held. This means that in first phase the requirement of speed will be more and that of torque will be less, and soon as we enter into the second phase the requirement switches as now less speed and more torque is required. The case can be different if such an object is held which deforms as the force in grasping it is increased. Example of such a compliant object can be, process of squeezing a lemon. These two phases are called synergetic prehension in which the transformation of first phase into the second one is sudden. In case of prostheses this can be achieved by the use of multiple motors, which operate simultaneously, or in collaboration. Use of multiple motors increases the number of parts, which means that failure probability of parts has increased. Moreover it not only increases the space requirements but also the cost of the prosthesis [7].

In order to design a hand mechanism it is necessary to incorporate some structure of backlock mechanism, so that the on removal of power the fingers are not forced backward and open themselves. This means that on removal of control signal the hand machinery holds its arrangement.

1.6 Anatomical Design Considerations

1.6.1 Prehension or Grasp

A hand of a human being has the capability to hold and manipulate different objects in numerous ways. Human hand Most frequently used forms of prehension limit the function of a hand. There are two basic types of a hand function, these are:

a. <u>Prehensile Functions</u>. All those functions performed by a hand which involve complete, or to a certain extent grasping and holding an object, come in the category of prehensile functions.

b. <u>Nonprehensile Functions</u>. All those functions which are performed by our hands and in which grasping or holding any object is not involved are called nonprehensile functions. Its examples can be, typing, touching something, pushing something or playing some musical instrument, like piano, guitar etc.

There are two main types of grasping techniques that are used by hands, namely power and precision.

a. Power Grasps. If the hand itself doesn't do the main movement which is involved in some action, but body or arm is doing that movement, then this grip is used. In this case the fingers are pressing the object against the flat portion of the palm, thumb involvement is not that much. Examples can be, rowing, when the batsman hits a short with the bat or gear shifting, etc. Power grasps has further four types:

i. Spherical Grasps. It is made once a ball shaped object is to be held, the fingers are spread and then curled in a way that the object is pressed against the palm.

ii. Lateral Grasps. It is used when the object is circular but is of larger size, such as holding the trunk of a tree. It is pressing the fingers against the palm in unison.

iii. Hook Grasps. In this grip thumb or palm does not take any part at all. The fingers are bent about the object, like in the case of holding anything with a handle.

iv. Cylindrical Grasps. It resembles the hook grasp but involves the thumb and palm for additional support and grip.

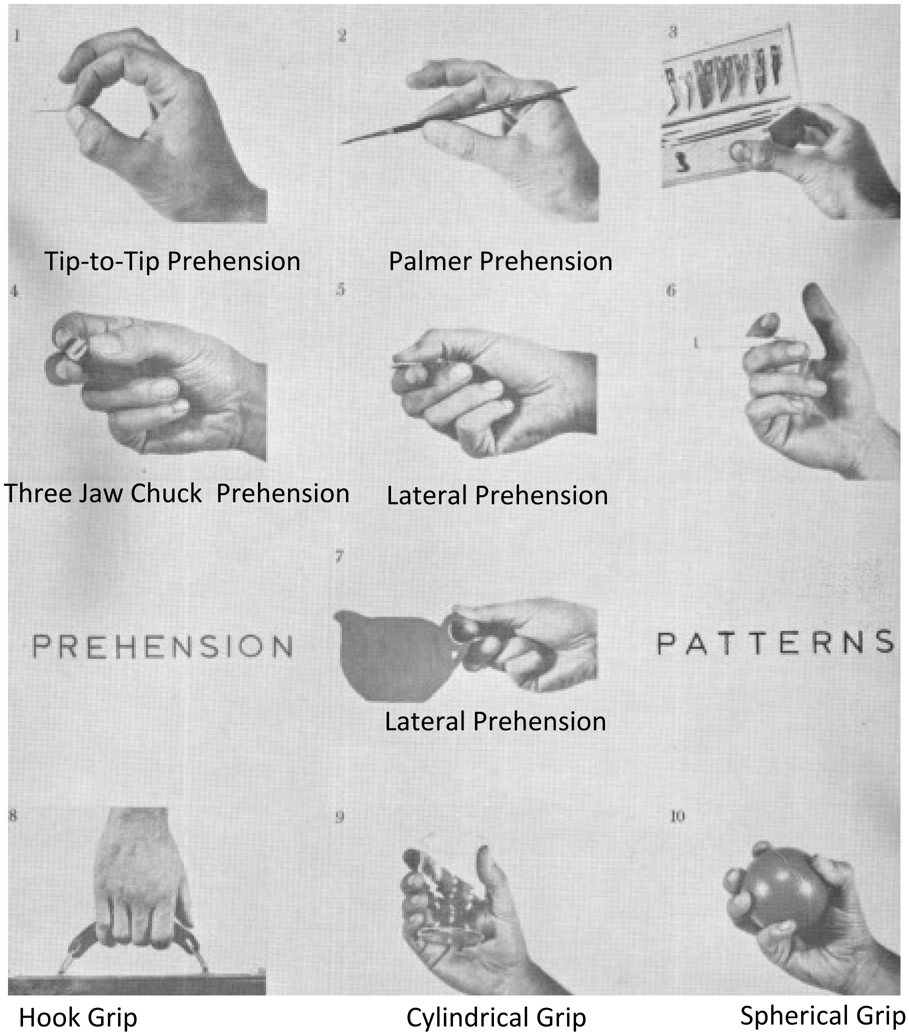


Figure 1-17: Various arrangements of prehension

b. <u>Precision Grasps</u>. Precision grasps are utilized for fine manipulations, involving very little motion of wrist and fingers. It is done by different combinations of fingers and thumb. Subdivided into further three types:

i. <u>Tip-to-Tip Prehension</u>. It is done by joining the index finger and the thumb, in order to grip some very small or fragile thing.

ii. <u>Lateral Prehension</u>. This type of grip is made by joining the thumb with the side of a finger or two fingers, example opening a lock with a key.

iii. Palmer prehension. In this case two or more fingers are pressed against the pad of thumb. Holding a pen is an example of it.

There are six grasping sample which were used by Keller et al. (1947), and which are widely accepted in prosthetic arm field. These are:

a. Tip prehension (b)

b. Palmar prehension (a1 and a2)

c. Lateral prehension (c)

d. Hook prehension (d)

e. Spherical prehension (e)

f. Cylindrical prehension (f)

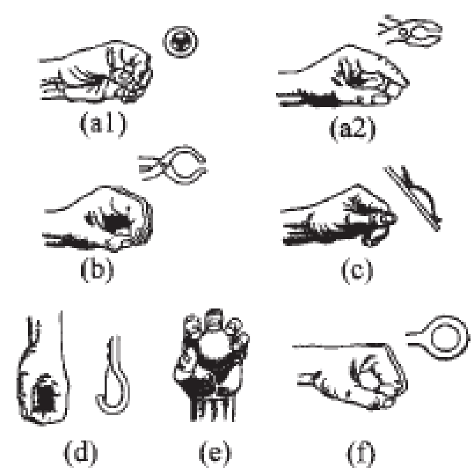


Figure 1-18: Various patterns of prehension

1.6.2 Dominant and Non-dominant Hands

Every person has a dominant hand and a non-dominant hand, it can be right or left, therefore this aspect must also be catered for while designing the prosthetics arm. The usage of dominant hand is different from that of non-dominant hand in people. Usually people use their non-dominant hand to grip the things while the work on those objects is performed by the dominant hand. It is pertinent to mention that an amputee who has lost his one hand only, will always use his artificial arm as his non-dominant hand, irrespective of this thing that it has replaced his dominant hand or non-dominant hand. Moreover the patient will have the tendency to carry the things with his dominant hand and then hold them in his non-dominant hand.

1.6.3 Submissive Adaptation While Grasping

Once an object is grasped by the hand, hand has the ability to submissively adapt the shape of the grasped object and thus improve upon its grip. Since the grasped object pushes into the skin as its grip is strengthened, it dents or depresses the soft tissues of hand which are coming under it and resultantly it experiences a little amount of reaction force. Accordingly, the depressed soft acquires the shape of the grasped object. These mechanical properties of soft tissue exhibit a nonlinear behavior, and the rigidity of these tissue increases with the increase in pressure. This property of the soft tissues ensures the tight grip of the hand. This characteristic of the hand must be incorporated by the prosthetic hand designers. This property of the hand can be mimicked In prosthetics, this adaptability offered by the soft tissue of the hand can be mimicked somewhat, by putting a thin lining of malleable plastic and a cosmetic glove over it [8].

1.7 Sensing Techniques

In the design process of a prosthetic arm and hand the physical characteristics like, appearance, weight and power are critical, yet their importance is not that decisive as is of its control, as to how an artificial arm and hand be so designed that it is operated and controlled almost without any kind of thinking process. The meaningful interfacing of a multifunctional artificial arm and hand with the amputee offers the main challenge in the designing of prosthetics. Meaningful interface means that the artificial arm must be controlled in a manner that proves to be an aid for the amputee instead of a weight slung with his shoulder only. Due to this fact control carries the main concern of designers of upper-limb prosthesis.

Main feature which are desirable in the control system of a prosthetic arm as narrated by Childress (1992) are as under [3]:

a. Minimum Mental Loading / Subconscious Control. Use of prosthesis must continue without unnecessary mental contribution. This means that the artificial arm must assist the amputee instead of burdening the patient.

b. User Friendly. Prosthetic arm must be so designed that its operation is as natural and instinctive as possible. Learn to use the device must not be difficult for the amputee.

c. Independent Control in Multifunction Operations. If a multifunctional task is to be performed the device should be able to perform these multifunctional instructions without any interference of any other control function.

d. Coordinated Multiple Functions Control. The device must be able to synchronize multiple instructions and operations simultaneously.

e. Instantaneous Response. All the available functions in the prosthetic arm, should be in direct access of the user. The response of these functions to the input commands should be prompt.

f. Available Human Abilities. The residual abilities of the amputees must be made use of, and the device must be so designed that it supplements his capabilities instead of subtracting them.

g. Appearance. Structures and motions which are unexpected, unusual i.e. more mechanical cannot remain unnoticed by the observers and gather undesired attention in social gatherings, which would not please the wearer.

By sensing technique, it is meant that pickup of a signal from the body, which is used as the input to the prosthetic arm to get a desired type of motion, or a specific function of prosthesis, its example can be, pronation, supination or flexion, abduction. If lesser sensing sources are available, then the functionality and movements of the prosthetic arm is more difficult to be achieved. Level of amputation of the patient bears very important role in the application of sensing techniques. The more the amputation level lesser number of sensing sites will be available and at the same time more control signal will be required. Hence it is an inverse relationship. In simpler words it can be phrased as for a patient with higher amputation level, sensing sources which are available for the device will be lesser, yet more number of functions would be desired from the device.

Brain waves, feet, voice, feet and eyes can be used to get the signal for the inputs of prosthesis, but these sources have not proved to be practical. Most widely used typical inputs of prosthetic arms are taken from the muscular activity, in different ways:

a. Direct from the muscle

b. Indirectly from the joints

c. Indirectly using the derivatives of muscular expansion / contraction

1.7.1 Myoelectric Control

1.7.1.1Introduction

Comprehension of EMG signals means to appreciate muscles and understand the bioelectrical signals they generate. It can be taken in two ways, one is the “forward problem,” that, how detailed machinery and phenomena manipulate the signals, and the other is the “inverse problem”, that, how does any signal mirrors a specific arrangement and a phenomenon and lets us understand their classification and explanation.

The name of Myoelectric control is taken from the electromyogram (EMG), which is used as an input for the prosthetic device in this system. Electric potential (EMG) is generated as a by-product, on contraction of a muscle. By placing the surface electrodes on the skin close to a muscle, this signal can be detected. This electrical signal is then required to be amplified and processed in order to make it useful for the prosthetic device. EMG signal’s intensity increases with the increase in the muscle tension. This is a compound and nonlinear relationship, and it is dependent on many variables, which includes position as well as the arrangement of the electrodes.

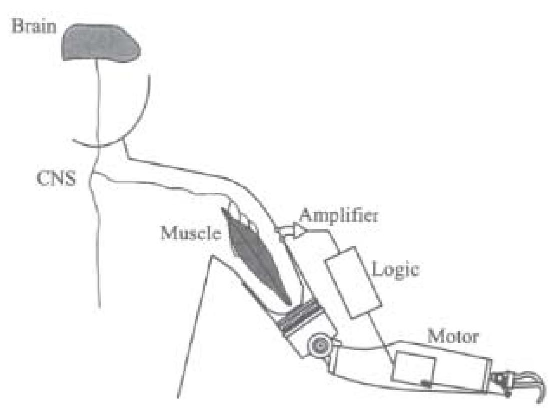


Figure 1-19: EMG operated prosthetic schematic

When the muscles contract or expand as a result of the brain signal to formulate a specific motion. As a result of muscle contraction electric potential is evolved, which is utilized by the myoelectric control system. This potential can be measured from the skin above the muscle but it is the at microvolt level. These discharged potential can be picked up by placing electrodes on the skin but since the potential is of very low value so it needs to be amplified in order to make it the input signals for the prosthesis. These myoelectric signals are used for controls only. As these signals are not that power that they can operate the motors in the prosthetic arms, therefore a 6-volt rechargeable battery, which can easily be housed in the prosthesis is used to ensure the movements of the prosthesis.

Presence of high-voltage electrical charge is necessary for the success of myoelectric prosthesis. Amputee's electrical potential must be determined, before a prescribing a myoelectric devise [9]. A highly sensitive voltmeter, must be used for this measurement, with the help of test electrodes and thus those places should be identified in the patient, where strongest signals are achieved, since the functionality of myoelectrical prosthesis is very heavily dependent on the proper and consistent signal from the electrodes, which is possible at specific lications only depending on the level of amputation of the patient.

If the amputation is below-elbow two muscles give the indicators for the operation of the prosthesis:

a. Wrist Flexor Muscle. Closing of hand is ensured by the wrist flexor muscles, hence their signal is utilized for the closure of artificial hand.

b. Wrist Extensor Muscle. Opening of the hand is carried out by the set of wrist extensor muscle, hence prosthetic hand is also opened by obtaining the signal from these muscles.

1.7.1.2 Historical Perspective

The study of EMG signals was first carried out with the help of string galvanometer by a German scientist H. Piper in 1912. After almost twelve years Gasser and Erlanger used Oscilloscope performed the same experiments in 1924. Proebster studied the signals produced by enervated muscles and established the study regarding clinical usage of EMG about within a couple of years. In 1949 Denny-Brown, talked about the "Interpretation of the Electromyogram". With the advent of computers in late 70s and early 80s, the disintegration of needle EMG into its ingredients Motor Unit Action Potential (MUAP) and ultimately observing, control systems of each motor unit became possible. This processing was completed in hours, which is done in a few minutes, today. Another advantage of computers was the simulation and developments of models to study the EMG.

An early application of EMG signals is for energizing the externally powered artificial arms. This appliance, which at a later stage was known as myoelectric sensing technique, it was exhibited for the first time in the 1940s, and achieved rapid development in 60s, 70s, and 1980s. At present the research and development in the field of EMG based controllers is progressing at a very fast rate.

Needle EMG methods can sense MUAPs to a smaller extent close to the tip of the needle and give limited information regarding either outward or deep muscles. The tissues interjected in between the EMG signal source and the electrodes, cause some information loss. This makes the interpretation of EMG signals picked up from surface more difficult than those of needle EMG. Despite of this fact, due to being noninvasive and easy to use surface EMG has gained more popularity. It is really easy to have a pair of electrodes on the skin over the muscle, acquire a signal and sketch some “findings” regarding the outline, modalities, and strength of muscle contraction / extension.

In order to resolve the issues associated with the surface EMG as compared to needle EMG, a researcher’s group suggested that European Community (EC) should support a determined research on *Surface EMG for Noninvasive Assessment of Muscles (SENIAM).* This research got the funding from EC in 1996 and continued to work for three years. Its purpose was to increase international coordination of European laboratories which were working in the field.

At present surface EMG technology is an important tool for many applications in the areas of ergonomics, prosthestics control, movement investigations, and it permits recurrent and unproblematic estimation and appraisal of neuromuscular occupations.

1.7.1.3Literature Review

In a research paper by Peter C. Doerschuk, Donald E. Gustafson, and Alan S. Willsky [10], in 1989 titled “Upper Extremity Limb Function Discrimination Using EMG Signal Analysis” designing of a system using latest digital signal processing methods in order to generate control signals to operate a multifunction prosthetic arm from surface EMG signals was carried out. Major work conducted in the paper was to estimate the forces which are generated in a set of muscles and further use of these estimates to operate the kinematic copy of the actual limb. The outputs of the design were actual arm, operations like, forces and / or velocities which could have been utilized to input the motors of a prosthetic arm. The operation was in two steps:

a. Process 1. Estimate the forces generated by a set of muscles

b. Process 2. Using the estimates to replicate the motion of limb

In this research a technique was developed to analyze the signal with the aim of differentiating the functions of lower arm and wrist while using signals from surface EMG. Four electrodes were positioned on the proximal portion of forearm and their data was obtained. Flexion / extension and abduction / adduction of wrist along with pronation / supination movements of forearm were analyzed. Each function of the wrist and forearm were modeled in multivariate autoregression models. Differentiation of these models was done with the use of a multiple-model theory recognition technique. This approach was a sequel of the work of Graupe and Cline [11] with the usage of spatial correlations and more generalized detection philosophy. These possibilities provide enough statistics for the problem.

In another research paper titled, "Removing Power Line Noise From Recorded EMG" by David T. Mewett, Homer Nazeran and Karen J. [12], simulated as well as recorder EMG signals were used and three techniques for offline elimination of power line nosiness (humming) from these signals were evaluated. The detail of the three methods is as follows:

a. Notch Filter. In the first technique a simple recursive digital notch filter was used.

b. Regression-Subtraction. In the second technique, the phase and amplitude of noise were approximated by regressing sine and cosine functions onto a 'quiet period' prior to the commencement of muscular contraction. A sinusoidal wave with this phase, magnitude and frequency was then deducted from the complete signal length.

c. Spectrum Interpolation. Third technique was based on the assumption that Signal's original component's magnitude can be approximated at the frequency of interference by interpolation within the adjacent frequency bins of power spectrum.

Previously EMG signals were simulated and comparisons between the three methods were made but with the usage of lesser satisfactory models [13]. Only on the basis of the simulated data, it was considered still hard to identify the 'best' processing technique for elimination of power line noises. Generally Regression-Subtraction was considered to be the most capable but not for all situations.

SNR gets degraded by notch filters, due to the nonlinear phase response and reduced signal frequencies, which introduces deformation in the signal. Spectrum Interpolation is also not an ideal method, since it cannot differentiate between the periodic and aperiodic interference in the signal of interest.

Another research paper by Richard F.*ff*. Weir, PhD, Edward C. Grahn, BSME, Stephen J. Duff, AASET, "A New Externally Powered, Myoelectrically Controlled Prosthesis for Persons with Partial-Hand Amputations at the Metacarpals"[14], described a novel externally powered, myoelectrically controlled artificial-hand and its interface, purpose was the need of a more modern device for the amputees. To position the hand mechanism, it was felt necessary to preserve the wrist motion, in order to achieve maximum functionality and cosmesis. The most challenging design issue was to have all the required mechanism and its allied electronics in that limited space, without distorting the performance. Initially a prototype transmetacarpal mechanism of hand was developed, which was completed. The mechanism's control and its interface was further refined. Areas of designs, which required improvements were identified.

In another research paper by Richard F.*ff*. Weir, PhD, Edward C. Grahn, BSME, Stephen J. Duff, AASET, "A New Externally Powered, Myoelectrically Controlled Prosthesis for Persons with Partial-Hand Amputations at the Metacarpals"[15], a new externally-powered prosthesis was developed for amputees of the level of the metacarpophalangeal (MCP) joint. Still the limitation of aesthetics restricted the accommodation of the entire drive mechanism.

In another research paper by M. Zecca, S. Micera, M. C. Carrozza, & P. Dario, titled "Control of Multifunctional Prosthetic Hands by Processing the Electromyographic Signal"[16], it was accepted that human hand is a multifarious structure, which has large figure of degrees of freedom (DoFs). Artificial hands developed uptill then were just copying natural hand, with reduced holding ability and literally no sensory feedback. Hence a review of the methods applied to control prosthetic hand using EMG, was carried out. Moreover future developmental possibilities as regards to control strategy were advised. The suggested solutions to the problems are as under:

a. The possibilities to resolve the limitations of the EMG based sensing techniques, can be interfacing the peripheral nervous system (PNS) with the artificial device i.e., a "natural" neural interface (NI). Fabrication of selective neural interfaces has become possible due to the latest technology of electronic implants and the understanding of nerve tasks. These can work by exchanging information between computerized instruments and nervous system. Sensory feedback of the user can be restored to some extent by a biocompatible neural interface. If the amputee will get some sensory feedback from the instigation of the afferent nerves, and the prosthetic hand is controlled directly through the efferent nerves, the user can still "feel" the prosthetic device as part of his own body.

b. Two situations can be possible,

   i. EMG based prosthetic hand can give a "cheap" solution, which will be of less cost, will use non invasive technique and will restore the functionality of the hand partially.

   ii. Multifunctional "cybernetic" prosthetic device using ENG-based control technique, giving the amputee a real hand like feel, which will be more sophisticated.

In another research paper by C. M. Lighty, P. H. Chappelly, B. Hudginsz and K. Engelhartz, titled "Intelligent multifunction myoelectric control of hand prostheses" [17], again it was emphasized that intuitive control is difficult in EMG prosthetic devices without the nonexistence of proprioceptive feedback, with it amputee can monitor the grip pressure visually. Presently the available prosthetic hand gives a pincer motion. In order to resolve this functionality issue multi-axis hands will be required. A hybrid controller has been presented in this paper, which enables various prehensile functions and those can be instigated directly by user's EMG signal. In order to regulate the grip pressure of a hand having six degrees of freedom, a digital signal processor (DSP) has been suggested, which ensures tight prehension continuously without even looking at it. The major drawback of these systems is the raised intellective burden on the user. This shortcoming can be removed by the integration of intelligent and multifaceted prehension.

In another research paper by M.C. Carrozza, F. Vecchi, F. Sebastiani, G. Cappiello, S. Roccella, M. Zecca, R. Lazzarini and P. Dario, titled "Experimental analysis of an innovative prosthetic hand with proprioceptive sensors"[18], the idea of an underactuated prosthetic hand for functional replacement of the physiological hand was presented. There are three main function of physiological hand, these are, seizing, handling and exploration. There are two basic steps, which are required to restore these capabilities of physiological hand:

a. Development of a hand furnished with synthetic proprioceptive and exteroceptive sensors

b. Provision of proper interface, which can swap sensory-motor signals with the residual limb of the patient and the nervous system

Structural design of the suggested hand is composed of five modules. First one is an main structure of the hand (muscoskeletal system), the second one is a proprioceptive sensory system, which can sense the position and force, the third one is an exteroceptive sensory system, which is a 3 Dimensional force sensor, fourth one is an inserted control unit, which can detect the control loop of low level only and is dedicated to control initial slippage and grasping, and the fifth and the last module of the design is an electromyographic (EMG) interface between human and machine, which will control the prosthetic hand. This paper gave the proposal of the manufacture and experimental characterization of that hand. Linear behavior has been achieved by the proprioceptive sensory formation.

In another research paper by Adrian D. C. Chan, Geoffrey C. Green, titled "Myoelectric control development toolbox"[19], it is again emphasized that Surface myoelectric signals (MES) can also be utilized as input signals for the control of prosthetic arm. In the beginning MES used to be parameterize by amplitude, but a practical limitation was imposed on it as three position system was required for all MES control sites, like hand open, rest and hand close[20], which necessitated the requirement of more MES control sites. Graupe and Cline [11] separated various movements of limb from a single MES site. Later in 1993 pattern recognition methods were utilized by Hudgins. [21] to use the existence of a deterministic pattern at the start of muscle contractions. On the basis of this a system was devised, which was capable of differentiating four limb motions, with an accuracy of approximately 90% when used by a normal limbed subjects and its accuracy was about 85% when used by amputees. However it was required that the user must control the system by the contractions which should start from rest. This means that the user can not switch between different states intuitively and continuously. Recently myoelectric control methods have been evolved in which the user have an intuitive user interface [22].

In another research paper by B.A. Lock, K. Englehart, Ph.D., B. Hudgins, Ph.D, titled “Real-time myoelectric control in a virtual environment to relate usability vs. accuracy”[23], in 2005 a MES control software tool has been developed, which gives the prosthetic hand the capability of a multifunction control and a real-time multifunction virtual limb. Initial results of the experiments of the software indicate a strong link in between usability and the accuracy. It features a multifunction prosthetic control software set which has specifically been developed for academic and clinical use.

In another research paper by L. Galiano, E. Montaner and A. Flecha Bioparx, titled “Research, Design & Development Project Myoelectric Prosthesis of Upper Limb”[24], in 2007, a design was researched and a project of a myoelectric prosthetic arm was taken up for pediatric congenital amputees with left below the elbow amputation. Prototype mechanical structure was designed and manufactured, incorporating the electronic circuitry involved in EMG signal aquisition, EMg signal processing and its control logic. Presently the the project team is working on its interface of the prosthesis with the patient.

In another research paper by, Edward A. Clancy, Mark V. Bertolina, Roberto Merletti, Dario Farina, titled ” Time- and frequency-domain monitoring of the myoelectric signal during a long-duration, cyclic, force-varying, fatiguing hand-grip task”[25], in 2008, amplitude and mean power spectral frequency (MNF) of the EMG of flexor digitorum superficialis and extensor carpi radialis muscles were observed during repeated, with a varying force, steady-posture, till the limit of endurance grip-force contractions. Moreover, short interval (8 sec) static-force contractions were interspersed within the periodic contractions with 5 min. MNF was pathed during these cycles. The observations of each subjects subject was the same, everybody observed an increase in uncomfortable, painful and fatigued experience in the contraction trials. The results show limitations in the usage of EMG descriptors for appraisal of fatigue during long-term, with a varying force contractions.

In another research paper by Slim Yacoub, Kosai Raoof, titled “Noise Removal from Surface Respiratory EMG Signal”[26], in 2008, researchers have worked on elimination of two main noises, the electrocardiogram ECG artifact and the line noise artifact. Lean Mean Square (LMS) is the proposed algorithm. A reference signal associated with the noise polluting the signal is required. This reference noise is extracted, it can be constructed mathematically by the use of two unlike cosine functions, 50 Hz and 150 Hz for line noise. Second with a matching search method, together with LMS structure for the ECG artifact estimation. The performance of the projected technique was evaluated with already performed research results.

In another research paper by 18. Md. R. Ahsan, Muhammad I. Ibrahimy and Othman O. Khalifa, "Advances in Electromyogram Signal Classification to Improve the Quality of Life for the Disabled and Aged People"[27], in 2010, research has been aimed at improving the Quality Of Life (QOL) of disabled, by development of simple, user friendly, robust and more real time interfacing devices. The research centered on the advancements in various techniques used for EMG signal categorization. This study unlocked a corridor for the future researchers to perform future comparisons between various EMG categorization techniques.

CHAPTER 2

EMG SIGNAL GENERATION, PROCESSING AND UTILIZATION

2.1 Historical Perspective

Surface electromyography (SEMG) is linked historically with the innovation of electricity and the advancement in the instrumentation, which made the mankind able to see or sense the things which could have not been felt, seen or sensed using the five human senses. The second step in the history of surface EMG is the appearance of the concept for gauging muscle's energy.

In mid-1600s, Francesco Redi [28,29] realized that energy of muscle was the actual source of energy of electric ray fish. Walsh demonstrated that spark of electricity could be generated by Eel's tissue of muscles in 1773. In 1790 for the first time direct evidence was obtained about the relationship between the contraction of muscles and electric signal by Galvani [30]. In early 1800s galvanometer was invented, which could have been used for measurement of electric signals and hence its relation with the contraction or expansion of muscle could be evaluated. By 1849, the evidence of electric signal in the human muscles while contraction or expansion was obtained or discovered for the first time by Du Bois- Reymond [31]. He experimented by placing a blotting cloth on the hands or forearms of a person and the hands were immersed in separate tubs of saline solution, and the electrodes were connected to the galvanometer. On any kind of movement of hand or forearm, very little but noticeable and predictable deflection was observed. The deduction obtained by Du Bois- Reymond was that impedance offered by the skin is the main reason of less magnitude of electric signal. In order to strengthen this concept, he repeated his experiment after removing some portion of skin from the forearm and placing the electrodes underneath, resultantly a spectacular increase in signal's magnitude was noticed during wrist movement.

Field of clinical EMG was opened in 1928 by Proebster as he observed the signals created by denervated muscles [32]. Adrian and Bronk in 1929 [33] developed concentric needle electrode, which became a powerful tool and is widely used today even. In the following decades Vacuum tube amplifiers [34] and solid state circuits were used, which includes contributions by Stalberg, Buchthal, Gydikov, Rosenfalck, Kugelberg, Petersen and Kosarov [35, 36, 37, 38, 39, 40, 41, 42] who can be called the founders of methodology and analysis of the Motor Unit Action Potential (MUAP). Along with many others who worked in this field of EMG, the work of Denny-Brown, who deliberated on "Interpretation of the Electromyogram" in 1949 [43], and Willison, who did the analysis of turns and amplitude of EMG signal in 1964 [44] are very important. First edition of *Muscles Alive* by J. V. Basmajian, which was published in 1962 can be called a milestone in the development of this field [45]. With the advent of powerful computers in late 1970s and early 1980s the huge assignment of decomposition of needle EMG into its constituent MUAP trains became possible.

Computers also permitted the advancement in the field of models and simulations in EMG studies. In the modelling field Dimitrova and Lindstrom, [46,47] are considered to the pioneers. Modelling contributes in understanding the EMG biophysics and helps in interpreting the information the signal contains. Moreover models are used for training purpose, improving the present applications and for developing new applications. A very significant and useful application of EMG signals, can be to drive or control an externally powered upper limb prostheses. This application which is called myoelectric control, was first exhibited in the 1940s [48], and much work has been done in this field during 1960s, 1970s, and 1980s [49, 50, 51, 52]. In this field pattern recognition on the basis of EMG and its utilization for the control of multifunction powered prostheses are the main areas in which research are going on [53, 54].

Intellectual research on surface EMG has also thrived. In early 1960s, Basmajian was the first one to conceive the idea about an international forum for having a platform to share information on surface EMG, resultantly in 1965 the International Society of Electrophysiological Kinesiology (ISEK) was established. This society exists today even, and publishes the only journal that particularly focuses on the issues of surface EMG (*The Journal of Electromyography and Kinesiology*). Academic communities of American and European (specifically the Scandinavians) have worked in this field and given a strong base for the work of EMG and surface EMG. The work of many contributors needs to be acknowledged but due to the space constraints it is difficult, however the work of Carlo DeLuca and his equals at the Neuromuscular Research Institute in Boston can never be forgotten. Their work on muscle fatigue and spectral analysis [55] has given a lead in the field of muscle physiology and its measurement methods.

2.2 Basic Physiology of Motor Control and Muscle Contraction

An experimental technique used for development, reading and analyzing the myoelectric signal is called Electromyography (EMG). Physiological variations in the membranes of muscle fibre cause these myoelectric signals.

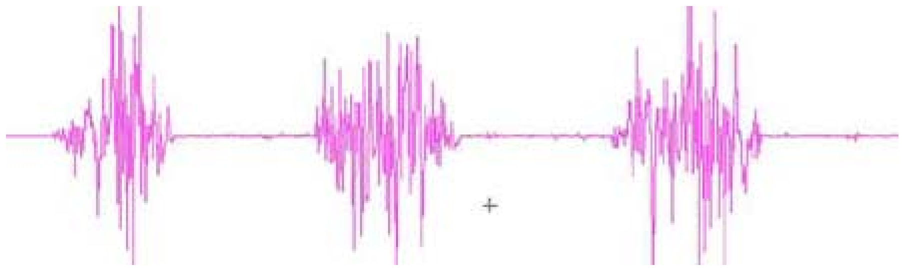


Figure 2-1: Electromyography Signal

It would not be fair to study the human musculature system without having a background of human body which is the most complex machine. Connective tissues work as **"sack"** for the fibres of muscles. Without their assistance the muscles can neither remain hinged with the bones nor can they be organized to perform a task.

Muscle is the main organ and the most dominant tissue of our body as stated by Huxley [57]. 70% to 85% of our gross weight comprised of muscles, moreover maximum of energy of our body is consumed by muscles. The increment with work in the metabolic needs of various organs of our body is very less as compared to that of muscles. Our body comprises of many small muscle cells, which are known as **myofibrils**. When these muscle cells work, they shorten their resting length, in this process it ratchets myosin fibres instead of actin fibre.

In order to understand the function of muscles, understanding of bones and connective tissue is necessary. Connective tissue are not only the edges of each muscles, but they also join them with the body and the connective tissues which join the muscles with the bones are called **tendons**. Movement and erect posture of our extremities is ensured by the **bones**, our body quiver on the floor and would not be able to do any work in the absence of these bones. If we say that fasciae is the sacks of our muscles and rigidity in our posture is due to the bones then, the final shape of our body is due to these muscles. Our skeleton cannot remain in erect position by itself, the muscles gives us our posture.

2.2.1 Motor Unit

Motor system of a human being has to be diversified to cope with the internal and external demands and constraints. These demands and constraints can be requirement of force for powerful and exact movements, locomotion, upright posture and all the gestures in our inventory. Skeletomotor system is the main controlling system of movement and force in the humans.

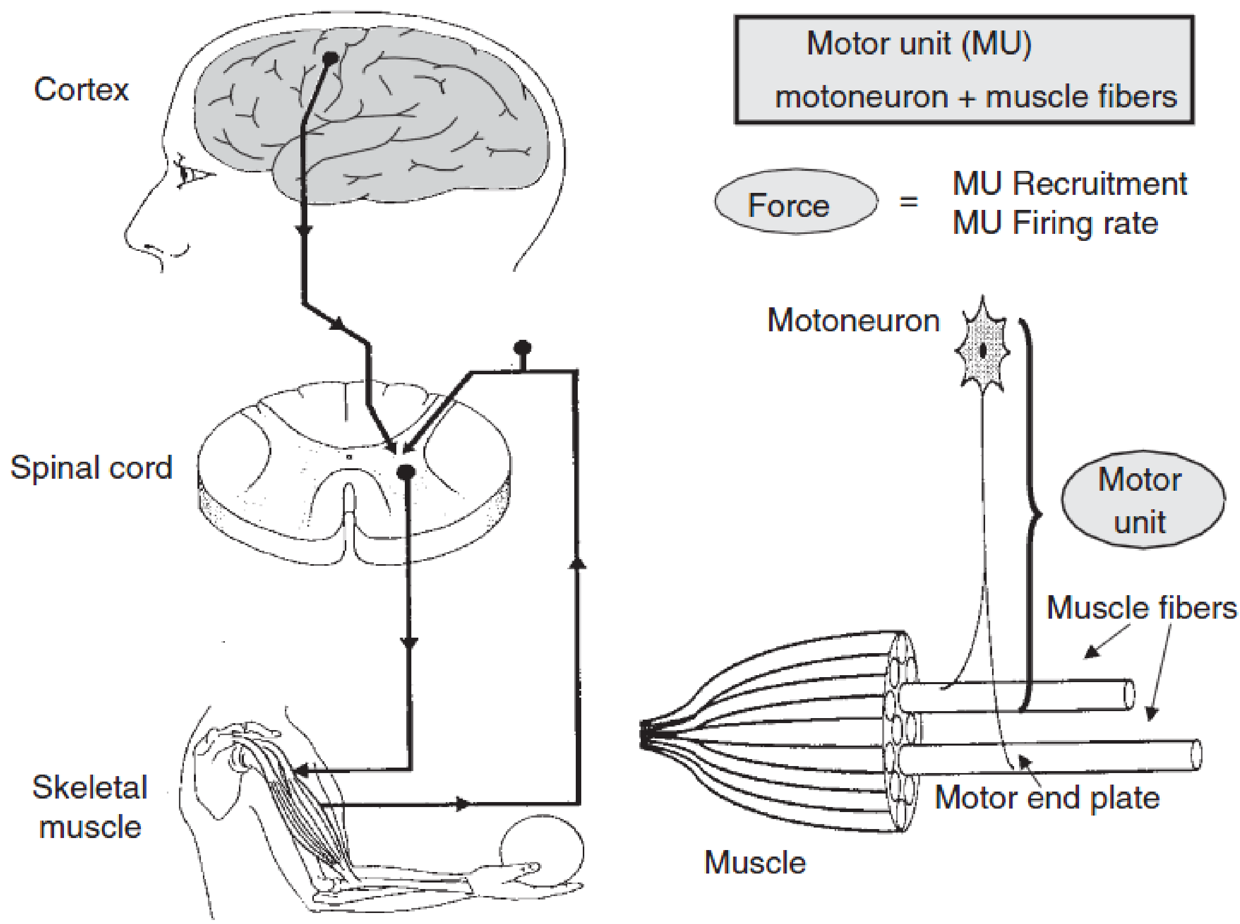


Figure 2-2: Mechanism of motor control (Block Diagram)

Programming of an intended movement is carried out in the premotor cortex, supplementary motor area, and its other associated areas. This programming becomes the input of primary motor cortex and stimulates or restrains various neurons of primary motor cortex. The resultant output of primary motor cortex is influential for interneurons and motoneurons of brain stem and of spinal cord. There is a linkage between the corticospinal tract and alpha (α)-motoneurons, which controls the muscle activity directly.

A motor unit (MU) comprises of an α-motoneuron, which is in the spinal cord and the muscle fibers, which it innervates. All the descending inputs sum up at α-motoneuron, which is its end point. Activity of MU and its discharge (firing) pattern is determined by the total membrane current induced in this motoneuron by various joining inlets in it. MU in one muscle in human beings can be from 100 to 1000 depending on the size of muscles [58].

Motor Units (MU) have been classified into three types on the basis their physiological properties, like sensitivity and fatigue [59],

a. Fast-Twitch, Fatigable (FF or type IIb)

b. Fast-Twitch, Fatigue Resistant (FR or type IIa)

c. Slow-Twitch (S or type I), which is most resistant to fatigue.

2.2.2 Motor Unit Recruitment and Firing Frequency (Rate Coding)

Henneman in 1960s, advised that MU are recruited as per the size of α-motoneuron [60]. Due to the huge number of data in support of order based on size of α-motoneuron in a many experiments, it is referred as "normal sequence of recruitment" or "orderly recruitment" [61]. Electrical activity in a muscle is determined by the quantity of MUs recruited and mean discharge of their frequency of excitation [62, 63]. Therefore direct relationship exists between the exerted force and the electromyogram (EMG).

A set of raw surface EMG reading along with the corresponding force curve are shown in the figure below. Power spectral data of the frequency of surface EMG frequency are also highlited in the figure. A progressive increase in the EMG activity along with teh generated force is clealy evident, which indicates gradual recruitment of MU and modulation in their firing rate as per the demand of required force. Hence it can be said that MU recruitment and modulation of its firing frequency is represented by the increase in the amplitude of EMG [63].

However, recruitment of MU and its firing frequency are not the only contributing factors for changes in surface EMG, as fibre potential of each muscle, fatigue and MU discharge synchronization also influences the amplitude of EMG signal [62, 64, 65, 66, 67].

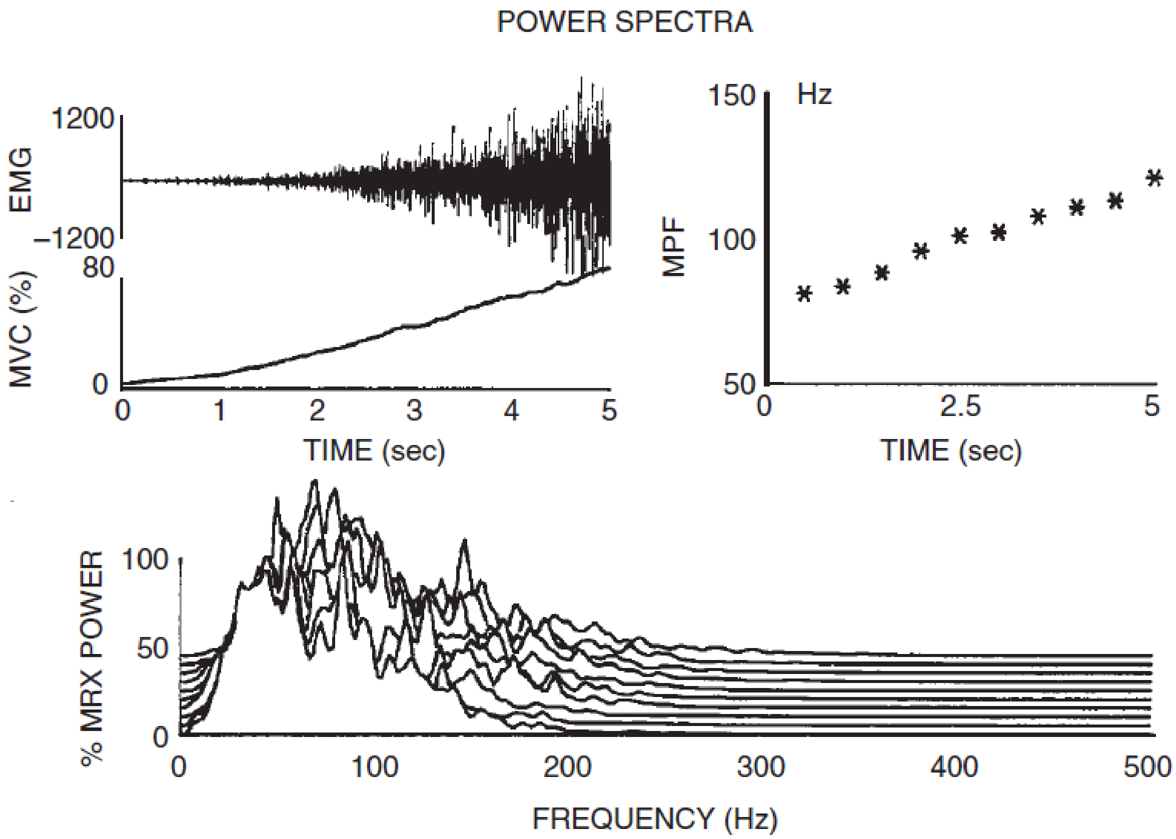


Figure 2-3: Variations are shown in EMG

Figure (below) represents the recording of a direct single MU using bipolar wire electrodes. Greater spikes are representing the additional MU, they can even be seen even at about 80% of maximal force production.

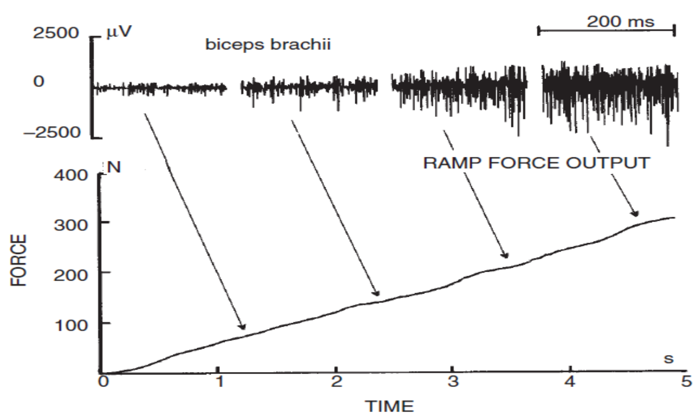


Figure 2-4: Spikes of EMG signal

2.3 Basic Electrophysiology of Muscle Cell Membrane

EMG signal is generated as a result of bioelectric phenomena, which takes place in the muscle fibre membrane. Nerve cells has remained the focus of most of the studies conducted on cell electrophysiology. However the complexity of muscle cell membrane is greater than that of nerve cell membrane, due to the difference in its invaginations, layers and electrical parameters. It has small tubes (tubules), which are oriented radially into muscle fibres and make a network which is known as tubular system (T-system). Radial current, which carries the action potential from the outer membrane passes through these tubules. [68].

2.3.1 Excitability of Muscle Membranes

In the physiology of muscles, one of the major factors is the excitation of fibres of muscles is its excitability by neural control. In order to understand this phenomenon, let's consider a model of a semi-permeable membrane, which exhibits the same electrical properties as that of sarcolemna.

a. <u>Resting Potential</u>. It is structured due to the existence of an ionic equilibrium amongst the outer and inner layers at the muscle fibre membrane in a muscle cell, its value ranges between approximately -80 to -90 mV when the muscle is not contracted. A physiological process like ion pump, which is responsible for maintaining this difference in potential, concludes on the formation of a negative intracellular charge as compared to the outer surface.

b. <u>Depolarization</u>. When the central nervous system activates an alpha (α)-motor neuron anterior horn cell, this excitation is conducted along the motor nerve. As a result of this conduction of excitation some transmitter substances is released at the motor endplates and hence at the muscle fibre, which is innervated through the said motor unit, some endplate potential gets formed at the muscle fibre. Formation of this potential difference at the muscle end plate causes a brief modification in the muscle fibre membrane's diffusion characteristics and $Na+$ ions starts to flow in. Resultantly the membrane gets Depolarized.

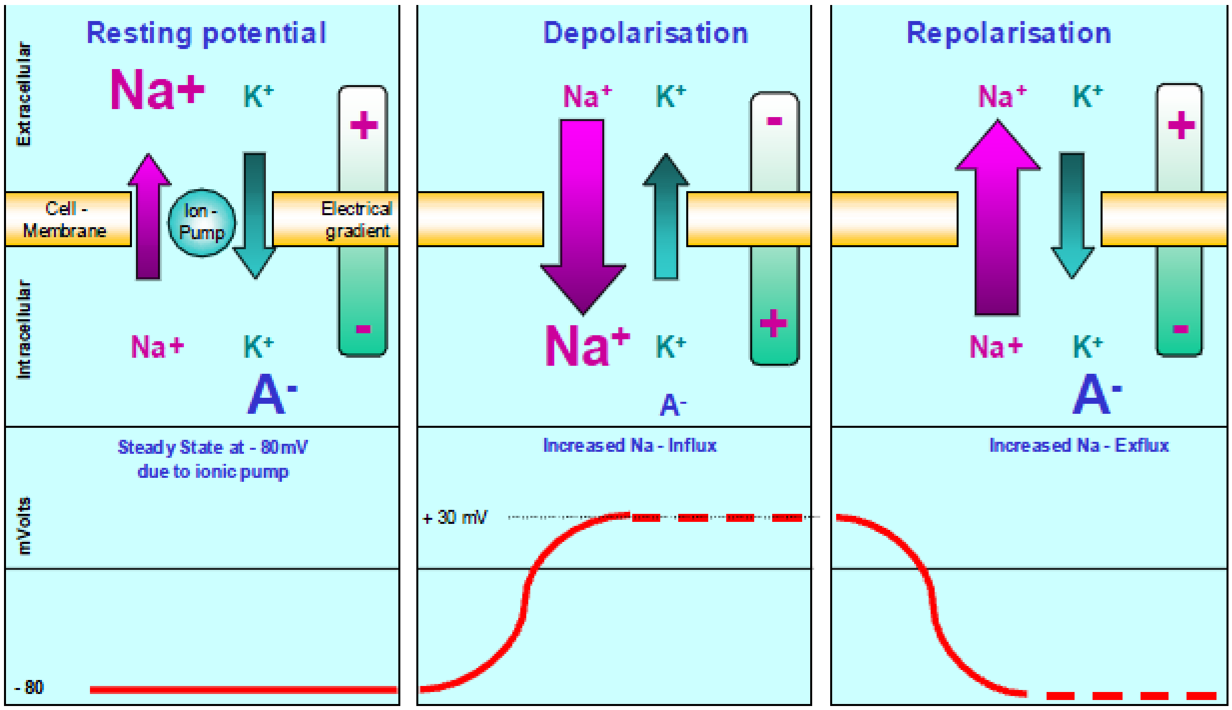


Figure 2-5: Generation of Potential

c. Repolarization. This depolarization gets restored immediately due to the exchange of ions in backward direction due to the mechanism of active ion pump, this phenomena is called Repolarization.

2.3.2 EMG Signal Generation

If the Na+ influx exceeds a specified threshold level, the muscle fibre membrane gets depolarized and resultantly an action potential gets changed from – 80 mV up to + 30 mV very quickly. This phase can be referred to as a monopolar electrical burst, which is restored immediately through the repolarization phase, but it is continued into another phase called an after Hyperpolarization. This cycle originates at the motor end plates, and the action potential extends in both directions into and inside the fibre of muscles by the T-system.

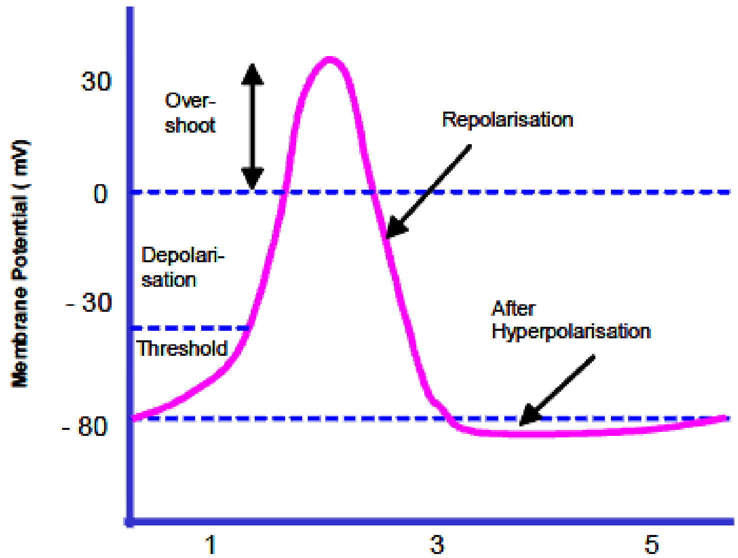


Figure 2-6: Potential Generation

As a result of this excitation, calcium ions are released in the intra-cellular space. This release of calcium ions is linked with a chemical processes (which is a combination of electrical and mechanical processes) due to which the muscle cell's contractile elements gets shortened. There exists a great relationship in between the excitation and contraction, and it results in weak but recognizable electrical signals. Electrical signal bases upon the action potentials fibre membrane of the muscles and is a result of combined depolarization and repolarization procedures.

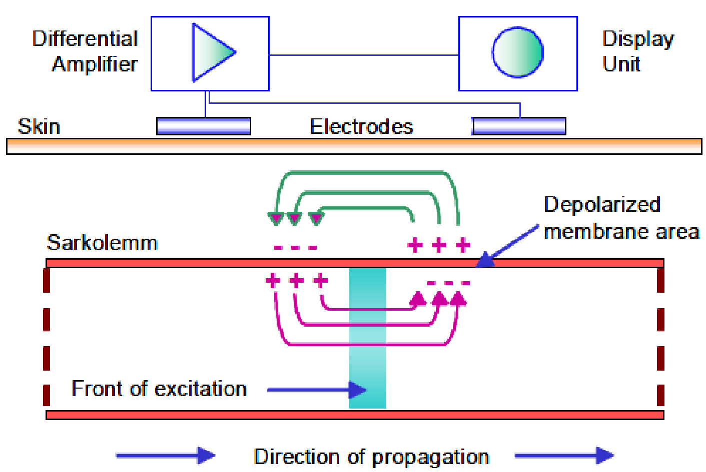


Figure 2-7: Phase of depolarisation

2.4 An electrical model for the motor action potential

A depolarization wave is formed by the depolarization and repolarization cycle, this wave passes through muscle fibre's surface. Usually a bipolar electrode along with differential amplification is the configuration, which suits the measurement of kinesiological EMG. In order to have a better understanding only the detection step is described in the following figure. On the basis of the distance between first and the second electrode a potential difference is formed between the two electrodes by the dipole.

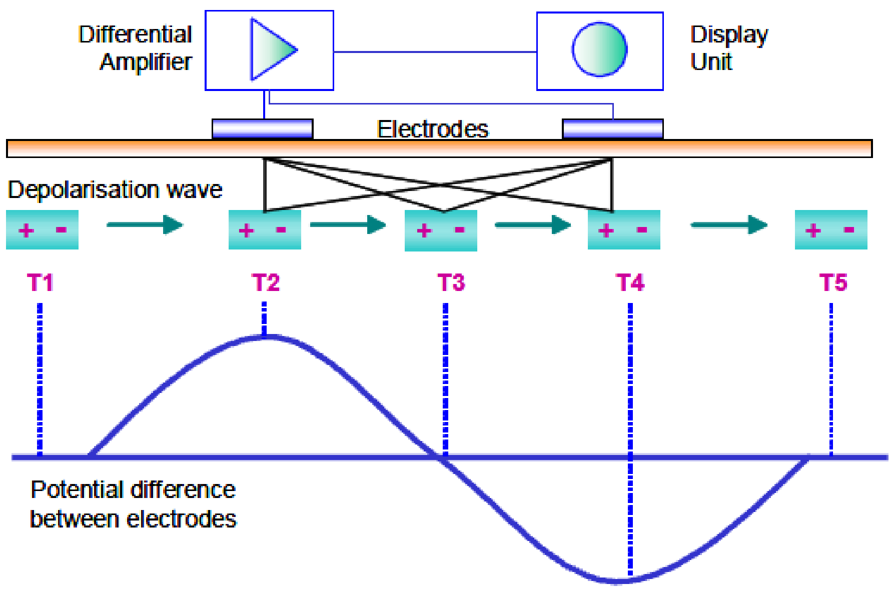


Figure 2-8: Electrical dipole model on the membrane of muscle fibre

In the above figure, action potential is created at time point **T1**, it is then taken towards the pair of electrodes for detection. In between the electrodes a rising potential difference is gauged which is at its peak at point **T2**. The potential difference crosses zero line and becomes higest at point **T4**, if dipole arrives at equal distance between the two electrodes. This means that there is a shortest distance from second electrode. A question arises that how a bipolar signal is experienced during the differential amplification process. Answer can be that MU comprises of numerous muscle fibers, and the magnitude of all the muscle fibres in this MU is detected by the electrode pair, on the basis of the their resolution and spatial distance. Usually, the result is a triphasic Motor unit action potential (MUAP), which varies in its shape and size on the basis of its geometrical fiber orientation.

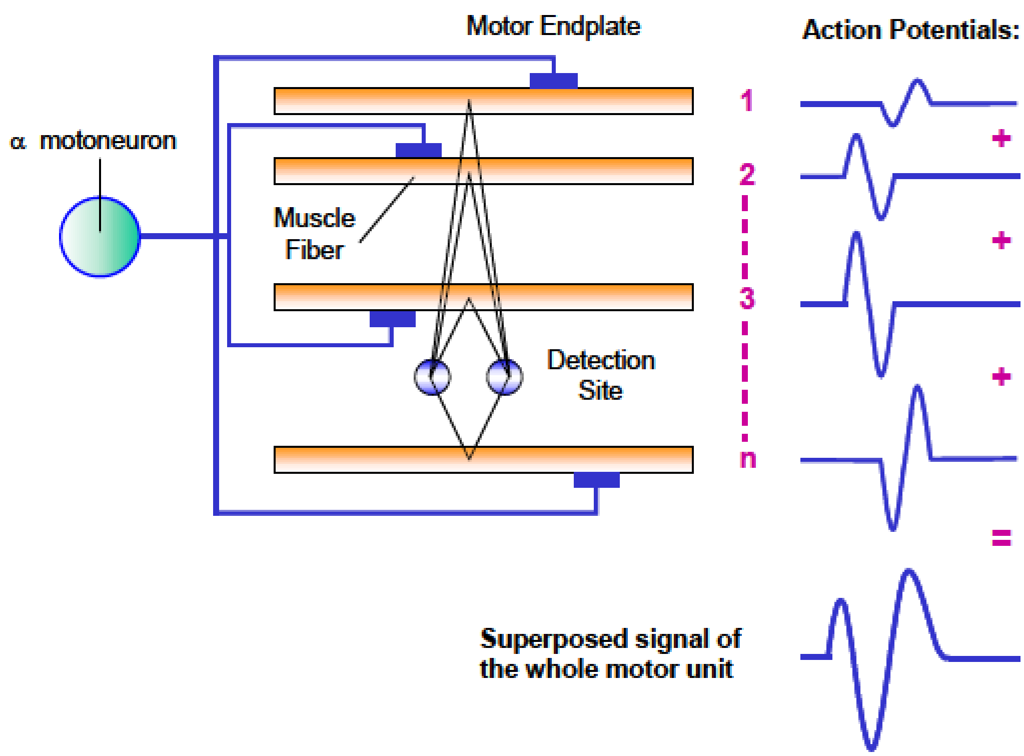


Figure 2-9: Motor Recruitment along with frequency of firing

2.5 EMG Signal Acquisition

2.5.1 Choice of Electrodes

In order to measure the intramuscular EMG signal, the electrodes must be so configured that the possibility of acquiring MUAPs for every active MU become maximum. It can be ensured by having an electrode which has a small detection surface, so that the fibres of distinct MUs have different distances from the electrode. However, the drawback associated with this small detection surface is that that greater changes in the detected MUAPs will be observed due to surface movements, this will make the recognition of MUAP difficult. Conversely if the size of detection surface is kept larger, the distance of more muscle fibres of each MU from the detection surface becomes same. Therefore preference is always given to monopolar, concentric, single fibre or fine-wire needle electrodes [69, 70].

2.5.2 Protocol for Signal Detection

The detection of EMG signal is a complex ask and is dependent on electrode type, placement of electrode, the selected muscle and its contraction profile. Placement of the electrode must be such that active muscle fibres are close to it and is able to detect the MUAPs of maximum sharpness and highest amplitude. This way the relative variation in the distance between the surface of electrode and the fibres of different MUs can be maximized. This helps in avoiding noise as the MUAPs which are different from the background noise can be separated. Recommended steps are as follows:

a. The electrode should be positioned at a place where the contraction of muscle is minimum, so that the MUAP of maximum sharpness and highest amplitude can be detected.

b. The increase in the muscle contraction should be as isometrically as possible.

c. Data acquisition should be started only once the contraction of muscle reaches a desired level.

d. If the signal processing can be done during the muscle contraction, then data should be acquired as soon as the electrode is placed.

2.5.3 Attributes of EMG Signal

Ideally the decomposition system used with EMG signals must have the capability to process the signals successfully having following characteristics:

a. Five or more motor unit action potential trains (MUAPTs)

b. Nonstationary MUAP shapes, usually due to electrode movement

c. Variable MUAP shapes due to variability in the operation of neuromuscular junctions and background biological noise due to the activity of other MUs

d. Two or more MUs with similar MUAP shapes

e. Frequent superpositions of MUAPs

f. Nonstationary MU firing pattern statistics

g. Intermittent recruitment and decruitment of MUs.

2.6 Detection of MUAPs or Signal Segmentation

Theoretically all MUAPs which were generated by the active MUs while the signal was acquired must be detected for signal decomposition. However practically there are many MUAPs whose fibres are away from the detection surface. They are minute and having less frequency, which makes it difficult to assign to their correct MUAPTs. Therefore it is better to detect only those MUAPs which have such a high frequency and size that they can be assigned correctly. A statistics is computed for each signal sample and then this is compared with a preset threshold. If the obtained value is more than the preset threshold, then it can be said that the MUAP is representing neighbouring signal [71, 72].

Low-pass differentiation or bandpass filtering, curtails the length of MUAPs, resultantly their sequential overlap and their quantity of superimposed waveforms is reduced. It also shrinks the amplitude of several MUAPs of different MUs, whose fibres are not in close vicinity of electrode.

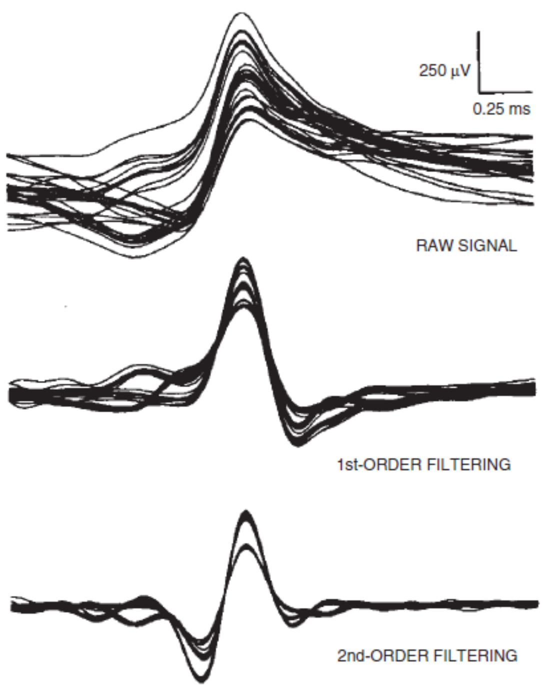


Figure 2-10: Signal after a bandpass filter

The effects of 1st and 2nd order difference filtering are shown in the above figure. It is evident that a few of non-discriminative baseline noise are removed and MUAPs have shorter duration, after the process of filtering. Difference filters, which have been proposed by McGill [73] are arranged in a way that it suppresses high-frequency noise (above 3 kHz) and low-frequency signal (below 1 kHz).

2.7 EMG Detection, Electrode Montages and Electrode Size

Detection of EMG can be carried out using intramuscular electrodes or by electrodes which are attached surface of skin. If intramuscular electrodes are used, the electric potential is measured at a location, which is very close to its source, hence the effect of volume conductor is minimum. This helps in separation of the action potentials of various MUs.

While using surface electrodes, EMG source is at a distance from the detection point and this distance acts as a low-pass filter. In order to eliminate the common mode components, which are caused due to technical interference (like power line) as well as to partly compensate the effects of low-pass filtering due to tissues which separate the EMG source and electrode, different electrodes are used to measure the reading at different locations and have a linear combination of signals. It can be seen as spatial filtering of monopolar EMG signal [74].

EMG signal is also influenced by the physical size of electrode. In case the impedance between the surface of skin and material of electrode is equally distributed and

a. is less as compared to the amplifier's input impedance but

b. is more as compared to within tissue impedances,

it can conveniently be said that the potential that the electrode will measure will be equal to the average of potential distribution of skin under it [75, 76, 77]. Consequently it can be said that the shape of filter is defined by the dimensions of electrode.

2.8 Electrodes and Their Transfer Function

Skin can be taken as a boundary between the two surfaces, one side is subcutaneous tissue and muscle, which can be called the source of electric potential and on the other side is an insulating semispace (air). A two dimensional potential is generated on skin surface by this sources. Ideally there should be a point electrode, which should be connected to a voltmeter having infinite input impedance, and the potential must be measured with respect to a reference at a remote location, where the potential is zero.

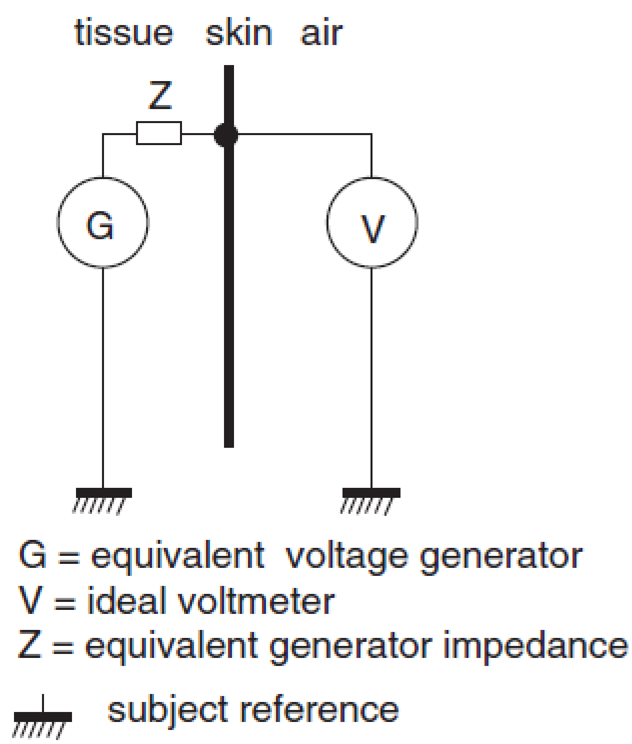


Figure 2-11: Ideally the input impedance should be infinite

The above configuration is often referred to but it is not realistic as there are certain physical dimensions of an electrode. The impedance of the junction of skin and electrode is complex and a finite input impedance is associated with the voltmeter (amplifier). Moreover there are other potentials which add their share to the obtained reading, these are noise and dc voltages which are generated at the interface of skin and electrode, line voltage and other electrical phenomena unrelated to EMG [78].

Electrode comprises of a metallic surface, which is in contact with the surface of skin. At this point there are four considerations, which must be taken care off:

a. The conduction of skin is moderate as it is actually a sort of conductive tissue which is made up of cells. Intracellular and extracelular material of these cells is electrolyte solutions and in it ions carry the current. On the other hand metal is a conductive material and in it electrons are responsible for flow of current. Therefore the interface of these two distinct mediums is inherently noisy [79].

b. Interface of skin and electrode is a complex one and the R and C components of its capacitive impedance are dependent on frequency and current. It incorporates a dc generator to account for "battery" potential of this interface of metal and electrolyte [80, 81].

c. Because of the presence of metallic surface, the contact area will be forced to become equipotential, and thus modifies the potential distribution of skin in its neighbourhood.

d. The modelling of EMG amplifier input impedance as a resistor (109–1012W) in parallel to a capacitor (2–10 pF) is done and therefore it is frequency dependent.

In EMG signals, the dominant part is capacitive component and it must not be neglected. Amplifier will give an output which will be the filtered version of measured EMG with an addition of offset and noise.

Simple case of rectangular electrodes having dimensions of a and b and circular electrodes of radius r in the skin plane (x, z), and correspondingly in the spatial frequency plane (f_x, f_z) is described by the following equations:

$h_{size}(x, z) = 1/S$ under the electrode area and $h_{size}(x, z) = 0$ elsewhere

$H(f_x, f_z) = \text{sinc}(af_x)\,\text{sinc}(bf_y)$ for rectangular electrodes

$H(f_x, f_z) = 2J_1(kr) / kr$ for circular electrodes

where S is the electrode area, sinc (w) = sin (πw) / πw for $w \neq 0$ and sinc (w) = 1 for $w = 0$,

$J_1(w)$ is the Bessel function of first kind and first order, and [82, 83]

$$k = 2\pi\,(f_x^2 + f_z^2)^{1/2} \quad \text{......... (2.1)}$$

Smoothing of the monopolar potential increases with increase in size of electrode. If a circular electrode is used then its cutoff frequency f_e is not minor to compute as the correlation between spatial and temporal spatial frequencies ($f_t = v\, f_s$) does not remain valid in two dimensions.

However, as a first approximation and for $v = 4$ m/s,

f_e = 360 Hz for electrode diameter Ø = 5mm

f_e = 220 Hz for electrode diameter Ø = 10 mm

f_e = 100 Hz for electrode diameter Ø = 20 mm

It can be observed that the cutoff frequency is decreasing with the increase in diameter or size of electrode, hence preference is given to small electrodes over large ones and loss of information is experienced in the electrodes of diameters above 5 mm [84, 85, 86].

2.9 Noise, Impedance and Dc Voltages of Electrodes

Most commonly the skin is cleaned, shaved and rubbed with a little coarse water or some solvent soaked cloth, then electrodes of Silver (Ag) or Silver Chloride (AgCl) are applied with the help of some conductive gel to have a stable and better contact [87]. In 1970 painton electrodes manufactured by glue and silver powder were used by Hollis and Harrison [88]. Once again it is emphasized that miniature electrodes, having diameters 5 mm and below particularly designed for EMG must be chosen.

Skin preparation has a significant effect on the impedance and at the same time impedance is inversely proportional to the surface of electrode. If a layer of gel is used in between the electrode and the skin now two contact portions are formed, one is the skin and gel contact and the other is the gel and metal contact, the former being more important. As the impedance of represents a nonlinear function so its measurement is not simple. Reduction of electrode and skin impedance can very effectively be done, if the skin is rubbed with medical abrasive paste.

"Battery" affect also generates a dc voltage at the contact of metal and electrode [89, 90, 91]. In As the two electrodes are used at different locations hence slowly changing voltages or dc voltages would exist between two locations of skin due to many physiological reasons [89]. This dc voltage can be of the range of few hundred mV, and the design of EMG front end amplifiers must be done so as to prevent saturation. However mild abrasion of skin or "peeling off" of the skin are good tools to shrink the noise, impedance of skin and electrode and dc voltages [91, 92, 93].

2.10 Configuration, Location and Distance of Electrode

Importance of configuration and location of electrodes along with reproducibility of readings has never been denied, since the advent of this field [94, 95, 96, 97]. Differential configuration shown below is also known as single differential (SD) or bipolar differential. This configuration is most extensively used and in order to understand and interpret EMG signal correctly it is important to know this configuration [98].

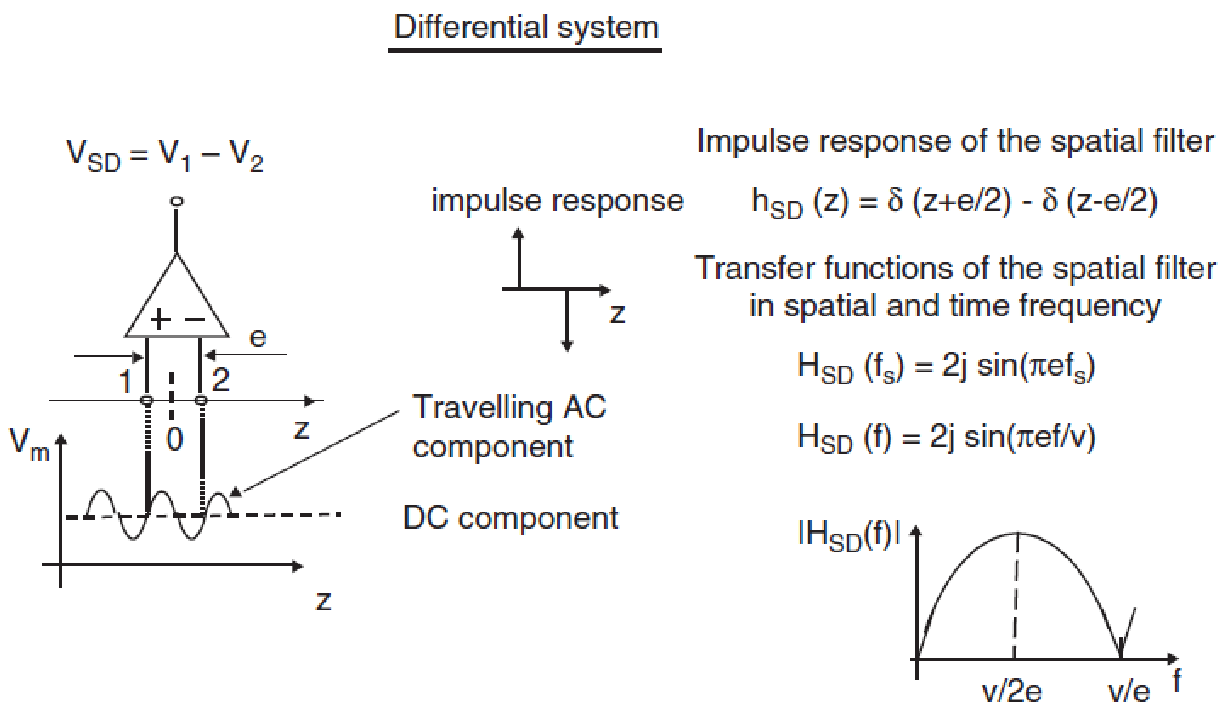


Figure 2-12: System based on single differential

This configuration is chosen by the life scientists and the engineers to pick the voltage between two pints. Its transfer function works as a spatial filter. To understand, think of an ideal differential amplifier, having a pair of point electrodes, they are at a distance ***e*** apart from each other and are aligned along the direction of fibre, and the zero of *z*-axis is located at centre point of two electrodes. The potential distribution is varying as a function of time and space and these tow electrodes are their sampling points.

At any time instant the detected voltage and amplified by the system is:

$\boldsymbol{V(z)\,\delta(z + e/2) - V(z)\,\delta(z - e/2)}$, where $\boldsymbol{\delta(w)}$ is the Dirac delta function.

If V (-e/2) = V (e/2), this means that the difference is equal to zero. This means that no common mode voltage has been detected by the system. Potential distribution $V(z)$ can be observed either in space domain, (function of z), or in spatial frequency domain, as a sum of sinusoidal harmonics representing Fourier amplitude spectrum (in space) of $V(z)$. Each spectral line, will have a frequency f_s and corresponding wavelength $\lambda = 1 / f_s$.

Let's consider potential distribution moving along ***z-aixs*** at a velocity ***v*,** consider one of its harmonic at a time. If $e = n\,\lambda$, with $n = 1, 2, \ldots$, and λ is the wavelength of this harmonic, zero voltage will be detected, irrespective of the value of propagation velocity v, as any integer of periods in space will fit within the distance e and two identical sine waves will be detected by both the electrodes. Conversely, if $e = n\,\lambda \pm \lambda/2$, maximum possible value will be detected, as difference of two opposite and equal sine waves will be detected. Using simple trigonometric ratios it can be demonstrated that for the intermediate positions the system will give a sinusoid with an amplitude function of f_s. Hence SD is a spatial filter whose output is dependent on the input frequency. Recalling the basic relationships between v, time and spatial frequencies f_t and f_s,

period $T = 1 / f_t$ .... (2.2)

wavelength $\lambda = 1 / f_s$, ... (2.3)

$T = \lambda / v$, ... (2.4)

or $ft = v\,fs$. .... (2.5)

Now it is evident that the magnitude of the transfer function of the differential system is a sinusoid, i.e., for $\lambda << e$ the system acts as a differentiator, a maximum for $\lambda / 2 = e$, it approximates an integrator for $\lambda/2 < e < \lambda$, and it shows its first dip for $\lambda = e$, indicating the behaviour of an overall band-pass filter. The frequency of the dip in space is $f_{s\text{-dip}} = 1/e$ and in time is $f_{t\text{-dip}} = v/e$. Table below depicts the (time) frequency of the first dip as function of v and e [99].

Table 2.1: Frequency response at different IEDs

Conduction velocity *v*	Interlectrode Distance e	Frequency of first Max	Frequency of First Dip
3 m/s = 3 mm/ms	0.010 m = 10 mm	150 Hz	300 Hz
3 m/s = 3 mm/ms	0.020 m = 20 mm	75 Hz	150 Hz
3 m/s = 3 mm/ms	0.030 m = 30 mm	50 Hz	100 Hz
4 m/s = 4 mm/ms	0.010 m = 10 mm	200 Hz	400 Hz
4 m/s = 4 mm/ms	0.020 m = 20 mm	100 Hz	200 Hz
4 m/s = 4 mm/ms	0.030 m = 30 mm	66 Hz	133 Hz
5 m/s = 5 mm/ms	0.010 m = 10 mm	250 Hz	500 Hz
5 m/s = 5 mm/ms	0.020 m = 20 mm	125 Hz	250 Hz
5 m/s = 5 mm/ms	0.030 m = 30 mm	83 Hz	166 Hz

Dip location is affected by misalignment between the muscle fibres and electrodes [99]. However, modifications in spectral shape become evident with bigger interelectrode distances. Interelectrode distance should be 20 mm (or lesser for shorter muscles) [100], when both the electrodes are placed on same side in innervation zone. It gives a compromise amongst the requirement of limiting spectral modifications and the requirement of having increased signal/noise ratio and signal amplitude.

Reduction in detection volume and increment in spatial selectivity, is possible either by a reduced interelectrode distance or by employing double differential (DD) detection system. It's employment helps in the estimation of conduction velocity, limiting the detection volume and reduction in crosstalk [101].

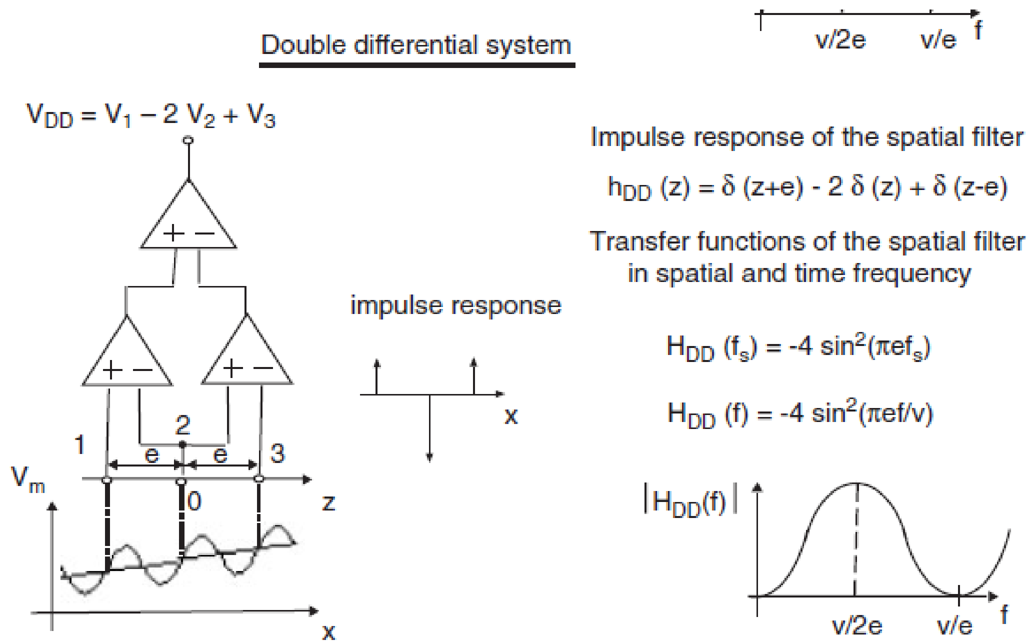


Figure 2-13: System based on double differential

In it two single differential are employed, which utilize a common electrode and the difference of their outputs gives the transfer function and impulse response DD system. Impulse response of DD system is a set of three Dirac delta functions **(with weights 1, -2, and 1)**. Transfer function of DD system is a sinusoid raised to power 2. That is, for **λ** << ***e*** the system behaves as a second-order differentiator, its transfer function shows a maximum for **λ /2 = *e***, and it presents its first dip for **λ** = ***e***.

Gydikov [102] proposed a variation in DD system, which is known as “branched electrode”. All three systems are generally placed in muscle fibre direction, however they can also be positioned in transversal direction [103].

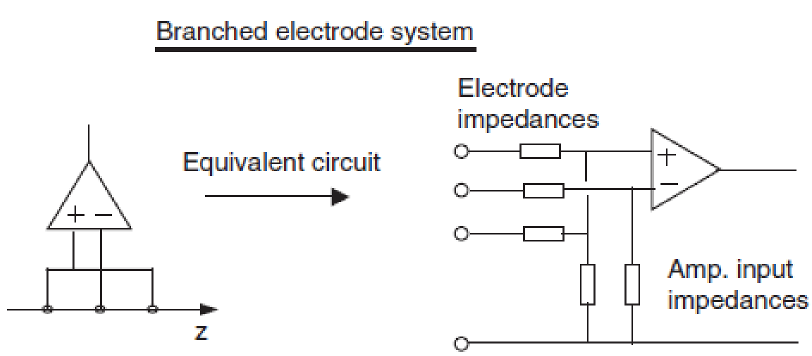


Figure 2-14: System based on branched electrodes

2.10.1 Interelectrode Distance (IED)

It has been established uptill now that detection volume of an electrode system can be limited by decreasing IED, this will consequently reduce crosstalk. Following function describes the effects of the space between recording electrodes and the motor unit:

$$V = \frac{V_o}{\left(r/r_o\right)^D} \quad \text{.......... (2.6)}$$

where V_0 and D are constants, and r_0 is some reference distance from MU's electrical centre, where $V = V_0$. Electrical center is location of equivalent generator of MUAP. [104, 105]. Exponent D is a function of the detection system (SD, DD, etc.) and IED. This implies high values of D for reduced IED. However, with **IED > 40 mm**, deeper MUs are represented relatively better in the surface EMG signals then superficial ones. This suggests that reducing IED, minimum to 6 mm, is not a proper technique to limit electrode's view.

2.11 EMG Front-End Amplifiers

High CMRR, high input impedance and less noise are desired characteristics of a surface EMG front-end amplifier. Circuit configuration employed affects these parameters. For instance, a comparatively less-input impedance operational amplifier (OA) joined in voltage follower configuration gives an input impedance hundred times greater than its own.

As a thumb rule the input impedance of a surface EMG amplifier should be at least two orders of magnitude higher than the highest expected value of impedance of electrode and skin. Usually the impedances above 100 MW are believed to be acceptable, but the preferred value is of the range of 1000 MW if dry small electrodes having a skin electrode contact impedance or the range of 1 MW are used [106, 107]. As per this rule the choice of front end amplifier is restricted to three types only:

a. OAs in voltage follower configuration

b. Classic three OA instrumentation amplifier configuration

c. Classic two OA instrumentation amplifier configuration

Such like circuits, and differential FET stages, are in use since the early 1970s [108, 109, 110, 111, 112, 113]. Very recently applications for the detection of multichannel variations were developed [114, 115, 116, 117]. A few of the basic combinations are shown below:

a. Two OA instrumentation amplifier

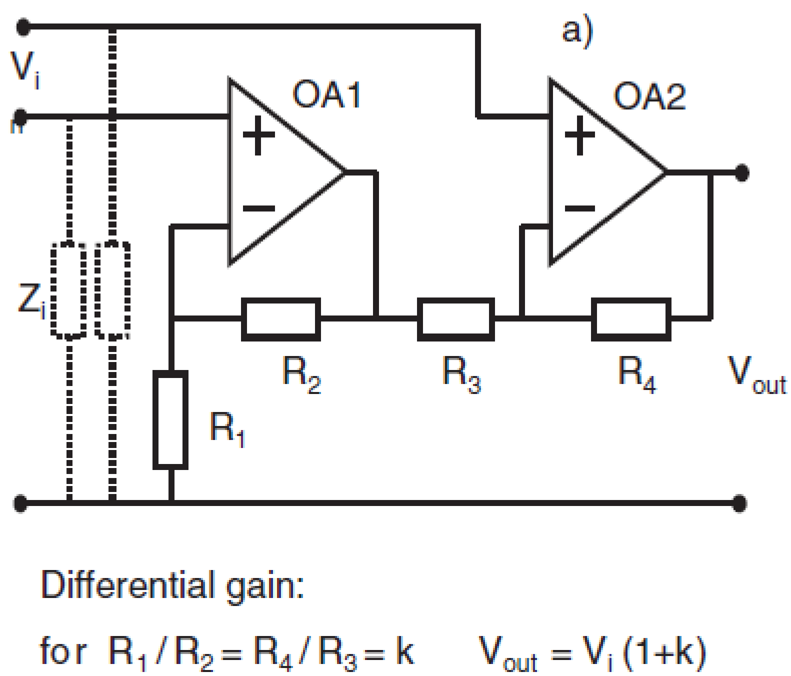
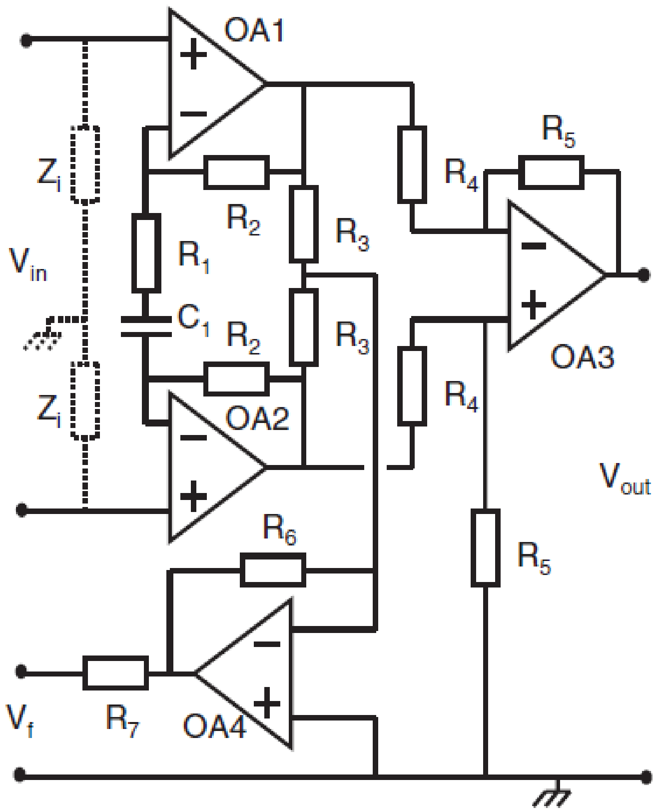


Figure 2-15: Preamplifier developed with two Operational Amplifiers

b. <u>Three OA instrumentation amplifier with common mode feedback</u>



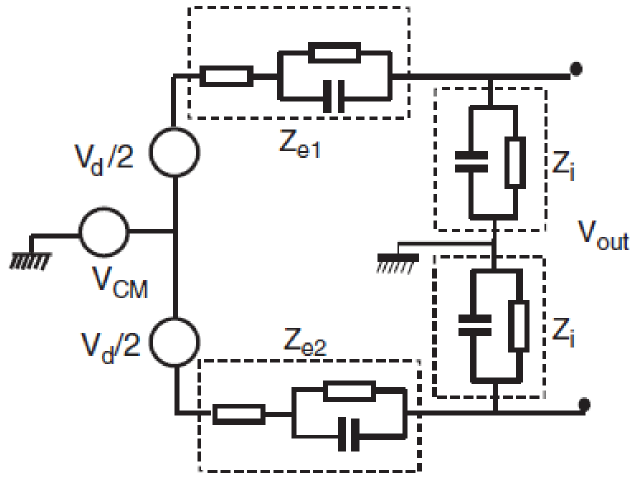
Differential gain:

for $f \gg 1/\ 2\pi R_1 C_1 : V_{out} = V_{in}(1+2R_1/R_2)\ R_5/R_4$

for $f \ll 1/\ 2\pi R_1 C_1 : V_{out} = V_{in}\ R_5/R_4$

Figure 2-16: Preamplifier constructed using three Operational Amplifiers

c. effect of unbalance of the electrode–skin impedances



for $V_d = 0$, $Z_{e1} \neq Z_{e2}$, and $\Delta Z = |Z_{e1} - Z_{e2}| << Z_i$ it is $V_{out} = V_{CM}\, \Delta Z / Z_i$

Figure 2-17: Preamplifier configurations showing imbalance effect due to skin-electrode junction

One of the important aspect of surface EMG amplifier is common mode rejection ratio (CMRR). It is a measure of the amplifier capability to reject common mode voltages (these are primarily power line voltages which are present in between the subject and the mains ground which are usually in the range of a few volts, i.e. over thousand times the surface EMG signal). CMRR is described by:

$$CMRR = 20\ \mathrm{Log}_{10}\,(A_d / A_c) \qquad \text{.......... (2.7)}$$

where A_d and A_c are respectively the differential and common mode gains of the amplifier. Amplifier's output due to the common mode input voltage is given by:

$$V_{out}/A_d = V_{cm}\,(\Delta Z/Z_i + A_c/A_d) \qquad \text{........... (2.8)}$$

This output is a function of or it is dependent on following three things:

a. Operational Amplifier's common mode rejection ratio

b. Resistor bridge balance around the differential to single ended stage

c. Unbalance of the two input voltage dividers due to the electrode impedances and the amplifier input impedances

The $V_{cm}\, \Delta Z/Z_i$ contribution creates a differential voltage because of common mode voltage and because of the difference of two electrode–skin impedances. For example, If the ratio of

$\Delta Z/Z_i = 10^{-3}$ it will contribute a voltage of 1 mV. Common mode input voltages because of the parasitic capacitive coupling in between the subject and power line can be in the ranges of a few volts. Consequently CMRR in the range of 10^5 to 10^6 (100 – 120 dB) and $\Delta Z/Z_i$ in the range of 10^{-5} to 10^{-6} are needed to limit the equivalent input voltage to a value negligible with respect to EMG. As it is difficult to get such values so common mode feedback is adopted to decrease the common mode voltage on the subject.

2.12 EMG Filters: Specifications

Surface EMG signal processing system utilizing front-end consists of a high-pass filter and a low pass filter. The cutoff frequency of high pass filter is approximately 10 – 20 Hz and that of low pass filter is 400–450 Hz. Both the filters can be included in front-end circuitry.

The EMG signal exhibits slow variations because of the movement artefact and due to the instability in the interface of electrode and skin. These signals areunwanted and are in the range of 0 to 20 Hz frequency, that is why high-pass filter is designed having a cutoff frequency ranging from 15 to 20 Hz. In the analysis of movement this information is not of any interest and high-pass filter is used even with a higher cutoff frequency i.e. 25 to 30 Hz. Artefact which are there because of the sliding of innervation zone under electrodes, result in amplitude modulation, and they are not eliminated by this filter. Movement artifacts which are associated with fluctuations in the impedance of electrode and half-cell potentials are somewhat attenuated but not removed.

These high and low pass filters are there to decrease artefacts and noise. In certain cases analog notch filters has been utilized to shrink 50 to 60 Hz interference. Generally it is not supported due to :

a. In the frequency bands where EMG shows high power density is removed in it

b. It brings in phase rotation which extends to frequencies above and below the central frequency, as a result of which the waveform gets changed dramatically.

2.13 Sampling and Analog to Digital Conversion

In order to evade loss of information and “aliasing”, Nyquist theorem suggests that the signal should be sampled at a rate which is at least two times of its highest harmonic’s frequency. Figure below describes that how the signal becomes ambiguous if a signal is sampled at a very low frequency. This issue becomes more critical for the signals of higher frequencies and for wideband noise. In case of most of the applications of all muscles the greatest harmonic in the signals of surface EMG is ranging from 400 to 450 Hz, which requires low-pass (anti-aliasing) filters having their cut off frequencies in this range and sampling rate not less than 1000 samples per second.

Analog to digital conversion changes the sampled voltages into “levels” of binary codes. The signal in an A/D converter is accepted within a specified range (e.g., ±5 V) which is then subdivided into discrete levels which can be calculated by the formulae $\mathbf{2^n - 1}$, where $\boldsymbol{n}$ represents the number of bits of converter. Table below provides the data of resulting resolution for an input range ±5V and gain of 1000.

Table 2: A/D convertor Bits, levels and resolution of input

Number of Bits *n* of A/D Converter	**Number of Levels *N* (*N* = 2^n - 1)**	***V*/Level (±5V Range) 10/*N***	**Resolution of Input* (Amplifier gain = 1000 and ±5VA/D Input range)**
8	255	39.06 mV	39.06 µ V
10	1023	9.765 mV	9.765 µ V
12	4095	2.441 mV	2.441 µ V
14	16383	0.610 mV	0.610 µ V
16	65535	0.152 mV	0.152 µ V

* Voltage difference corresponding to the least significant bit.

2.14 European Recommendations on Electrodes and Their Locations

The Europeans took an initiative by establishing Surface Electromyography for Noninvasive Assessment of Muscles (SENIAM), in 1996. The basic purpose was to have a consensus on important issues like, sensors, their placement, processing of signal and its modelling. So that the data of results obtained from surface EMG electrodes can be exchanged. Here certain recommendations regarding surface EMG as given by SENIAM have been included.

2.14.1 Electrode Material

Silver (Ag) / Silver Chloride (AgCl) is the most frequently used material for electrodes and mostly it is applied with a pre-gelled surface.

2.14.2 Electrode Shape and Size

Electrode shape is taken as the shape of conductive area of surface EMG electrode. Most often circular electrodes having a diameter within the range 8 to 10 mm are used. As per the recommendation the size of electrodes along the muscle fibre should not exceed 10 mm.

2.14.3 Interelectrode Distance

In the bipolar configuration Interelectrode distance (IED) is taken as centre to centre distance between the conductive areas of two electrodes. Largely preferred distance is 20 mm.

Bipolar surface EMG electrodes should be applied between a tendon and the innervation zone, while IED should not be more than 20 mm. If bipolar sensor are to be applied on small muscles, then the IED must not be more than 1/4 of length of muscle fiber. Moreover both the electrodes must be on one side of the innervation zone. This will help i avoiding tendon and motor end plate effects.

2.14.4 Sensor Construction

The mechanical construction for the integration of an electrode including the cables, if applicable amplifier combined is known as the "Sensor construction". It does not have a direct effect on the electrode characteristics. However, it has its effect in a way that the electrodes and cables should be able to be moved, like they should be portable, must not restrict or hinder the movement of hands or arms and should not cause the instability of prosthesis arm.

It is recommended that it should be light weight and have fixed IED. If used with hands so the sensor assembly water resistant.

2.14.5 Sensor Location and Orientation on the Muscle

Location of an electrode is taken to be that point where the centre of the conductive area of the electrode rests on the muscle. Orientation is the direction of bipolar sensor relative to the direction of muscle fibres. The recommendations in summarized form are attached as per Annexure 'A' to this chapter.

2.15 EMG Signal Processing

2.15.1 Comparison of Research papers

several research papers [118], [119], [120], [121], [122] have been studied and after comparing the advantages and disadvantages of each circuit, a circuit has been proposed, which gives the optimum signal output, that can be fed to the ADC as its input.

a. <u>Analog reconfigurable technologies for EMG signal processing</u>

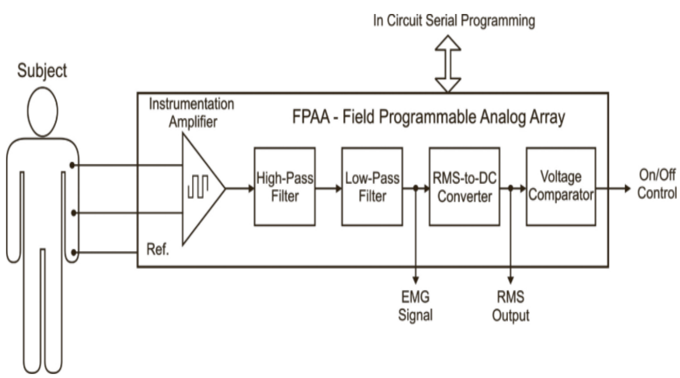


Figure 2-18: Circuit of research paper [118]

In this study paper [118], Field Programmable Analog Array (FPAA) has been used. FPAAs allows to have complete analog circuits required in one single component, which is programmable. It provides better reliability and flexibility of the system and a reduced size and cost of the circuit. The chopper amplifier in the FPAA has a CMRR of 102 dB and it not only suppresses common mode interference signals but also eliminates power line interference of 60 Hz.

In this research paper the first filter stage is kept as a band-pass having its central frequency at 200 Hz, 5× gain and a bandwidth of 300 Hz. Then there is a second filter, it has a cut-off frequency of 500 Hz and gain of 20. The total gain of the signal conditioning circuit was 6,400 (76 dB).

The disadvantage of this circuit is that CMRR can be even higher in order to have better suppression of noise signals.

b. Design of an Electrical Prosthetic Gripper using EMG and Linear Motion Approach

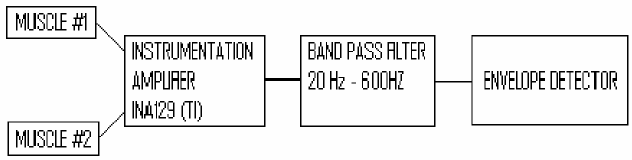


Figure 2-19: circuit of research paper [110]

In this research paper [119], INA129 has been used as an Inst Amp. INA 129 gives very good accuracy and it is a low power Inst Amp. It also gives a high CMRR (120 dB at G>100). Its gain may be set from 1 to 1000 V/V. It has chosen R = 2.2K, thereby making the input gain of the circuit be:

$$G = 1+49.4k / 2.2k = 23.45 \text{ V/V} \quad \text{............. (2.9)}$$

Output of the Inst Amp is then passed through a band pass filter, which is designed for the frequencies of 20 Hz to 650 Hz. The first one is a first order High Pass Filter having a limiting frequency of 20 Hz, it helps attenuate the small frequencies which are there due to motion artifact in between the skin and the electrodes. Then the signal passes through the second stage of band pass filter, it is a second order KRC Low Pass Filter having a limit of 650 Hz frequency. This research paper has selected the limit of Low pass filter at 650 Hz frequency due to the reason that after research it found the range of muscles signal in between DC – 1000 Hz, however strong signal were found from 50 Hz – 350 Hz. Therefore, by keeping the cutoff frequency at 650 Hz, it has been guaranteed that optimum performance will be obtained as no signal content will be lost at the same time higher frequencies will also be filtered.

Gain of the HPF is set at 12.2 V/V and that of LPF is kept at 10 V/V.

After the BPF, the signal passes through an envelope detector. Envelop Detector makes the AC signal obtained from the muscles a stable and regulated output, which will be altered according to the RC constant and the frequency of the circuit as shown in Fig 6.

The disadvantage of this circuit is that the CMRR of Inst Amp can still be kept higher by selecting some alternative, cost of the Inst Amp is on the higher side, and instead of envelop detector a simple rectifier circuit can be used, which will not only keep the cost of the complete circuit less but will also keep the dimensions of the circuitry smaller.

c. Fuzzy Control of a Robotic Arm usingEMG Signals

This research paper [120], does not employ an off the shelf Inst Amp, instead a circuit of Inst Amp having a CMRR of 46 dB along with a driven-right-leg (DRL) circuit to further boost the CMRR is used. Main noise, which is created due to the power lines, is common to both readings, and in order to remove this voice content the circuit has to have a good CMRR. To have better and higher CMRR, an Inst Amp with 46 dB gain along with a driven right leg (DRL) configuration is implemented. DRL feedbacks the common mode voltage back into the human body, and thus further raises the CMRR as shown in Fig 7.

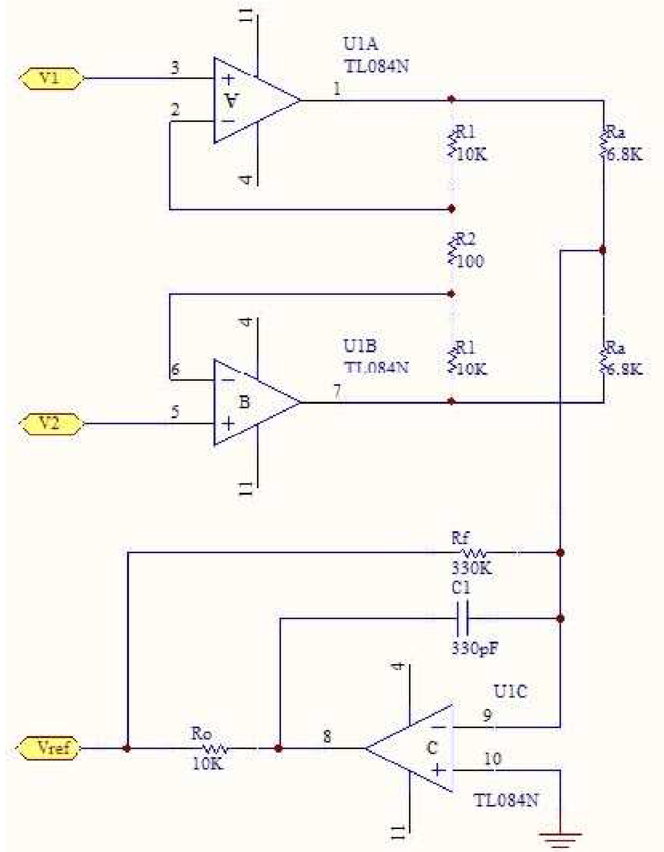


Figure 2-20: DRL circuit from research paper refrenced [122]

The signal is then passed through a high pass filter so that the bias from EMG signal can be eliminated. Further it is passed through a low pass filter to remove higher frequencies over 1 kHz to evade aliasing effects.

A comparison of all the circuits proposed in the research papers referenced [118] - [122] on the basis of the Inst Amp used in the circuits has been carried out. Inst Amplifier being the first stage of signal processing is the most important stage as most of the noise content is removed at this stage. Alike signals, which are common in both the readings, are suppressed in this stage.

Table 3: Comparison of Research Papers

Research paper	CMRR	HPF	LPF	Drawbacks
Analog reconfigurable technologies for EMG signal processing	102 dB	0 Hz	500 Hz	1. Low CMRR 2. HPF incl ambient noise 3. LPF may miss some useful signal content
Design of an Electrical Prosthetic Gripper using EMG and Linear Motion Approach	INA-129, 120 dB	20 Hz	650 Hz	1. Low CMRR 2. INA-129 is expensive
A Myoelectric Controlled Partial-Hand Prosthesis	INA-118, 110 dB	50 Hz	500 Hz	1. Low CMRR 2. INA 118 expansive 3. LPF may miss some useful signal content
Fuzzy Control of a Robotic Arm using EMG Signals	Inst Amp with 64 dB and DRL	60 Hz	1 kHz	1. Low CMRR 2. limit of LPF is kept unnecessarily high
Design and Development of Low Cost Circuitry of Myoprosthetic Limb	INA 128, 106 dB			1. Low CMRR 2. INA 118 is expensive

2.16 Design of Optimized Circuit for EMG Signal Processing

Three circuits have been developed keeping in view the drawbacks of circuits proposed in the research papers [118] - [122]. The developed circuits were initially simulated on Proteus 7.6 version and on the basis of the outputs obtained one circuit has been recommended as the optimized circuit for the processing of EMG signals.

Quality of EMG signal, is dependent generally on the signal conditioning processes, and primarily on the features of the preamplification process. Amongst all the stages of amplification, EMG signal is most influenced by the pre-amplification stage and hence it becomes the most vital stage. Pre-amplification stage has certain parameters which are important and they characterize the pre-amplification process, these are:

a. High common mode rejection ratio

b. Very high input impedance

c. Short distance to the signal source

d. Strong DC signal suppression

2.16.1 Pre-Amplifier

The AD620 performs good as a preamplifier as it has a low input voltage noise. It is an Inst Amp, which has a high accuracy of the range of 40 ppm maximum nonlinearity, it has low offset voltage of 50 µV max and an offset drift of 0.6 µV/°C max. These characteristics make it an ideal selection for use in applications involving precise data acquisition systems, like transducer interfaces and weigh scales. Moreover, less input bias current, low noise and low power of the AD620 make it most suitable for medical applications like, non-invasive blood pressure monitors and ECG. It works on lower power (only 1.3 mA max supply current), this property makes it a good choice for portable, battery powered applications. Characteristics of AD620 are as follows:

Instead of INA series AD620 has been used as the Inst Amp in the proposed circuit. Reasons for using AD620 are high CMRR, high input impedance, low cost and easy availability in the market which enables the amputee to have a prosthetic device in minimum cost.

2.16.2 First Circuit

The circuit has been simulated on Proteus 7.6 version, salient features of the circuit are as follows:

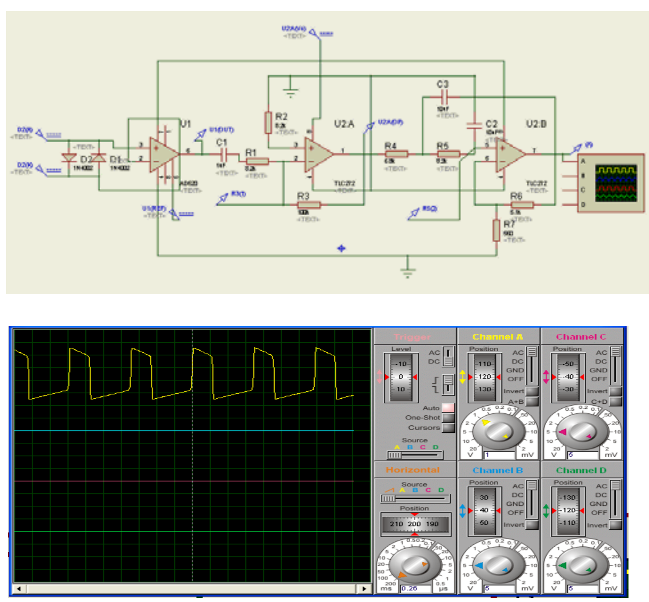


Figure 2-21: Schematic diagram of first circuit along with output

2.16.2.1 Diodes for Safety of Circuit / Device

Two diodes have been employed in the circuit at the input to provide safety to the circuitry and the device. Usually the voltage across a muscle is of the tune of mV. A diode will "turn on" at 0.7 V. If ever more than 0.7 V is present across the inputs (may be due to short circuit), a current passage with much less resistance than our body will be provided by the diodes. The resistance of our body is approximately 300Ω and 1500Ω, hence when a diode is ON, it will offer very less resistance as compared to our body, hence current will pass through the circuit.

2.16.2.2 Instrument Amplifier

AD620 is a differential amplifier, which removes ambient noise.

2.16.2.3 Band Pass Filter

Band pass filter has been taken from the research paper [119], which is designed for the frequencies of 20 Hz to 650 Hz. First is a High Pass Filter of 20 Hz, it helps attenuate small frequencies which are there due to motion artifact. Then is the Low Pass Filter having a limit of 650 Hz frequency as it guarantees optimum performance, since no signal content is lost also the higher frequencies are filtered. Gain of the HPF is set at 12.2 V/V and that of LPF is kept at 10 V/V.

2.16.2.4 Input Vs Out put

The values of output and input given by the circuit during simulation are as under:

a. Input at V1 - 2 mV

b. Input at V2 - 5 mV

c. Output - 3.4999 V

2.16.3 Second Circuit

The circuit has been simulated on Proteus 7.6 version, salient features of the circuit are as follows:

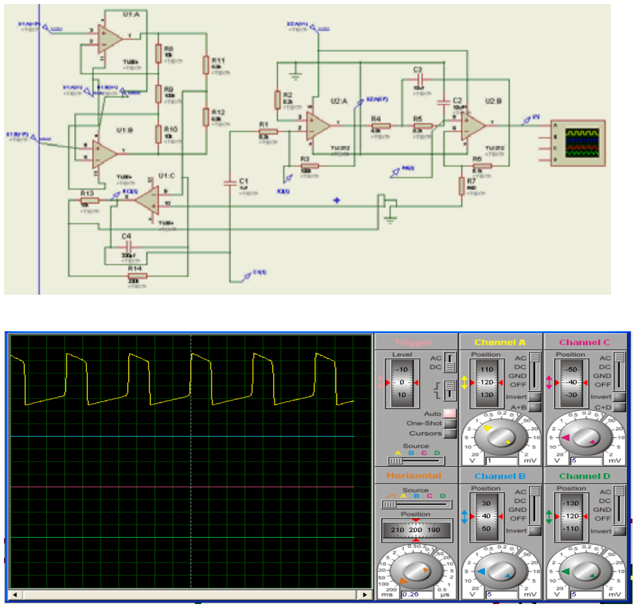


Figure 2-22: schematic diagram of second circuit along with its output

2.16.3.1 *Inst Amp with DRL*

Inst Amp along DRL has been taken from [122], in this paper EMG signals is amplified by an Inst Amp having a CMRR of 46 dB and uses a driven-right-leg (DRL) circuit for further enhancement of CMRR. Main noise, which is created due to the power lines, is common to both readings, and in order to remove this voice content the circuit has to have a good CMRR. To have better and higher CMRR, an Inst Amp with 46 dB gain along with a driven right leg (DRL) configuration is implemented. DRL feedbacks the common mode voltage back into the human body, and thus further raises the CMRR.

2.16.3.2 *Band Pass Filter*

Same band pass filter is being used as in the research paper [119].

2.16.3.3 *Input Vs Out put*

The values of output and input given by the circuit during simulation are as under:

a. Input at V1 - 2 mV

b. Input at V2 - 5 mV

c. Output - 3.456 V

2.16.4 Third Circuit

The circuit had been simulated on Proteus 7.6 version, salient features of the circuit are as follows:

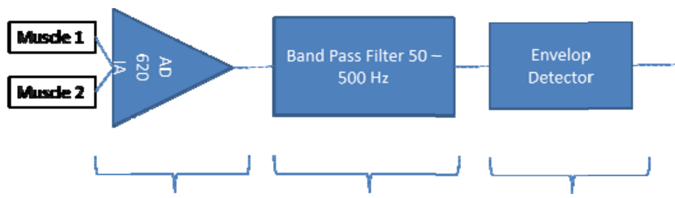


Figure 2-23: Block Diagram of third circuit

2.16.4.1 *Instrument Amplifier*

AD620 is a differential amplifier, which removes the ambient noise.

2.16.4.2 *Band Pass Filter*

Band pass filter had been taken from the research paper [118], which uses a High pass filter having a cutoff frequency of 50 Hz and a low pass filter having limiting frequency of 500 Hz.

2.16.4.3 *Envelop Detector*

Envelop detector had been taken from the research paper [119], it makes the AC signal obtained from the muscles a stable and regulated output.

2.16.4.4 *Input Vs Out put*

The values of output and input given by the circuit during simulation are as under:

a. Input at V1 - 2 mV

b. Input at V2 - 5 mV

c. Output - 3.234 V

2.16.5 Physical Implementation of EMG Signal Processing Circuit

Amongst all three circuits the first one gave the best output, i.e. 3.4999 V, hence only this circuit had been physically implemented and the tests had been conducted on it.

2.16.5.1 Results Obtained

The graphical representation of the results obtained are as under:

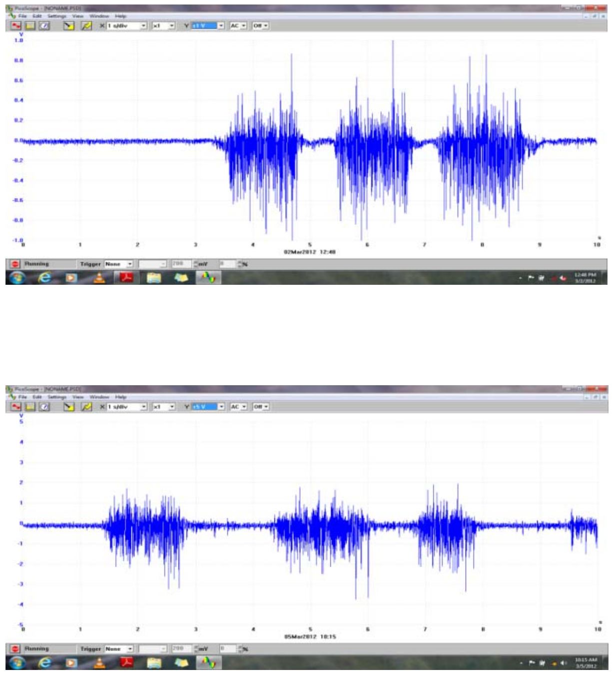


Figure 2-24: Output obtained by human hand

2.16.6 Conclusion

Various circuits has been studied and on the basis of the output obtained during simulation, the circuit which furnished best results, has been used to operate the prosthetic device, and a successful operation had been conducted. This shows that it is giving the best possible signal value to the device.

CHAPTER III:

PROSTHESIS CONTROL USING NEUROELECTRIC TECHNIQUES

3.1 Introduction

Basic aim in the technological advancements in the field of artificial hands is to have a controlling technique which mimics the performance of prosthetic hand as close as possible to the biological hand, and to give sensory feedback to the user i.e, touch and proprioception. The artificial limbs must provide graded, accurate, proprioceptive sensation and distally referred touch. Moreover the purposefulness of these prosthetic devices can be, and must be improved by having a control mechanism which is more natural and permits the amputee to feel the prosthetic limb as if it is a natural part of his / her body. Advanced cybernetic hands have been developed due to the considerable progress in the field of technology. Complex motions have been performed very finely by underactuated prosthetic hands without controlling each single joint independently.

There are two main objectives while designing the artificial hand, one is to develop a dextrous and cosmetic hand and secondly design a hand which is controlled by the bio inspired artificial sensory system. First example of application of these two design parameters is in the cyberhand which was developed at ARTS Lab of Scuola Superiore Sant'Anna [123].

Neuroelectric control, i.e. controlling a prosthetic arm through nerve impulses, will yield a device which would be closest to the physiological hand and this technique will be a natural control approach. Scientists have been working for controlling the artificial devices through nerves and neurons (Edell, 1986; Kovacs et al., 1989; Andrews et al., 2001) but the functionality of human-machine interface is problematic. Sensitivity of nerve tissue to mechanical stresses is a hindrance in the progress.

The problem area in a hybrid bionic system, which comprises of a human subject and a robotic artifact, is their interface. Factually major constituent of these systems is a bidirectional interface between the neural system of human being and the device. This interface must be fast and intuitive. Presently most of the prosthetic devices are controlled by electromyographic (EMG) signals, but the main drawback of these devices is that they rely on visual feedback and are small in number. Due to this reason, some other interface is required which should have sensory feedback and a bigger number of controls. Moreover in case of high degree amputees who do not have any of the part of their muscles available, some other sensing techniques is required to control the prosthetic device.

Use of electroencephalogram signals (EEG's) is a variant in the field of peripheral neural interfaces. EEG signals are electrical signals which can be obtained from skull's surface and they are a byproduct of natural function of brain. Reger et al. [124] exhibited an amalgamated neurorobotic system, which had bidirectional communication between a mini robot and the brain of lamprey. Although practical use of this technique in prosthetic devices is still ahead but it exhibited a two-way interface between a machine and a nervous tissue.

3.2 Nervous System

Nervous system is the main processor or the main processing system of our body, it keeps human beings connected with the outside world. The existence of human beings is well appreciated by this nervous system, and with the help of muscles it ensures the movement of different organs and our appropriate reaction to different stimuli. Our thoughts, emotions and consciousness dwell in nervous systems.

a. Nervous system is responsible to coordinate all kinds of movement, respond to external environmental stimuli, self awareness, intelligence, thought process and our emotion.

b. Nervous system is composed of nerve cells known as neurons, and these neurons are specialized to convey nerve impulses.

c. Nervous system is further subdivided into two major portions. The distribution is arbitrary, however the two portions perform together in unison and are interlinked with one another. These two systems are:

(1) Central Nervous System (CNS). It is comprised of spinal cord and brain. This system controls behavior. All the stimulations from the external

surroundings, received by receptors and which demand some reaction are sent to CNS. Nerve impulses which cause contraction of muscles or secretion from glands are processed and receive signals from the CNS.

(2) Peripheral Nervous System (PNS). Peripheral nervous system comprises of nerves. It is actually the pathway from and to internal organs. PNS acts as a communication linkage to the brain for all five senses and assist humans to adapt to the world outside.

The cells of nervous system are very complex and are so many in their quantity. They are so distributed in the body that they reach each and every part of our body and serve as the constituents of central and peripheral nervous system. They function in a way that they are the recipients of stimuli from the internal and external environments and resultantly translate, coordinate, modify, integrate and convey (through electrochemical process) these stimuli into meaningful conscious experiences or they coordinate motor activity through muscular tissues. Generally there are two types of nervous system cells:

a. Nerve Cells (Neurons)

b. Supporting Cells (Glia)

Nerve cells are very intricately linked with each other and with the end effector organs, such as glands or muscles. The place where they join each other are known as synapse. These nerve cells are influenced by each other by special contact areas, which are called synapse. The behavioral complexity of human being is due to the complex synaptic relationship between billions of neurons.

3.3 Components of Nervous System

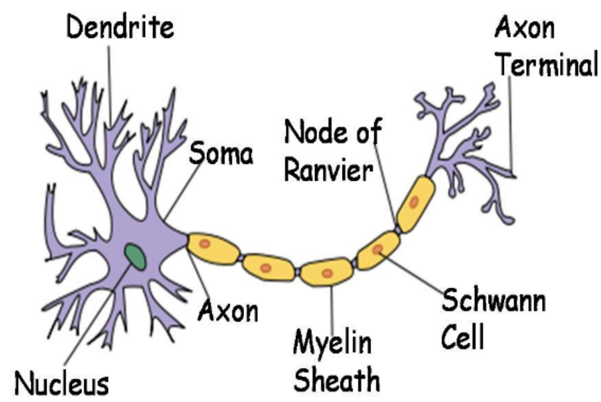


Figure 3-1: Neuron

3.3.1 Neuron. Nerve cell (neuron) is comprised of a cell body called (perikaryon) and its processes (axon and dendrites). Variations in the shape and size of neurons are extraordinary. Cell body diameter can be as small as 4 µm and on the other side it can be as large as 125 µm.

Smallest size neurons are granule cells of cerebellum and the biggest size neurons are the spinal cord motor neurons. Shape of cell body can usually be flask shaped, pyramidal or stellate. The shape of the cell body is dependent on the organization and number of its processes. Process of a neuron is its most astonishing feature. In human beings, the length of axon can be one meter or more, it extends from the spinal cord and goes up till fingers or toes or it emanates from the cerebral cortex and reaches distal extent of spinal cord. On the contrary Dendrites vary in their quantity and in pattern of branching, due to which their surface area is extraordinarily increased in certain instances.There are three types of neurons:

a. Sensory Neuron. They take messages from a sense organ to CNS, i.e. from the body to the brain. Long ones are known as dendrites and short ones are called axons.

b. Motor Neuron. They take the messages from CNS to any muscle fibre or gland i.e. from the brain to the body. Here the short ones are called dendrites and the long ones are known as axon.

c. Inter Neuron. They reside completely within CNS. Their function is to take and convey the messages between parts of the system.

3.3.2 Perikaryon. Body cell constitutes of a nucleus and so many of the organelles. Generally the shape of nucleus is circular and usually it is located in the centre. Nucleoplasm is homogenous and stains poorly with nuclear stains, this indicates that the deoxyribonucleic acid (DNA) is in active, dispersed and euchromatin form. In the nucleus a deeply stained nucleolus comprised of part of ribonucleic acid (RNA) is present in stark contrast. Contents of nucleus are encompassed in a distinct membrane called nuclear membrane.

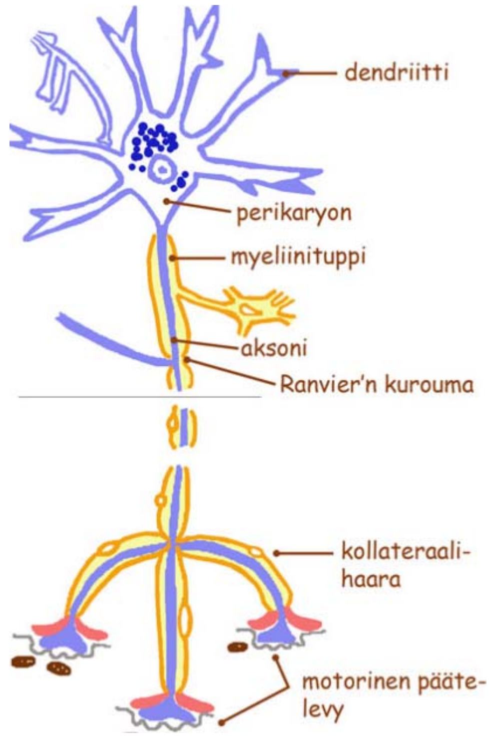


Figure 3-2: Neuron

3.3.3 Axon. Rise of axons take place on the cell body at the axon hillock, it is a slim cylindrical process and it varies in length. It may be as short as I meter or can be as long as it reaches the finger or toe. Axon hillock and axon proper lacks Nissl substance, neurofilaments,

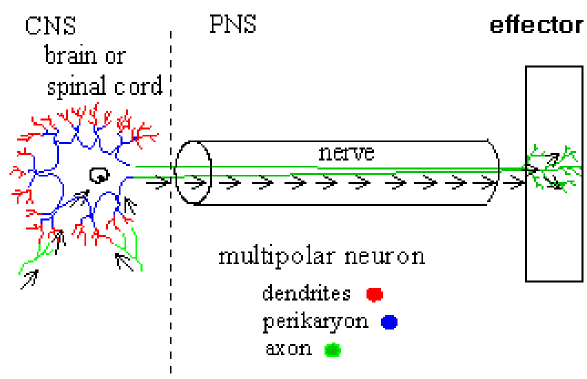


Figure 3-3: Axon

mitochondria and tubules are kept in the axoplasm. The diameter of axons remain uniform throughout their length. Axon can have collateral branches proximally and usually have extensive branches at their distal ends (telodendria) before ending by synaptic contact with dendrites and cell bodies of adjacent neurons or end effector. Basic conducting unit of neuron is axon. It can convey electrical signals through distances in the range from 0.1 mm to 2 m. Most of the axon split into numerous branches, thus they convey information to several targets [124].

3.3.4 The Axon Hillock

The place where the axon joins to the cell is known as axon hillock. This is the place from where the electrical firing actually occurs, this electrical firing is called as an action potential.

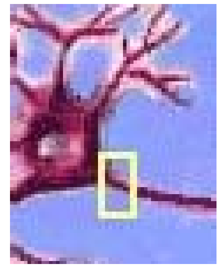


Figure 3-4: Axon Hillock

3.3.5 Dendrites

These formations are structured in the formation just like a tree and they branch out and perform as the main tools for receipt of signals. Their function is analogous to an "antennae" so they can be called the antennae of neuron and they have a covering of thousands of synapses. It is distally tapered and can have enormous branches. Neurons posses usually a single axon but they have more than one dendrite. Dendrites rise from the surface of cell body and they have the capability to increase this area. Dendrites are roofed by a huge quantity of spines, these spines are tiny projections, which represent locations for synaptic contact.

3.3.6 Ganglia

Collection of nerve cell bodies is called ganglia, they are placed out of the central nervous system. There two types of ganglia:

a. Craniospinal Ganglia

b. Autonomic Ganglia

3.4 Generation and Transmission of Nerve Impulses

3.4.1 Signal Generation

Conduction of nerve is an electrochemical change which moves along the entire length of nerve fibre in a single direction. It involves voltage changes along with variations in the concentration of certain ions, that is the reason it is called electrochemical. Oscilloscope can be used to gauge the generated potential difference.

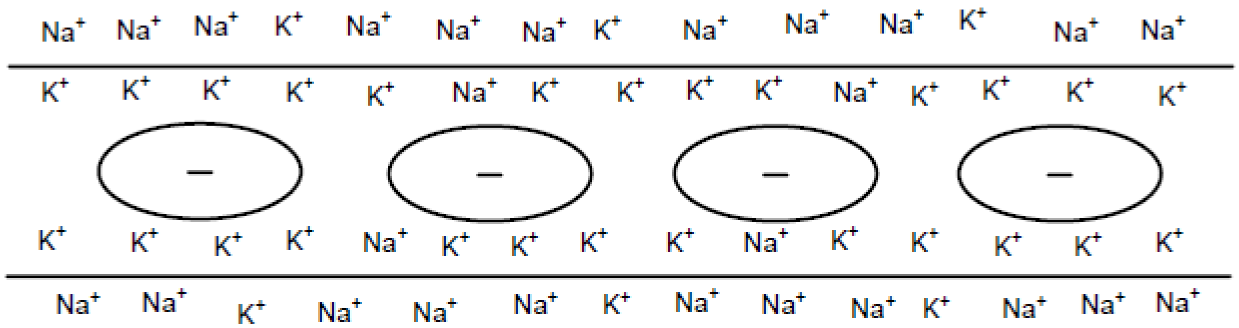


Figure 3-5: Nerve Potential

Three distinct phases occur during the generation of a nerve impulse alongside an axon, the resting phase, action phase which is followed by recovery phase.

3.4.1.1 Resting Potential

Potential difference of about – 60 mV exists across the membrane of axon, even when no impulses are being conducted. Negative charge inside the axon is for the reason that a large number of negative ions are present inside it, i.e. the existence of massive organic negative ions in the axoplasm (cytoplasm inside axon). Number of Sodium ions Na+ outside the axon is more as compared to their number inside the axon, and conversely more potassium ions K+ are present inside as compared to their quantity outside the axon. This irregular division of Potassium ions and Sodium ions is continued by active transfer across Na+/K+ pumps which operate during the period no impulse is being conducted by the neuron.

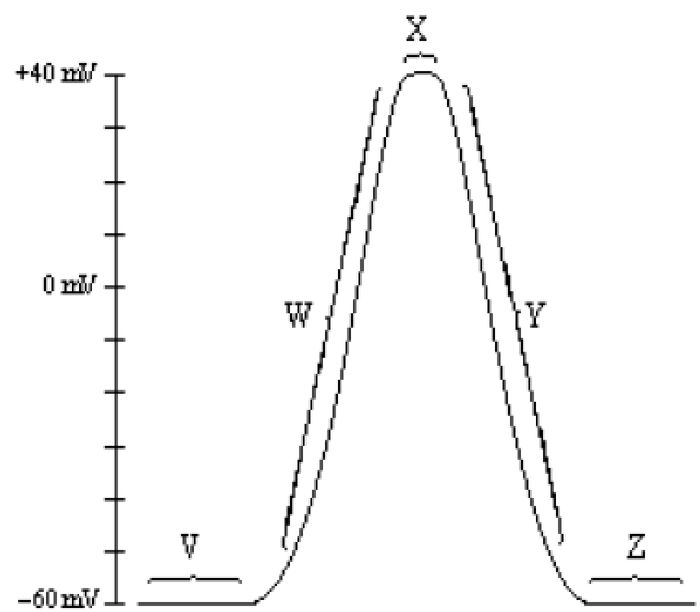


Figure 3-6: Phases of Recovery and Resting

3.4.1.2 Action Potential

In case the nerve is excited due to electric shock, change in pH value, any kind of mechanical stimulation, resultantly a nerve impulse gets generated and this change in the potential may be observed on the oscilloscope. This nerve impulse is known as action potential.

During the upstream (-60 mV to +40 mV), membrane becomes permeable to Sodium (Na+) ions. Na+ ions shift from outside to inside of axon, this makes a positive charge on the inside of axon, the process is called depolarization.

In the downstream (+40 mV to -60 mV), this membrane develop permeability for Potassium (K+) ions. Thereby shifting K+ ions from outside of axon to inside of axon takes place. This makes the inside of axon negatively charged again. The process is called repolarization.

3.4.1.3 Recovery Phase

between transmissions, K+ ions are returned to inside of axon, Na+ to the outside. This is done actively.

3.4.2 Signal Transmission

3.4.2.1 Synapse

The region between cell body or dendrite and the end of an axon to which it is attached is called synapse. Its end or terminating region is called Synaptic Ending, it is a little swollen terminal knobs on the ends of axon terminal branches. Only one way transmission from a synapse is possible due to the fact that synaptic vesicles are present on the ends of axons only and these synaptic vesicles can discharge neurotransmitters, due to which the potential of next neuron is affected.

On the receiving end of many synapses is a neuron, out of which some can be delivering inhibitory impulses and a few can be discharging stimulatory impulses. Response of neuron depends upon the combined effect of all of these receipts. So the summary effect of all of these excitatory neurotransmitters received dictates that whether the neuron fires or otherwise. If the number of received excitatory neurotransmitters is more and it overcomes the number of received inhibitory neurotransmitters, then the neuron fires, and if it is not so then local excitation occurs only.

Nerve impulses are taken across the synapses by the neurotransmitters. These neurotransmiters are tiny molecules. Their chemistry may be short chains of amino acids, single amino acids or they can be derivatives of protein. Proper function of nervous system and brain is dependent on balance between inhibitory and excitatory synaptic transmitters.

3.4.2.2Peripheral Nervous System

Since PNS is the pathway of neurons so it is comprised of nerves that include only long axons and long dendrites. As neuron cell bodies are present only in the spinal cord, brain and ganglia. Ganglia are the cell bodies which are found within the PNS.

3.4.2.3Somatic Nervous System

These are all the nerves that communicate with the musculoskeletal system and the organs which have exterior sense, that includes skin. Exterior sense organs are actually receptors, which receive stimuli from the environment and from where nerve impulses originate. Reaction to the stimulus is done by the muscle fibres.

3.4.2.4Cerebellum

Balance of the body and complex movements of muscles is controlled by the cerebellum. Cerebellum is a butterfly shaped and is a large portion of brain. It ensures that skeletal muscles function smooth and in complete coordination. Its responsibility is to maintaining normal postures, tone and balance of muscles. Sensory information regarding the balance of body is furnished to cerebellum by the inner ear.

3.4.2.5Electroencephalogram (EEG)

A machine known as electroencephalograph can record the electrical signals being generated by the brain and its output is called EEG. It functions by attaching electrodes onto the scalp and thus it receives electrical signal from the brain. 20 Watts electrical power is generated by an average brain, this power can hardly lit a compact fluorescent light bulb. EEG is usually used to detect the proper functioning of brain and to diagnose dysfunction of brain.

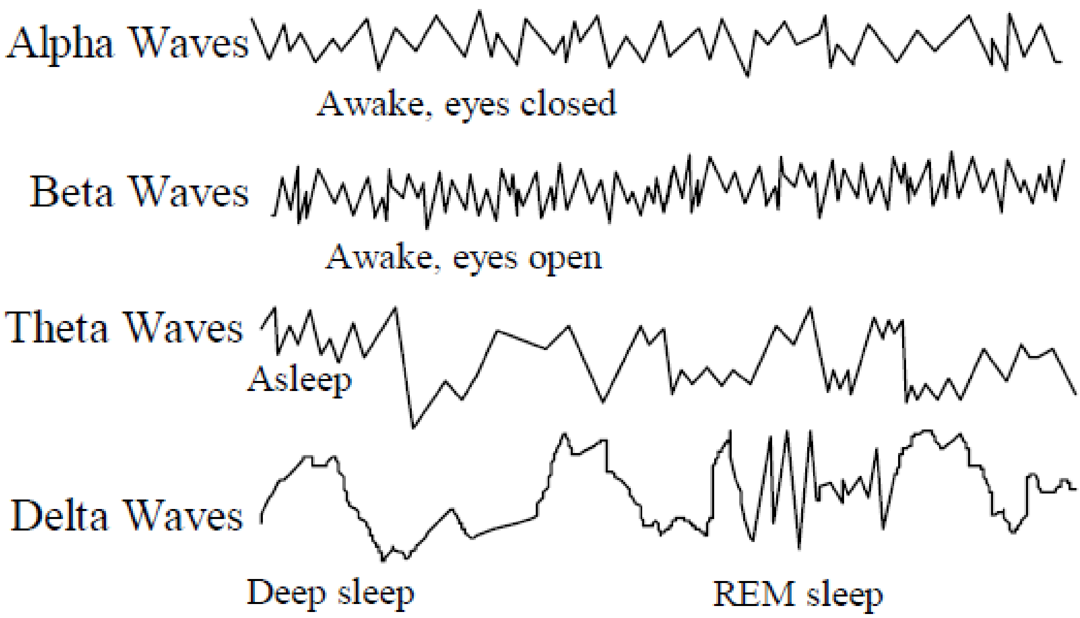


Figure 3-7: EEG waves

Alpha waves and beta waves are received when a person is awake. Predominantly alpha waves are received when a person is awake but his eyes are closed, whereas beta waves are seen in case the patient is awake and his eyes are open, these waves have higher frequencies but low voltages.

REM (rapid eye movement) is the period when a person is asleep but having some sort of dream. During this phase of sleep, the waves are larger and slower, and the eyes are having irregular back and forth movements. This state arbitrarily occurs 5 times in each night. This phase of sleep is required for normal functioning of our brain.

3.5 Nerves Affecting Hand Movement

Essentially there are three types of movements of the upper limb, which are being considered at the moment, these are:

a. Flexion and Extension of forearm

b. Pronation and Supination of forearm

c. Opening and Closing of the hand

Now once it has been established that what all movements are to be duplicated by the prosthetic device, the nerves which cause these motions must be segregated. These nerves are:

a. Flexion of Forearm: Musculocutaneous Nerve

b. Extension of Forearm: Radial Nerve

c. Pronation of Forearm: Median Nerve

d. Supination of Forearm: Radial Nerve and Musculocutaneous Nerve

e. Opening of Hand: Radial Nerve

f. Closing of Hand: Median Nerve and Ulnar Nerve

Hence it can be very safely said that particularly there are three nerves which control the three essential degrees of freedom of our hand and these are musculocutaneous, median and radial nerves.

3.6 Advantages of Neuroelectric Sensing Technique

3.6.1 Closed Loop Control System

In order to have an effective control of a prosthetic device is dependent on a closed loop control system [125]. In the forward track motor command signals of CNS are used to give inputs to the device and for the reverse path i.e. to get the feedback, sensory signals like from the proprioceptive receptors of the joints and muscles are utilized. Preferably a prosthetic device which replaces the physiological limb must operate in a closed loop manner with the residual neuromuscular system. In order to have a closed loop system it is required that both the paths have an appropriate interface between the neuromuscular system and the prosthetic device.

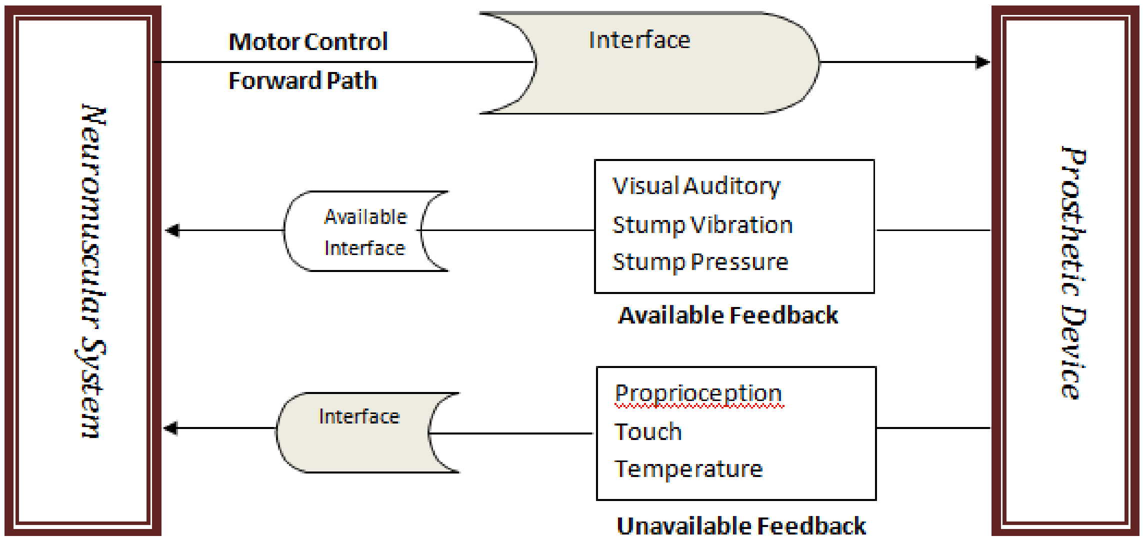


Figure 3-8: Block diagram of a neuromuscular prosthetic device

It may be noted that both the paths i.e. of motor and feedback must be interfaced with the neuromuscular system of body perfectly. Feedback has been shown in two modes, one is available and the other is unavailable in current prosthetic devices, hence the problematic area of the design remains interfaces of both the paths.

In the present prosthetic devices the feedback to the machine is given by visual monitoring of prosthetic movement, noise of machine and the fluctuations in vibrations and pressures observed by the sockets which come with operation of the device. It is therefore accepted that improvements in the feedback for the CNS is desired. The work which has been done in this regard is still a long way from success [126, 127, 128, 129, 130].

Scientists have proved that intact proprioception sensory feedback is not very much essential to control the movements of limbs [131].

3.6.2 Level of Amputation

There can be instances in which the level of amputation is more and the residual portion of muscles is insufficient that the EMG signals can be picked up from them. Option left is to pick up the myoelectric signals from the muscles which do not cause the movement, which is desired to be controlled. In this case the displacement of the prosthetic device is not directly propotional to the contraction of the muscle. In these cases the patient has to concentrate more to supervise the motion of the device. This reduces the acceptance of the amputee towards the device and the person feels bored and fatigued while using the prosthetic device. It also reduces the degree of freedom of the device. In this case the dynamic characteristics of the prosthetic arm becomes far less from the limb it replaces.

Another option on which Kuiken et al. [132, 133] has worked, is to transfer residual nerves of an amputees to his other muscles in the near vicinity of the residual limb. The advantage of this approach is that the function of a particular nerve is physiologically correlated with the corresponding function in the prosthetic device. Thereby enabling the patient to operate in natural manner, which becomes even easier to learn and operate. Moreover, sensory feedback through external stimulation becomes possible both with electrical and mechanical stimuli [134, 135, 136]. However, this technique seems most appropriate for patients having a proximal amputation (shoulder or near axillary level) and who require to use external devices, and noninvasive techniques.

3.6.3 Degree of Freedom

Neuroelectric approach is considered in the cases where several degrees of freedom are required and the problem is compounded due to the absence of the muscles which cause a desired set of movements. In this scenario the muscles which control a desired movement does no longer exist, however the peripheral nerves which connects the missing muscles and brings motor neurons for this muscle is present. Hence this peripheral nerve can be accessed for getting the signals for the prosthetic device.

There are three main nerves, i.e. musculocutaneous, radial and median nerves which carry sufficient signals and are related to the three main degrees of freedom. The main three degrees of freedom of upper extremity are forearm’s flexion-extension, forearm’s pronation-supination and opening and closing of hand. A prosthetic device can conveniently be controlled by employing the above mentioned nerves and getting degrees of freedom of the device. This device would be operated in a manner as to give natural function and volatility. Moreover the individual would have the liberty to desire a particular series of movements, by impulsively starting a series of events, which would commence in higher centers of CNS and terminate with appropriate movement of prosthetic device.

3.6.4 Band Width of Neuroelectric Signal

Another advantage of controlling the prosthetic device by neuroelectric signal is a technical one. The band width of neuroelectric signals ranges from dc to approx 7.5 kHz [137]. The peak of frequency spectrum is approximated at 2 kHz. Now the advantage of this high frequency is that the obtained signal can be processed through a High Pass Filter of 180 Hz, thereby eliminating electromagnetic interference of low frequency without losing useful energy of the signal. In contrast the EMG signal obtained through the surface electrodes has a peak at approximately 50 Hz.

3.7 Complications of Neuroelectric

3.7.1 Implantable Electrode

The electrode which is used to pick the neuroelectric signal from the nerves is to be planted in the body and this process is carried out without effecting the residual portion of nerve, so that it remain in a state that neuroelectric signals can be picked up from it.

3.7.2 Surgical Intervention

Planting of the electrode is carried out by a surgical procedure, which requires the assistance of doctors. This electrode has to be replaced after every three years, the procedure can be a diciding factor for the amputee to say NO to neuroelectric prosthetic device. Moreover it would have cables / wires protruding out of the body, which can be a cause of some becteria infection at the opening in the body. Another hazard associated with this procedure is the breakage of wire, which means another minor surgery of the patient.

3.7.3 Planting Electrode

Planting an electrode inside human body with the nerve is the basic problem. It has to be placed as close to nerve as possible while causing minimum physical damage to the nerve and causing minimum restrictions to nerve operation. Initially the experiments have been performed on cats and rabbits. In the first instance tungsten microprobes were introduced in the sciatic nerve’s severed end of rabbits and cats. However, they could not be recommended for implantation for longer duration due to mechanical problems of stability of electrodes and they damaged the nerve. Subsequently, a pair of stainless steel rings encapsulate in a Silastic thin-wall tube was used. This was placed into the severed medial gastrocnemius nerve, which was separated by microdissection. After the implantation for about 10 – 15 hrs neuroelectric signals of physiological origin were received, but afterwards nerve ceased conduction. Result of all of these implants was necrosis of nerve fibres, reason of which may be damage to blood supply [138]. However, Hoffer *et at.* [139] has demonstrated that a little more sophisticated and careful microdissection technique to separate fasciculi can give better results.

3.7.4 Transmitting Neuroelectric Signals

There can be a possibility that the neuroelectric signals are transmitted out of the body, but this requires making a lightweight, small and durable device which includes transmitters, amplifiers and receivers which must be so located that it is close to the nerves. Integrated circuits and embedded systems have made it possible to have such like miniature devices but encapsulating this device inside the body beyond approximately three years is still difficult.

3.7.5 Nerve Electrode Interface

The basic concern after implanting the electrode becomes interfacing the electrode with the neuroelectric system of the body. Electrode having two charecteristics will be suitable.

3.7.5.1Mechanical Bond With The Nerve

The electrode must have a stable bondage with the residual portion of the nerve so that there is minimum relative movement between the nerve and the electrode.

3.7.5.2Signal to Noise Ratio

The electrode must have maximum signal to noise ratio, so that the recordings have a dominant portion of usable signal and lowest noise component.

3.7.5.3Myoelectric Signals

The electrode must be so placed that either it is so properly encapsulated that it is not in contact with the adjacent muscles or it should be able to disregard the EMG signals from the nearby muscles.

3.7.5.4Biocompatible Electrode

The electrode should be placed in a way that it is closest to the nerve yet it posses minimum physiological hindrance to the nerve and does not cause any damage to the nerve. Moreover the materials used in the construction of electrode and its associated ciruitry should be boicompatible. In the past few years the electrode which is to be omplanted in the body underwent a series of improvements [140, 141] and resultantly the presently available electrode has been reached [142]. This design has been made from six Teflon-coated standard wires (Medwire 10 1R 9/49T) which are helically wound around 2-0 surgical silk suture. Complete cable is encapsulated in a medical grade silastic (for flexible, inert silicone elastomer). All the six wires made three set of contacts of electrode, i.e. three channels. These were in the inner surface of the tube cloth. However excellent neural interface is achieved by peripheral nerves based intrafascicular electrodes. They offer excellent compromise amongst relatively less invasiveness and high selectivity [143].

a. Physiological Basis. Longitudinal intrafascicular electrodes (LIFEs) are intraneural electrodes and are inserted longitudinally in the tissue of nerve [144], these electrodes are potentially very appealing owing to their comparatively less invasiveness and selectivity. Extracellular electrodes (e.g., LIFEs) compute the activity of axons and act according to the terms dictated by the populace of axons in close vicinity. The interface between the neural system and the electrode is nonspecific and varies person to person and place to place. Moreover the information which is computed by the electrode in a unit activity is usually a mixture of varying and time-overlapping data. These activities originate from efferent (outwards) and afferent (inwards) units.

In the single-unit recordings, information is not carried by the shape of action. Required information is kept rate of action potential and firing distribution. Simply, signal-to-noise ratio is amazingly superior. In case of multiunit recordings, information is sacrificed if single unit spike trains cannot be recovered from the interleaved spiking activity.

Neuroelectric signals associated with various nerve fibres may be extrapolated and identified basing on the shape of the unit got from multiunit recording. Shape of a spike is established by:

(1) Membrane's surface area (which is dependent on axon's diameter)

(2) Type of fibre, i.e., myelinated or otherwise

(3) Orientation of the nodes of Ranvier

(4) Distance between the electrode and nerve fibre

(5) Inhomogeneity of the conductivity of the intrafascicular space

Once the shape of the spike is identified with the use of spike sorting (as distinct nerve fibres carry distinct information: e.g., which motor units are required to be activated to get a desired movement), spike sorted data is used to extract precise information, which is contained in the single unit activity, from the mixed populace record.

b. Certain experiments were carried out by using Thin-Film LIFEs Thin-film LIFEs (tfLIFE) [145, 146]. These electrodes had been developed on a micropatterned polyimide substrate, the purpose of choosing this material is that it is biocompatible, flexible, and its structural properties [147].

3.8 PNS Neural Interfaces

There are attractive opportunities related with the usage of PNS neural interfaces, however, selection of the most appropriate interface in order to control advanced sensored prostheses, various aspects of the different solutions must be considered.

3.8.1 Cuff electrodes

Cuff electrodes are being used and have undergone test and trials in animals and humans. Hence, they are considered as a medium / short-term feasible technology for peripheral nerve interface. Cuff electrodes enfold the nerve and take the readings of combined activity of all axons enclosed. These electrodes permit the recording of a single nerve action potential from small fascicles, but their limitation is that cuff electrodes cannot differentiate different fibres. So, cuff electrodes symbolize an inserted neural interface with comparatively good selectivity, low invasiveness but also low selectivity.

interfascicular cuff electrodes [148], Multisite cuff electrodes [149, 150], innovative cuff structures [151, 152], and advanced processing algorithms [153, 154, 155] have considerably raised the selectivity of cuffs. Despite of all of these improvements, they still are not better or significantly improved than the surface EMG techniques. Actually higher selectivity is required for, a smart sensored robotic hand prostheses.

3.8.2 Sieve electrodes

Sieve electrode or regeneration-type electrodes comprise of a thin insulating plane along with a lattice of metallized via holes, which is implanted in between two endings of a sectioned peripheral nerve. Eventually regenerating axons grow through the via holes, thus making the recording of action potentials possible and the excitation of individual axons. These electrodes can be applied only after transecting the peripheral nerve and supporting the fibres in the transected nerve stump to regenerate the axons through the interface.

Despite of hopeful results in the experimental models [156, 157], a few challenges are still there, which limit the clinical utility of these electrodes [158]. With a silicon-based chips, only a little proportion of proximal axons cross the via holes and often morphological abnormalities are shown by the regenerated fibres [159].

Comparatively better biocompability [160] is possessed by micromachined polyimide sieve electrodes [161] as compared to silicon dice, as they offer bigger total open area and higher electrode flexibility. These electrodes permit compound action potentials recording and of recordings of bursts of single action potentials as a response to sensory stimuli.

A little open tissue is presented by the polyimide sieve electrodes [162]. Regeneration speed of small nerve fibres is higher than that of large nerve fibres, hence that bigger myelinated sensory and motor axons are underrepresented in the holes of the electrode.

3.8.3 Multielectrodes Arrays

Multielectrodes arrays (MEAs) [163] are joined arrays of hundreds of piercing silicon, polyimide, or glass microelectrodes, so designed as to record selectively or stimulate electrically the neurons. It is primarily developed for the interface with CNS, however they are also used in peripheral nerves and are shown as a device for selective recording with single unit resolution and a low-current and high-selectivity stimulation interface. Experiments on them have been performed on the animal models [164, 165], as well as in a human volunteer [158]. Unluckily, they are very much invasive. Factually they give high nerve damaging risk because of their rigid structure, invasiveness and the high electrode density.

3.8.4 Longitudinal intra-fascicular electrodes

Longitudinal Intra-Fascicular Electrodes (LIFEs) is also a different type of intraneural electrodes. They are manufactured from thin insulated conducting wires. LIFE are inserted longitudinally in the nerve tissue [166, 167] and are designed so that they can be laid in-between and parallel to the nerve fibres.

They give more selective recording than cuff electrodes as they gather signals from less number of axons only. Moreover, invasiveness of these electrodes is less than MEAs as they are implanted transversely into the nerve posing a higher risk for damaging the nerve. LIFEs are and have been development particularly as a neuroprosthetic device since the late 1980’s [168, 169, 169] and recently are being implanted semi-chronically in amputees [17, 171, 172].

Lately, a newer version of LIFEs using polyimide substrate has been developed, it is known as

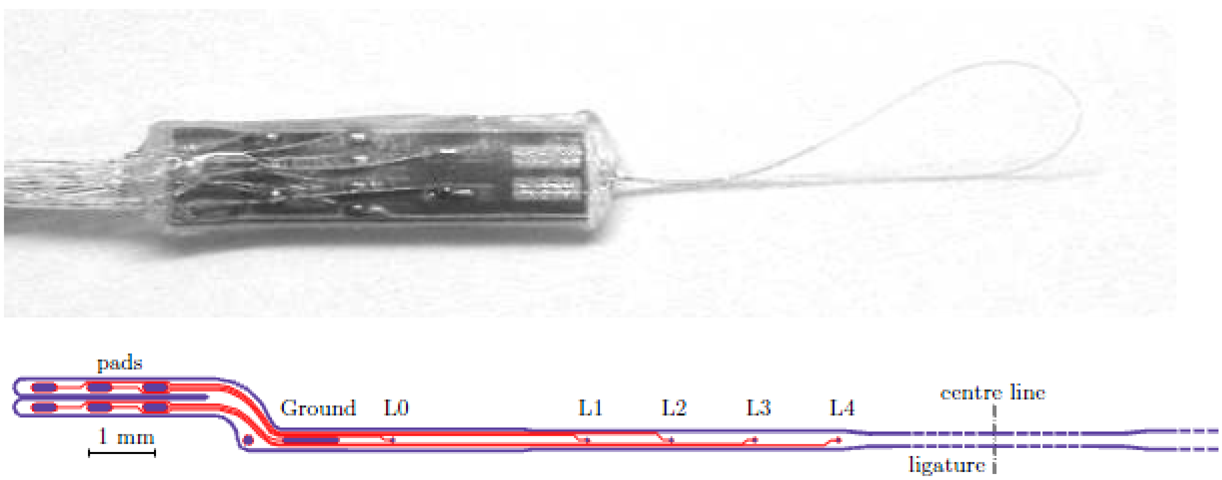


Figure 3-9: tfLIFE Electrode

thin film LIFEs (tfLIFEs) [173, 174]. Microfabrication techniques have been used for its manufacture and the process has been matured for mass production.

tfLIFE were manufactured on micropatterned polyimide substrate, this material has been used due to its flexibility, biocompatibility and its structural properties. Once the microfabrication is complete this substrate filament is doubled in half thus, now each side has 4 active recording sites. Hence, tfLIFEs offers multi-unit peripheral nerve recordings at 8 recording sites per structure.

3.8.5 Considerations

Generally, little invasive extraneural electrodes, like cuff and epineurial are less selective or they lack selectivity, due to the reason that they offer simultaneous interface to a band of axons in nerve. Conversely more invasive intrafascicular, regenerative and penetrating electrodes are more selective and offer interaction with small collections of axons within a nerve fascicle.

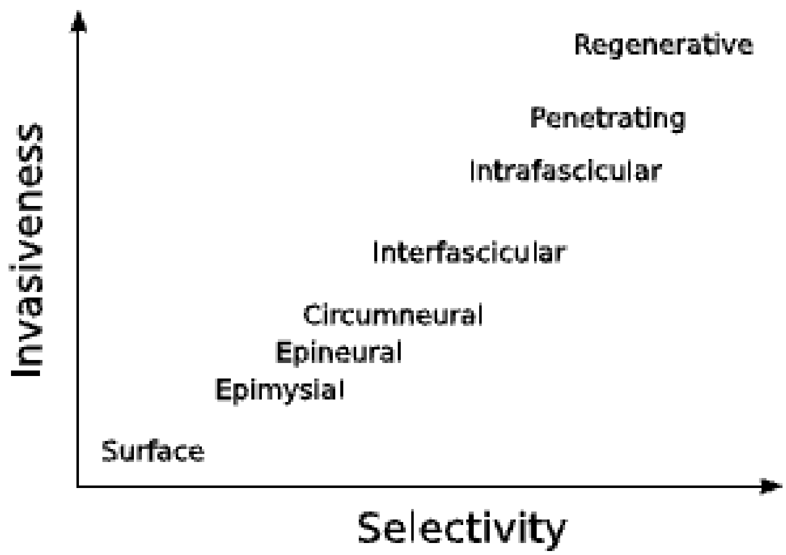
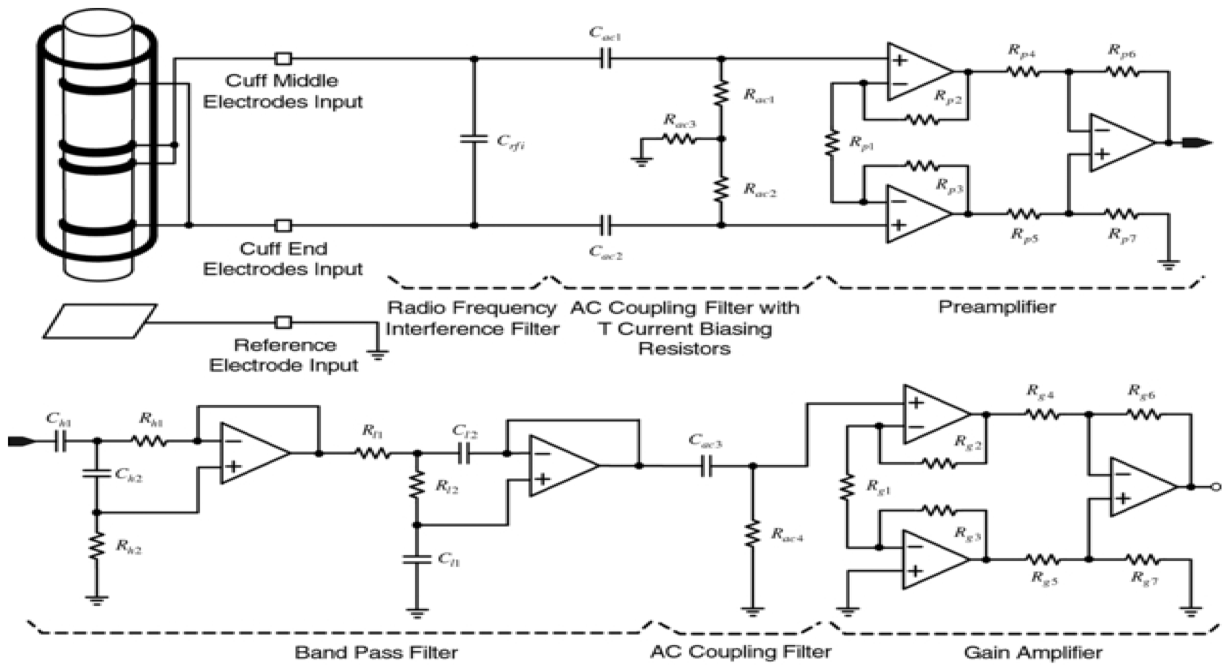


Figure 3-10: Invasiveness and Selectivity

Since both the characteristics, i.e. less invasiveness and better selectivity are not achievable simultaneously, hence a balance must be kept in between the two and the selection must be made according to the situation, requirement and application. For better sensored hand prosthetic devices, LIFEs can be a fine trade-off, due to reduced (although not eliminated) invasiveness and a high selectivity.

3.9 Neuroelectric Signal Processing

Signal processing of Neuroelectric signal is shown with signal acquisition performed by Cuff Electrodes, The two middle and 2 end electrode connections are short circuited and the signal is picked up from that. The reference signal is grounded. In implantable devices radio frequency components and wireless power transmissions are indispensible, and interference is generated due to these instruments.



In order to cater for these interferences following stages have been included in the processing circuit:

3.9.1 RIF Filter

1 nF Capacitor Radio Frequency Interference (RIF) Filter is used which reduces the unwanted high frequency components which are over 60 Hz frequency.

3.9.2 ac Coupling Filter

ac coupling filter is used to prevent the preamplifier from a high differential gain, which is generated due to the unwanted low frequencies.

3.9.3 Nerve protection

In the third stage, 2 x Capacitors 100 nF along with 2 x Resistors 10 KΩ are used which block any dc current flow through the electrode as it can cause electrolysis or damage the nerves and this damage can be irreversible.

3.9.4 Preamplifier

INA 118 (CMRR 110 dB) and INA 121 (CMRR 106 dB) has been used as preamplifiers, and the results show that INA 118 produces better results, however I would recommend the use of AD-620 as preamplifiers as its CMRR value is even higher i.e., 120 – 130 dB, moreover it is easily available in the local market and it is very cheap as well.

3.9.5 Bandpass Filter

Then a band Pass filter has been used with the following cut off frequencies:

a. HPF - 300 Hz

b. LPF - 5000 Hz

3.9.6 Gain Amplifier

In the end again the signal is passed through a gain amplifier just to further amplify the signal 10 times.

CHAPTER IV: NON-INVASIVE BRAIN MACHINE INTERFACE

4.1 General

Researchers are working since last 40 years to control the devices or to interact with the environment by mere thought process instead of manual control. However, the success in this field has been achieved in recent past [177, 178, 179, 180]. It is a This is a multidisciplinary field which is experiencing rapid emergence and is known as brain–machine interface (BMI). Latest trends and the modern technology in the field of robotics, like mechatronic design procedures, miniature actuators having better weight to power ratio, micro position sensors and tactile \ force sensors, have enabled the scientists to develop a compact, multi fingered and yet light-weight hand prostheses [181], incorporating embedded systems and having the facility of actively grasping control and capable to carry out dexterous manipulative tasks, by having proper interfacing with human brain. Preferably, a brain–machine interface (BMI) in a hand prosthetic device implements a closed-loop control by exchange of bidirectional, i.e. efferent (outward) and afferent (inward) information with the nervous system. Cyberhand system is one example of this approach. Cybernetic anthropomorphic prosthetic hand device particularly designed for an intended bidirectional neural interface connection with the PNS and CNS, due to which it will exchange afferent and efferent signals with the amputee [182].

Prototype and commercially available interfaces of a prosthetic device with the amputee are equipped use different types of human–machine interfaces, for the purpose to get the information about user intent (motor commands) and, sometimes, feedback of some kind of artificial sensory input from the prosthetic device to the amputee. Such kind of interfaces can be categorized in five basic segments:

a. Mechanical (body-powered) interfaces. Human machine interfaces which are powered by the amputee's body copy the intent of user in a mechanical fashion and takes the input from movements of one segment of the body, i.e. one shoulder or foot. This shoulder or foot is linked physically with the prosthetic device and thus translates real volitive movements into the movements of hand.

b. Myolectric (EMG-based) interfaces using non-homologous muscles.

In the myoelectric interfaces voluntary contraction of muscles is used for the communication of the human body with the prosthetic device. This voluntary contraction of muscles is picked up by surface electrodes in the form of EMG signal. In the usual cases of limb amputation, the muscles actually related to a specific movement of hand are no more available so the electrodes are placed on some other muscles. This case is referred to as EMG based interfaces using non-homologus muscles.

c. Myolectric (EMG-based) interfaces using homologous muscles

It is rare case in which the level of amputation is low and EMG signals are picked up from residual portion of the same muscles, which were originally causing the same set of movements.

d. Non-invasive neural interfaces. Very less has been done in the field of hand prosthesis control through non invasive neural interface, however some work has been performed to control the hand prosthetic device using non invasive EEG techniques. Although the success rate of non invasive neural interfaces has not been very encouraging in the prosthetic devices as it enabled the control of only one degree of freedom prostheses along with lot of undesired movement [183], or it requires high level user's attention [184], due to which the use of these interfaces becomes quite unpleasant for the amputee.

Despite above facts, in other devices it is becoming the more popular technique for brain machine interface (BMI) as they do not involve any kind of surgical procedures and are to be implanted inside the nervous system. These techniques get the user intent through the CNS and adopt various imaging technologies to implement these interfaces, like MEG, EEG, fMRI and near-infrared spectroscopy. Utilization of non invasive BMIs to control the assistive technologies, like electric wheelchairs or BMIs for the movement of a cursor on the screen by a paralyzed patient is available [185]. Integrated use of non invasive interfaces, for getting efferent commands as well as to communicate sensory feedback to brain, is yet be explored and it can offer strict limitations onto the development of bidirectional interfaces based on such technologies.

e. <u>Invasive neural interfaces</u>. Direct electric current connection is required to be established between the prosthetic device and the human nervous system in invasive neural interfaces (BMIs or BCIs). Experimental trials for invasive microelectrodes arrays or single electrodes implanted central as well as peripheral nervous system for controlling prosthetic device has reached clinical application phase. One example is when in 2004 Donoghue's group embedded a 96 microelectrode array in M1 of a patient. Procedure was done after a lapse of 3 years after spinal cord injury at C3–C4 vertebral level. The patient was able to control a one degree of freedom hand prosthesis and controlling a PC cursor with 9 months [186, 187].

Two diverse groups have been able to get the volitional motor nerve activity by peripheral intrafascicular electrodes implanted in the stump, from this the amputee was able to have a controlled hand grip of the prosthesis [188]. Moreover flexion and extension of an artificial finger has been controlled by peripheral intrafascicular electrodes implanted in the stump [189].

An invasive two directional interface on the basis of intrafascicular multielectrodes inserted in peripheral sensory motor nerves may give the best compromise between, amount and selection of exchange of information on one hand and implant invasiveness on the other hand.

Devices using the last two techniques are classified as brain–computer interfaces (BCI), however they are commercially known as brain–machine interfaces (BMI) [190, 191, 192].

4.2 Introduction to BMI

In this interface the activity of the user's brain is monitored, particular features, which are representing the human intent are extracted from the obtained brain signals, and then these extracted features are translated into desired actions (like wheelchair movement or letter selection in a virtual keyboard), without incorporating any kind of muscular nervous activity. The main principle of BMI is the ability to differentiate distinct brain activity patterns, each one of these is associated to a specific intent. The key factor of BMI is adaptation, since the subject should be trained to adjust his brainwaves voluntary via proper feedback, so that he is able to generate different patterns of brainwaves. In few cases, training of the user is accelerated and complemented through machine learning methods to ascertain the brain patterns of each individual [193, 194].

4.3 Brain Computer Interface (BCI)

From the advent of this study the main aim of scientists / engineers remained to transform the thoughts into act thereby improving the quality of life of physically impaired persons. The question arises that what type of signals from brain are required, which would be able to control a device directly? The best candidate comes out to be electrical activity as it has the best time resolution. Changes in the activity of brain at milliseconds range can be detected. Electrical activity of brain can be recorded invasively as well as noninvasively. Brain machine interfaces carried out noninvasively are known as brain–computer interfaces (BCIs). BCIs mainly utilize electroencephalographic (EEG) activity. In order to record EEG electrodes are placed on the scalp, it measures the simultaneous activity of thousands of cortical neurons [195 - 220]. There are three main components in a BCI system

a. Inputs. Primarily EEG signals obtained from the brain through electrodes placed on the scalp of the subject during any mental task performance.

b. Outputs. These are the output obtained from the BCI system in the form of computer commands to control any device, like prosthetic hand.

c. Algorithm which translates the inputs into outputs. These are a series of algorithms, applying various signal processes on the input, thereby converting it into the commands for the device, like an artificial arm [211].

4.3.1 Types of BCI Systems

There can be three classification of a BCI system, these are:

4.3.1.1Invasive / Non-invasive

If the signal is acquired by involving any kind of surgery, i.e. the signal acquisition is through cutting the brain, then it is known as invasive BCI systems. However if the signals are acquired directly from the scalp by placement of electrode cap then it is called a non-invasive BCI systems. Although the signal acquired by invasive system are stronger but still non-invasive BCI systems are preferred.

4.3.1.2Dependent / Independent

BCI systems can also be independent or dependent; if the system is dependent on the normal pathway of brain then it would be known as a dependent BCI system, otherwise it will be an independent system.

4.3.1.3Synchronous / Asynchronous

Classification is done on the base of the protocol in which the data is recorded. If the commands are given by the user a specific time intervals and the entire system works in finite time brackets, instead of working continuously, then it is known to a synchronous BCI system.

However if the system permits the spontaneous response of the device and it does not involve special thinking by the user then it is called an Asynchronous BCI system. Certainly this system is more practical and works in real time, however it is much more complex then the synchronous BCI system. The complexities of this system involves not only to differentiate between several mental tasks but also has to be able to differentiate between the rest and activity state of the brain. While dealing with brain signals it is the greatest challenge as it is very seldom that the brain is at rest.

4.4 Electroencephalography (EEG)

Easiest and simplest way to record reflection of the activity of our brain is electroencephalogram (EEG). It requires only some surface electrodes along with signal processing circuit which is not that expensive. Moreover EEG is a safe and convenient method of recording electrical signals, which makes it a popular BMI technique. Electrical activity is detected at the scalp. Due to these characteristics, in the first instance EEG got a lot of attention by the researchers to control the neuromotor prosthetic device. Certain device were initially made with the implementation of EEG signal and to some extent they were successful as well [208]. However, surface EEG has three main disadvantages, and they are:

a. EEG signals are relatively slow to modulate or engage (more than 1 second), hence the reaction of prosthetic device does not mimic natural actions

b. Mental concentration in order to exclude other activities is required

c. With the use of EEG signals achievement of continuous control for more than 1 dimension is difficult.

As a matter of fact, it can not only be utilized to enhance the capabilities of an amputee, a paralyzed patient but also opens new possibilities for a fit person, like in space applications and games. It provides an additional link for interaction between the brain and the outside world. Multiple devices can be controlled by human beings with the help of EEG signals, its examples are:

a. Keyboards or cursor movement [201, 203, 204, 206],

b. Brain games [201, 207]

c. Robots [196]

d. Hand orthoses [205]

e. Wheelchairs [200]

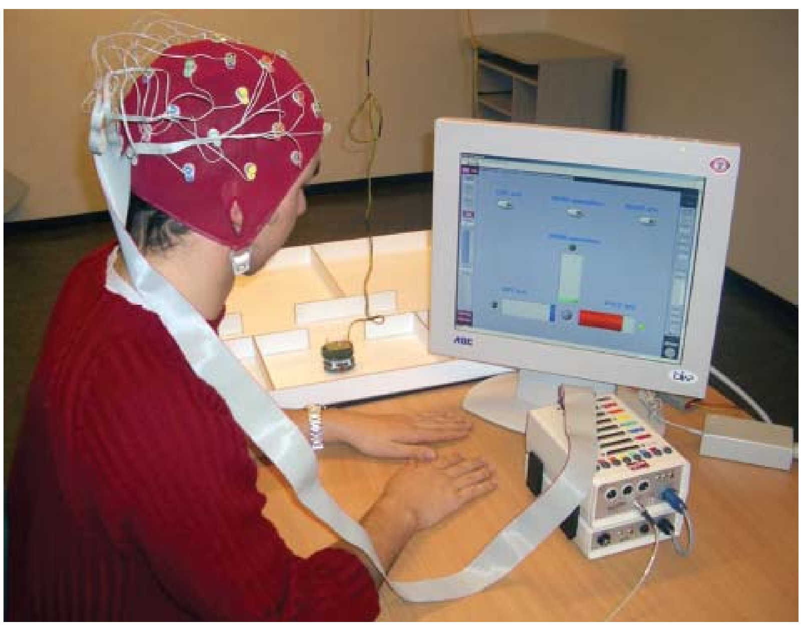


Figure 4-1: EEG Application

Figure 4-2: Electrode placing

4.4.1 History

Massive advancement has been seen in the field of encephalography in the past 100 years. Richard Caton, an English physician was the first one who discovered the presence of electrical current in human brain by observing EEG in monkeys and rabbits in 1875. Hans Berger, a neurologist from Germany amplified the electrical activity of brain with the help of his simple radio equipment, in 1924. Electrical activity of brain observed by Han was a function of brain status as it was continuously changing with the change in brain's status, like anesthesia, sleep and lack of oxygen. Most of application of electroencephalography were discovered by Berger. [212]. Adrian and Matthews wrote a paper describing the theory of "human brain waves" in which they described oscillations of about 10 to 12 Hz, to which they named "alpha rhythm" Later in 1934 [213].

4.4.2 Complications in EEG

4.4.2.1 Interpretation of EEG Signal

Same frequency of brain waves are not obtained from different regions of brain at the same time, hence many waves are obtained in the EEG signal received / recorded by electrodes positioned on the scalp and all these waves may present different characteristics. It is therefore difficult to interpret the EEG data obtained by the readings of a single electrode.

4.4.2.2Uniqueness in EEG Pattern

Patterns of brain waves obtained by each individual is unique. At times brain activity can become the basis in distinguishing distinguish people. Its example can be that persons who are rational or holistic/intuitive type usually demonstrate the same type of activity in the frontal right and left region of their brain.

4.4.2.3Reduced Spatial Resolution

Since simultaneous activity of thousands of cortical neurons becomes the main source of EEG signal, hence inherent problem with the signal is its shrinked spatial resolution. Moreover the signal is taken from the scalp, the signal is vulnerable to motion artifacts created due to optical movements and contraction of muscles, also due to outside sources. Resultantly, present BMIs based on EEG offer very low rate of information transfer and due to this reason this technology is taken as very slow for the control of complex devices like prosthetic arms. However, as EEG signals can be analysed online, in case when used along smart interaction designs and machine learning techniques, this problem is resolved. Furthermore, people can learn the use of brain actuated devices very swiftly, if the BMI and the user are coupled together and both adapt to each other, [220, 221].

4.4.2.4Training

Various devices actuated by the brain can be operated by different subjects by through a similar EEG pattern which they can regulate by virtue of their training. Mental and EEG patterns associated with them are required to be learned by the subjects. Use of machine learning techniques at two levels has enabled the people to do so. In the first level that EEG pattern must be discriminately discovered, at which the user swiftly learns to regulate wilfully. In the second level, continuous EEG signals must be intelligently analyzed, so that a mental command must be delivered only when enough evidence has been accumulated by the BMI for that command.

4.4.2.5Abstract Information

Despite of the fact that EEG provides accurate two-dimensional control of the movement of wheelchairs and control, but the information that is obtained by EEG regarding intended actions, intended targets and preferences more abstract. That is why EEG becomes a perfect control signal in case, shared control principles are to be followed for designing smart interaction devices. This is predominantly effective in case of neuroprostheses and robots [197, 198].

4.4.2.6Non Uniform distribution of potentials

Since the brain's structure is spiral and layered, a non-uniform pattern of potential distribution is observed on the cortex or scalp [223]. Source localization of EEG signal becomes problematic due to this reason.

4.4.2.7Memory Requirements for Signal Processing System

If 128 electrodes are used for recording and the EEG signal and the sampling rate is 500 samples/s for one hour duration, then the memory size becomes:

$$\text{Memory size required} = 128 \times 60 \times 60 \times 500 \times 16 \approx 3.68 \text{ Gbits}$$

$$\text{Memory size required} \approx 0.45 \text{ Gbyte}$$

Hence, if the signal is to be recorded for longer duration, then sufficient memory must be required to process the EEG signal. For this reason latest technology, like CDs, Zip disks, external hard drives, etc must be utilized.

4.5 EEG Recording and Measurement

Recording of physiological and functional changes in the brain is possible through MEG, EEG, or fMRI, however fMRI application are very less as compared to MEG or EEG, due to the following reasons:

a. Time resolution of the image sequence of fMRI is very low (example can be approx 2 frames/s), on the other hand in case of EEG signals complete bandwidth is visible.

b. Using fMRI various mental disorders, brain activities and brain malfunctions cannot be viewed as they have a very low effect on the level of oxygenated blood.

c. Accessibility system of fMRI is very costly and limited.

d. Quantity of electrodes placed on the scalp dictate the spatial resolution of EEG signal.

EEG signal acquisition system comprises of electrodes, differential amplifiers and filters [224]. Just after the marketing of this system, digitization and storing of EEG signal became the priority of researchers, hence the EEG signal must be in the digital form, for its analysis. Data in digital form means that it should be sampled, quantized, and encoded. More recording electrodes means increase in number of bits of data volume.

Various kinds of electrodes used for recording EEG signals are:

a. Disposable electrodes (pre-gelled and without gel)

b. Reusable disc electrodes (silver, gold, tin, or stainless steel)

c. Electrodes caps and headbands

d. Saline-based electrodes

e. Needle electrodes

Electrode caps are preferred to carryout multichannel recordings using a huge quantity of electrodes. Usually Ag-AgCl disk type electrodes, having less than 3 mm diameter are used on the scalp. Impedance between the electrode and the cortex must not be high, moreover the impedance of electrode should be low as it will distort the signal and it can even mask actual EEG signal. For a successful recording of EEG signal the impedances of electrode must be below 5 kΩ.

4.5.1 Conventional Electrode Positioning

Primary motor cortex and the adjacent brain regions are the places where the occurrence of motor imagination as well as motor tasks takes place, as shown in figure.

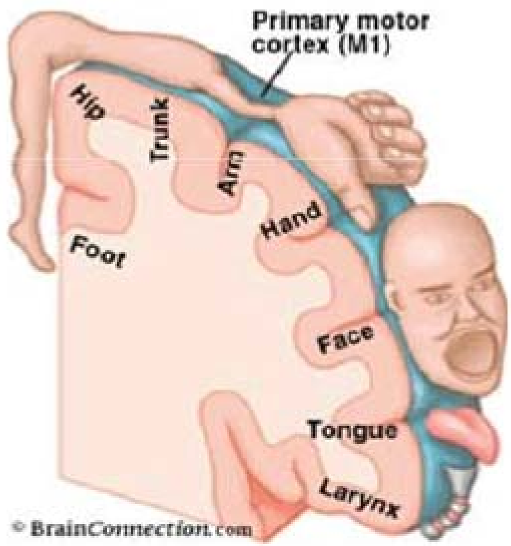


Figure 4-3: Motor Cortex map

From the above figure it is evident that, for any BCI system, dealing only in motor functions, the it will be sufficient to record the data by placing electrodes on these areas only. There are few schemes for placing of electrodes.

4.5.1.110-20 Electrode System

Conventional placement of 21 electrodes as recommended by International Federation of Societies for Electroencephalography and Clinical Neurophysiology, which is also called 10-20 setting, is shown in the following figure [225]:

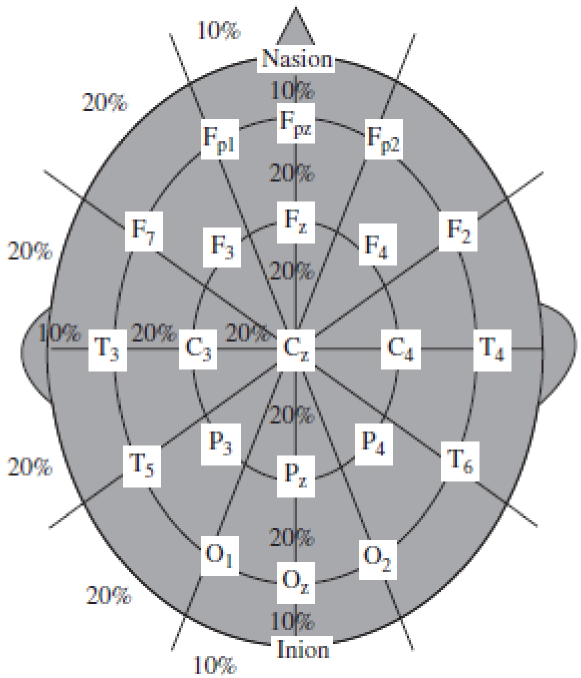


Figure 4-4: 10–20 EEG setting

A1 and A2, electrodes used as reference electrodes are placed on the left earlobe and right earlobe. The 10–20 placement of electrodes system takes some regular distances keeping in view particular anatomic landmarks, which are used to take the measurements. Then it utilizes 10% or 20% of that particular distance as interval between the electrodes. In this system, even electrodes are placed on the right hemisphere of the brain and odd ones are on the left. In case of 10-20 system, if more electrodes are to be added, then they are positioned equidistantly in between the above electrodes. 10-20 system incorporating 75 electrodes is shown in the following figure.

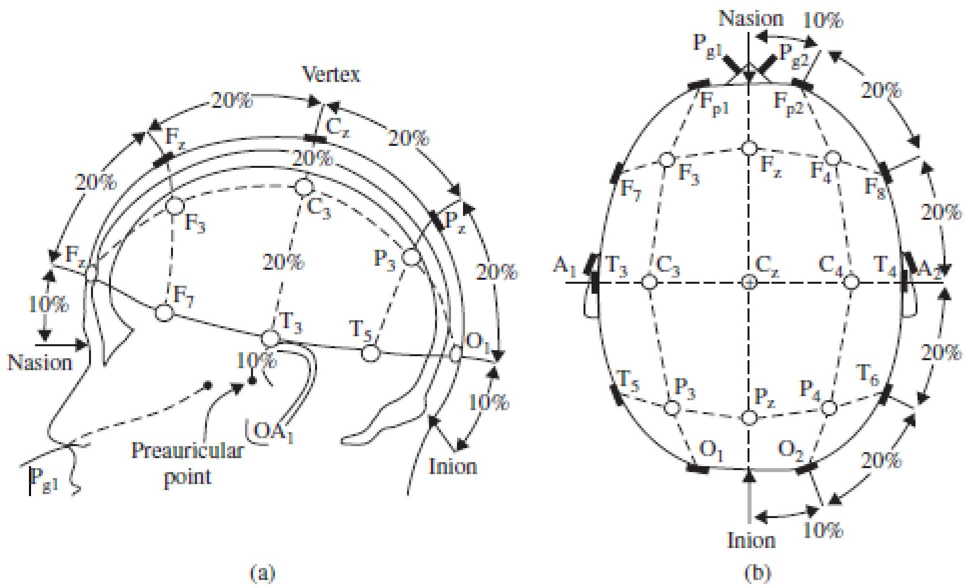


Figure 4-5: 10–20 electrode settings using 75 electrodes: (a) and (b) measures represented in three-dimensions

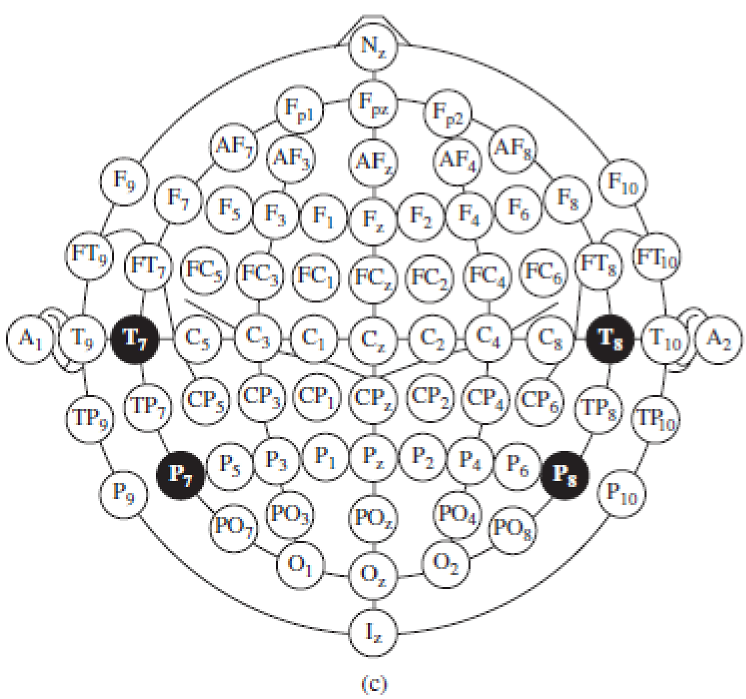


Figure 4-6: 10–20 electrode configuration using 75 electrodes: (c) View with two dimensions

There are two modes used for taking the reading of electrodes, they are differential and referential.

4.5.1.2 Differential Mode

If the differential amplifier gets the input from two electrodes, then this recording mode is known as differential mode.

4.5.1.3 Referential Mode

If one or more reference electrodes are utilized then this mode of recording is known as referential mode.

With the advancement in instrumentation, the measurement is not truly dependent on the selection of reference [225]. In these cases some other references like FPz, leg, or hand electrodes can be utilized [226].

4.5.1.4 Maudsley Electrode Positioning System

In this system a slight modification has been made in the conventional 10–20 electrode system in order to acquire better the EEG signals. In this system, the outer electrodes has been somewhat lowered to facilitate enhanced capturing of EEG signals. The capturing of EEG signal gets enhanced due to the lowering of outer electrodes as the coverage of lower portion of cerebral convexity is increased, thereby the sensitivity for the recording from basal subtemporal structures is increased [227]. This is the main advantage of this system over 10-20 electrode system.

4.6 EEG Signal Features

Signal features are the characteristics which defines or distinguishes various signals. Nature of EEG signals is stochastic, i.e. the single values of EEG signal do not carry any meaning and are unreliable. EEG signals are not stationary and vary very frequently with time, i.e. a change is observed in frequency components after every 200 ms.

After acquisition and digitization of EEG signal, it is divided into such features which can provide information on the user intent. Time domain features like amplitudes of the potentials which are evoked or the firing rates of the neurons can be used by the BCI system. Features of frequency domain like mu / beta rhythm can also be used by the BCI system. Simultaneously both the features can also be utilized by the BCI system. A few of the features which can be used by a BCI system are described in the succeeding paras.

4.6.1 Frequency Domain Features

Brain patterns of individuals are obtained by making the subject relaxed and closed eyes position. Commonly sinusoidal brain waves are formed. Waves are computed peak to peak and normal range of their amplitude is from 0.5 to 100 μV, (approx 100 times less than ECG). State of brain of an individual can show some frequencies as dominant. Important features may be extracted from EEG signal frequency [13 of [214]]. EEG signal frequency is further subdivided into 5 smaller bands.

a. Delta Band ~ 0-4 Hz

b. Theta Band ~ 4-7 Hz

c. Alpha Band~ 8-13 Hz

d. Beta Band ~ 14-30 Hz

e. Gamma Band~ 30-80 Hz

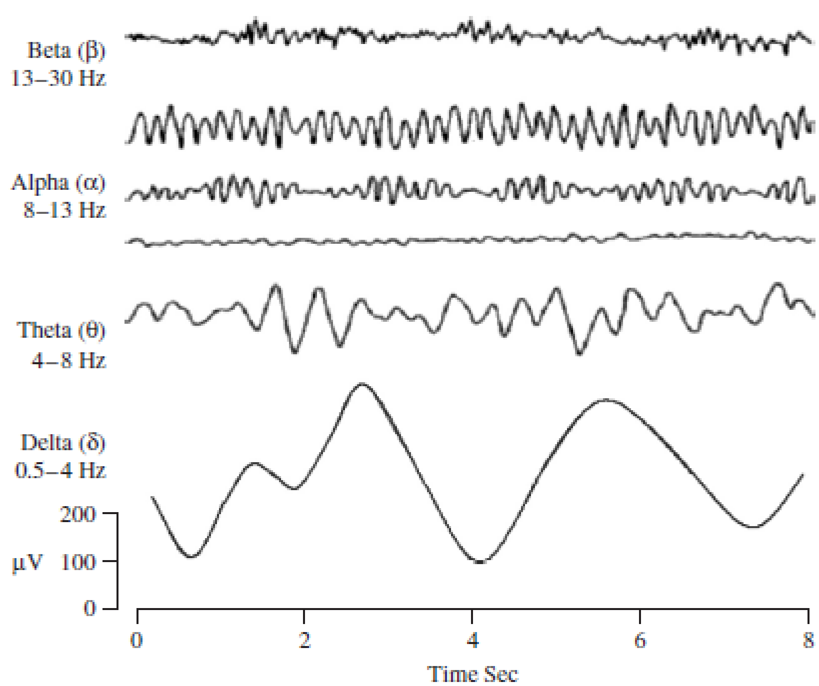


Figure 4-7: Distribution of brain waves in 5 different catagories

4.6.1.1 Mu and Beta Rhythms

Alpha waves (α, 8-13 Hz) are called Mu-Rhythm and is in the central sensorimotor (C) part of the scalp which overlays the sensorimotor cortex. Most of the information regarding limb movements, its imagination and preparation are contained in this region [14 in [214]].

Often beta rhythms and mu-rhythms are associated with each other. They are visible together in the areas of brain where the motor output channels of the brain are situated, hence maximum information about the real or imagined movement of limbs can be obtained from them. Amplitude of these rhythms gets reduced in case of movement and increased when the subject is at rest. They present excellent features in order to classify various movements of limbs, since they contain good spatial information. An amputee can easily learn, controlling the amplitude of his / her beta and mu rhythms through a little training, thereby having a better performance of the prosthetic device [228, 229, 230, 231].

4.6.1.2 ERD/ERS Maps

Event related potentials (ERP) and the oscillatory signals of the brain change with the performance of any mental task, these changes are distinguished by two factors which are called event related desynchronization and synchronization (ERD/ERS).

If the motion reduces the mu or beta rhythm then it is known as 'event-related desynchronization' or ERD. If it causes an increase in the mu or beta rhythm then it is called 'event-related synchronization' (ERS). Its occurrence takes place once the movement is completed and the subject is relaxed [1 in [214]].

If the actual movement of any limb takes place or even if it its imagination takes place ERD / ERS is generated, which are temporally and spatially apart, hence the region where the movement is originated can be known. [232].

4.6.1.3 Auto-Regressive (AR) / Adaptive Auto-Regressive (AAR) Features

Regression (in statistics) means a functional relationship amongst two or more variables which are correlated and their values are utilized to predict the values of another variable which is unknown. If the variables are calculations or measurements of an event which is continuous (ongoing) and are time-related, e.g., in case of EEG, autoregressive analysis can be applied to analyze the event [17 in [214]]. Autoregressive frequency analysis can also be utilized to get the higher resolution for short time segments, thereby be able to control the device more rapidly.

4.6.1.4Power Spectral Density

Power Spectral Density of EEG signal can also be used to control the device through a BCI systems. Since the EEG signal has normally distributed amplitude, statistical properties of EEG signal does not vary in time, and has an uncorrelated frequency components, hence they can be used for comparison purposes. Power Spectral Density presumes Gaussianality, linearity and minimum-phase.

4.6.2 Time Domain Features

Vital information is carried in the time domain of an EEG signal for clear understanding. Signal amplitude is measured with respect to time. Beginning of an activity of brain or distinction amongst various ongoing activities is possible by measuring the amplitude changes with respect to time.

Also the statistical calculations of a signal are performed in the time domain, like calculating the variance, calculating the root mean square, etc. Moreover signal's power and energy are also computed in time domain.

4.6.2.1Energy

Variations in EEG signal's energy can be related to conclude a change in the intent of a user. Gabor transform has been utilized by Vuckovic et al. [228] to compute EEG signal's energy. Significant variations were observed in the Energy density maps which was related to various movements in time domain.

4.6.2.2Fractal Dimensions

As the brain is a very complicated and non-linear organ hence the EEG signals originated from it are also non-linear in their nature. A self-affinity property [229] is possessed by the EEG signals, i.e. they are contain their own rescaled copies at progressively minute scales. EEG signal's this property is exhibited by its fractal dimension values. A characteristic response in the ERD/ERS mappings of various motions is shown by fractal dimension values. This can be utilized to differentiate between different states of our brain, such as relaxing and imagining. If a high FD value is obtained, it indicates a complicated structure of EEG signal, thereby indicating motion, and a lower FD value can be related to a relaxed mind [230, 231].

4.6.2.3Slow Cortical Potentials

Sluggish Cortical Potentials can be related to lousy voltage changes which are created in region of cortex, and they correspond other function or movement which involve cortical activation. Although these are also features, which can be relied upon, but since their response is very slow (0.5 – 10 s) they become inappropriate for systems which are online, or realtime.

4.6.2.4 P300

If the uncommon or significant visual, auditory, or somatosensory stimuli, are interspersed with routine or frequent stimuli, a positive peak is induced in EEG signal at 300ms, this is known as P300. Amplitude of P300 becomes very high as compared to the remaining signals, which suggests that an event has been triggered [232].

4.6.2.5Readiness Potential (RP)

A feature of EEG signal which is produced as a response of an imagination of a movement or of a movement on cortical motor areas is called Readiness Potential (RP). Extraction of RP is possible by applying signal averaging techniques in a specific time-period. It has already been exhibited by studies that a unique RP value is shown for each single-limb movements and its reliability is between 60-100% [233].

4.6.3 Joint Time-Frequency Domain

In order to have the maximum benefit of the information contained in EEG signal, conversion of the signal to joint time-frequency domain (JTF) is carried out. In it the frequency changes are viewed in specific time intervals.

4.6.3.1Wavelet Coefficients

It has become a widespread tool for analyses of localized differences in power in a time series of very small intervals. Decomposition of time series into time frequency space is then done and thus dominant modes of variability can be determined. These techniques have been by many researchers [234].

4.6.3.2Band Power (BP) Features

In this technique, the values of samples are squared in time domain thereby the result is smoothed. It can also be done in frequency domain by applying fast Fourier transform (FFT) on the EEG signal [235]. Band Power features are energy values of signal in various frequency bands, as a time function.

In order to distinguish different mental tasks suing BCI system, band power features has become very popular. Palaniappan [236] utilized spectral power and power differences in all five frequency bands.

4.6.4 Statistical Features

User intent can also be extracted from an EEG signal by using its statistical features, like variance, mean and ICA.

4.6.4.1Independent Component Analysis (ICA)

Independent component analysis (ICA) is a technique used to find components and factors which are underlying from data which is statistically multidimensional, the data which is non-Gaussian and is statistically independent [237].

ICA techniques is very commonly carried out for the removal of correlation effects, present due to the electrode locations. Vuckovic et al. [228] utilized ICA based features and exhibited that they give better results. However, the drawback of ICA is that it eliminates the spatial information in the signal along with the removal of correlation.

4.6.4.2Entropy

Entropy (ApEn) is a measure of non-linear complexity, developed recently. In it the irregularity of time series data is measured by a comparison of original time series and its time-shifted version. This technique has become suitable for online systems. Although, ApEn is expensive, computationally also it has parameters, which require tunings [237].

4.7 Conditioning the Signals

The amplitude of raw EEG signals is within the range of 10 μV and its frequency is up to 300 Hz. In order to utilize the effective information, the signals should be amplified before it is fed to ADC, however filtration can be performed either after or before the ADC. Filtration is necessary in order to shrink noise component in the signal and to make this signals appropriate for its utilization. Filters must be so designed, that they do not affect any kind of distortion or change in the signal. Low components of frequency generally less than 0.5 Hz are due to breathing and must be eliminated, hence the Highpass filters with the same cut-off frequency must be used. Similarly a Low Pass filter having a limit of 50 – 70 Hz is used get rid of strong noise of 50 Hz due to power supply. Often notch filters cutting off 50 Hz frequency is necessarily used to ensure removal of power supply effects, and simultaneously not having any effect on the useful signal. System artefacts are of the range of 50 / 60 Hz due to interference of power supply, fluctuations in the impedance, defects in the cable, electromagnetic noise due to electronic components, and due to imbalance in the electrode impedance. The purpose of signal conditioning is to mitigate these artefacts in the preprocessing stage and to restore the useful signal component.

4.8 Amplifiers and Filters

Amplification of acquired EEG signal is required, so that it becomes compatible with instruments, like recorders, displays or A/D converters. Amplifiers must provide the amplification, which is selective for each type of physiological signal. It should eliminate superimposed noise along with the interference signals. Moreover protection of the electronic equipment as well as the patient from the damage due to the surges of current must be ensured. Biopotential amplifier must satisfy following major demands [238]:

a. Amplifier should not have any kind of influence on the physiological process, which is being monitored.

b. Should not distort the measured EEG signal.

c. Maximum separation of interference and noise from the signal should be ensured.

d. Patient must be protected from the electric shock hazards.

e. Must have a provision of self protection against any kind of damages due to high input voltages.

4.8.1 EEG Signal Processing

Five components are present in the EEG recorded raw signal:

a. Desired biopotential

b. Undesired biopotentials

c. Interference due to power line, it is of the tune of 50/60 Hz and its harmonics

d. Interference / noise signals present due to the interface of tissue / electrode

e. Noise

The processing circuit must be capable to reject a sizeable portion of interferences present in the recorded signal. A differential amplifier is incorporated at the beginning and on its input terminals desired biopotential appears [239].

4.8.1.1 Gain of Amplifier

Gain of an amplifier is given by the ratio of its output to its input. A gain of 100 – 100,000 is desirable to get the best quality of output of differential amplifier, moreover it also gives appropriate level of voltage to the output signal, which is required for further signal processing.

4.8.1.2 CMRR of Amplifier

Common-mode rejection ratio (CMRR) is defined as the ratio of gain of differential mode (wanted signal) with the gain of common mode (original input signal). The differential amplifier has to have a high CMRR (minimum 100 dB) so that the effect of electrically noise environment can be reduced.

4.8.2 Filters

4.8.2.1 Low Pass Filter

Neuronal information less than 100 Hz are present in the EEG signals, however the useful information is below 30 Hz. Hence, all frequency components above 30 Hz may simply be removed using a low pass filter. Some researchers recommend that the cut-off frequency of teh low pass filter should be equivalent to the highest frequency of interest and that ranges from approx 40 Hz up to less than one half of our sampling rate. Advantage of analog low-pass filter is that it prevents the distortion of EEG signal from the effects of interference with sampling rate, which is known as aliasing. Aliasing effect will be there if the frequencies, which are greater than one half of the sampling rate are present in the recorded signal.

4.8.2.2 Notch Filter

If line frequency of 50 Hz has not been eliminated by the signal acquisition system, then notch filter must be used for its removal [240].

4.8.2.3 High Pass Filter

Amplification unit must have analog (hardware) filters. Low frequency components are present in the signal, which are present due to the bioelectric flowing potential (like breathing etc), the EEG signal is required to be passed through a high-pass to reduce these low frequencies. Range of cut-off frequency of a high pass filter, should generally be in between 0.1-0.7 Hz.

4.8.2.4 Equalizing filters

Equalizing filters are used for the nonlinearities present in the signal recording system, which are related to the frequency response of amplifiers. Although, the properties of external and internal noises which affect EEG signals are most of the time unknown. However, if the noise and signal subspaces are accurately separable, then the properties of the noise are known. Independent or principal component analysis can be used to crumble the multichannel observation in EEG signal, like noise and the neural activities. If these two are combines together, then the extraction of estimate of noise components becomes possible.

4.8.2.5 Finite Impulse Response (FIR) Filter

Digital filtering is performed after the conversion of analog signal into digital form. As the strength of analog filter has its own limitations, hence in order to display and further process EEG signal, DC component is required to be further reduced. Selection must be made out of the linear (FIR, IIR) filtering and novel non-linear filtering techniques. Most commonly FIR filters are selected as wave phases are not distorted by them. Width of the data points should be of the order of 1000. Designing of filters should be carried out in such a manner that their influence on the properties of EEG signal should be minimum [241].

4.8.3 Analog to Digital Converter

When the computers are incorporated in the signal processing, sampling of channels of analog is repeatedly performed at fixed intervals of time (sampling interval), and simultaneously conversion of each sample to its digital form is done by analog- to-digital (A/D) converters. Interfacing of this A/D converter with a computer is performed, in order to keep each sample in computers memory. Resolution of A/D converter is dictated by the lowest amplitude, which can be sampled. It is calculated by the following formulae [242]:

$$\frac{Voltage\ range\ of\ A/D\ convertor}{2^{No\ of\ bits\ of\ A/D\ Convertor}} \quad \text{.......... (4.1)}$$

4.9 Conclusion

Electroencehalography EEG is an electrobiological imaging tool, which is broadly used in medical and medical related research areas. EEG is a measure of changes occurring in the electric potentials, which are caused due to electric dipoles formed during neural excitations. EEG signal contains various brain waves, which reflect the electrical activity of our brain. Electrical activity of our brain is recorded as per the placement of electrode as the function and electric potential generation in the those regions of brain are noted. Following instrumentation is required for utilizing EEG signal of our brain and EEG techniques:

a. Electrode cap having conductive jelly or Ag-AgCl circular electrodes having a layer of conductive paste.

b. Gain of amplifiers must be between 100-100,000, their input impedances should be at least 100 M Ω, and CMRR must be minimum 100 dB.

c. Analog filters must be incorporated in the signal processing circuitry, 0.1 – 0.7 Hz should be the range of cut-off frequency of a high pass filter, and the cut-off frequency of low pass filter should be smaller than one half of the sampling rate. Actually, the involvement of above 50 Hz frequencies is very rare hence their contribution in power spectrum of EEG signal is negligible.

d. A/D converter must be minimum 12 bit, with an accuracy lesser than overall noise (0.3 - 2 µV pp), and its sampling frequency must be in between 128 – 1024 Hz.

e. Processing speed of PC must be sufficiently high so that it can take the data, record it and analyse it online.

f. The circuitry must have a digital high pass FIR filter, whose cut-off frequency should be the same as that of the analog high pass.

CHAPTER V

CONTROLLING THROUGH FORCE SENSITIVE RESISTORS (FSR)

5.1 Introduction

Hand is a fundamental organ of human beings, used to demonstrate the creativity inhibited in the mankind by the nature. It is therefore very dramatic for man to lose his hand due to some accident, as it entails a practical as well as psychological problem for the man, which necessitates the requirement of a prosthetic device for that person.

During the past years, advancement in the field of robotic hands, have materialized different concepts having the capability to show various movements, which can be applied in the field of prosthetic devices. Controlling such like sophisticated prosthetic devices has always been an issue for the researches, although scientists have worked on it and studies can be found on the subject [243, 244, 245]. Although the functionality and versatility of a device is not established only on the basis of its mechanical complexity, i.e., the DOF it provides, there is another very significant question, that whether it provides the sensorial system, which optimizes the grip and the increases the efficiency and speed of the tasks performed by the device.

Force sensitive resistors can be utilized in this field for the getting the signals from the residual portion of the amputees hand but also to provide a proprioceptive feedback to the user, which would provide an increased functionality to the device.

The activities of hand and arm and hand can be evaluated by mounting two sensors, as we know that:

a. Muscles of forearm control the motions of hand

b. Circumference of our muscles change with contraction and expansion of our muscles muscle contractions are accompanied by a change of muscle circumference [245]

Hence FSRs can be mounted on the forearm to capture the changes in the volume of a muscle thereby relating it to the intended motion of the hand. This signal can then be processed before it is fed to the mechanism driving a prosthetic device. Uptill now most of the work has been done in the field of prosthetic devices using electromyographic (EMG) signals for all such like applications, examples can be flight control [246] hemiplegic patients [247].

5.2 General

Force Sensitive Resistors (FSRs) now are more commonly described as force sensors, have been initially invented, designed, advanced and developed by Interlink Electronics, USA [248]. It is basically a sensor, dependent on resistance, and it is a **polymer thick film device (PTF)** which shows variation in its resistance according to the increase or decrease in the force, which it experiences on its active surface. It exhibits an inverse relationship between the resistance and the force exerted, i.e. the resistance decreases with the increase in the applied force, on the active surface of FSR.

Sensitivity of force in FSRs has been increased and has been made optimum for application involving ‘human touch’, which are applications having electronic control, and are required to be adjusted through human input. This property makes FSRs unsuitable for applications, which involve scaled and sensitive measurement of force, irrespective of this fact that they have a very similar physical structure to load cells and strain gauges.

However, for most of the application which are touch sensitive, and involve contact sensors, such as "how much the object has been grasped, how much prehensile force has been exerted" , FSRs offer a better deal.

5.3 Why FSR Instead of EMG

Surface electrodes which are used to get the Electromyographic (EMG) signals have their own limitations associated with their usage. These are:

a. EMG sensors need a very good contact with the skin of human beings, so that the artifacts can be kept low.

b. EMG electrodes are available with a moisturising gel in between the electrode surface and the skin. Still they are required to be connected to a fat-free, clean and hairless skin.

c. Non-gelled electrodes are mostly used in the mobile systems in case of Electrocardiogram (ECG) applications, e.g. [249], however the accuracy offered by the system is variable.

It is therefore recommended that simple sensors, which are inexpensive as well may be used to get the signals from the residual portion of amputees arm. It gives the following advantages:

a. Simple usage

b. low cost

c. Unobtrusive integration into garments

d. Little power consumption for extended lifetime

e. Simple interfacing

5.4 Operating Principle of FSR

FSR comprise of a conductive polymer (PTF), the resistance of PTF is changed predictably as per the force applied on its surface. Usually they are available as a **polymer sheet or ink,** whose application is through **screen printing**.

Electrically conducting and non-conducting particles are present in the sensing film, these particles are suspended in a matrix. Size of these particles is sub-micrometer, and they are so arranged to have a reduced effect of the temperature, have better mechanical properties and an increase in surface durability. Once force is applied on the active surface of the sensing film, these particles start touching the conduction electrodes, thereby altering the resistance of the PTF. Another added advantage of FSR (which is there with other resistive based sensors as well) is that they need a comparatively simple interface and are capable to offer good and satisfactory performance under moderately hostile circumstances / environments.

5.5 Construction of FSR

FSR is constructed of two layers, which separate from each other and have a spacer of adhesive between them. When the FSR is pressed, flexible substrate, which has a printed semi-conductor becomes connected to the active particles on the interdigitating electrode. If the force exerted on the FSR is increased, connection of more active element dots is made with the semiconductor, thus the resistance of the device goes down.

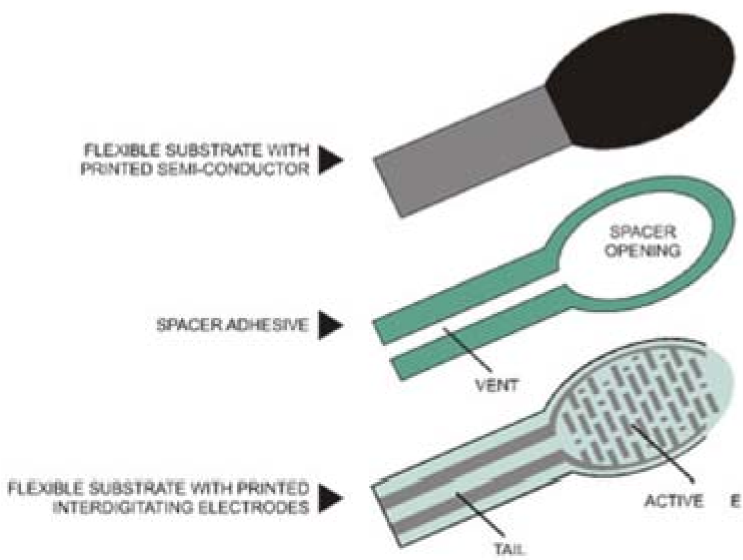


Figure 5-1: FSRs

FSR is marketed in a square or oval package having two pins, extending from the sensor, which are having a pitch of 0.1", so that it can be connected conveniently to a breadboard or any IC. One side of the FSR has a backing of peel-and-stick rubber, so that the FSR can be easily mounted on any surface.

FSRs are offered in different sizes and shapes, however application of prosthetic hand requires small like, squares of 5x5 mm or strips of 80x13 mm. 8x13 mm strip would be even more advantageous as a uniform sensitivity region will be determined by one element only along the finger. If the smaller square of 5 x 5 mm is applied, then it is must that minimum 3 FSRs are

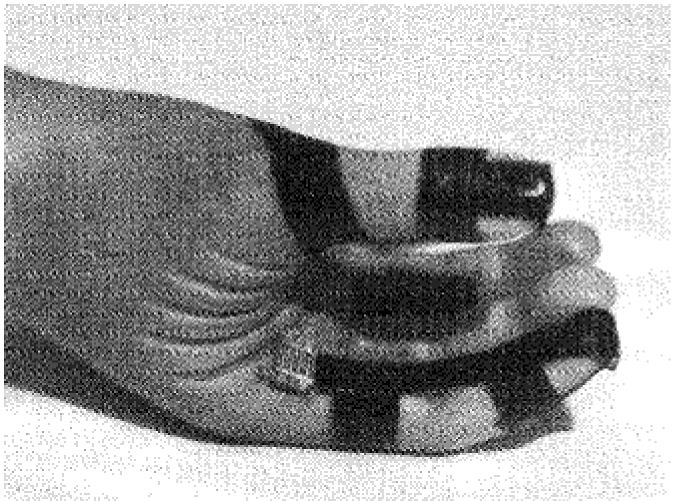


Figure 5-2: FSRs utilization as slippage sensors

connected in parallel so that sufficient sensitivity is obtained along the finger. The disadvantage of this would be that the complexity of the system will increase due to more electrical connections because of 3 FSRs the possibility of wear and tear will increase, thereby reducing the reliability of the system. It must be kept in view that largest region of sensitivity along the muscle must be utilized.

5.6 Physiological Aspects

Each skeletal muscle contained in our body is comprised of three parts, the central portion of the muscle (muscle belly) and its ends, through which it is connected to the bones, these are called tendon ends. Once the muscle gets contracted, it is the result of activation potential which is transferred to the muscle from the brain through the connection of nerve muscle. This potential is sensed by the EMG electrodes and used to control the prosthetic device.

Multiple patches of muscle are contained in the central portion of the muscle, i.e., the muscle belly. Each patch is basically a bundle of muscle fibres, which are constructed from filaments. Once the muscle is contracted the filament of each muscle fibre starts sliding against each other [250]. The contraction of muscle may be observed with naked eye as the increase in the circumference of the muscle belly because of the slide of filament. This fact can be exploited to sense the contraction of muscle.

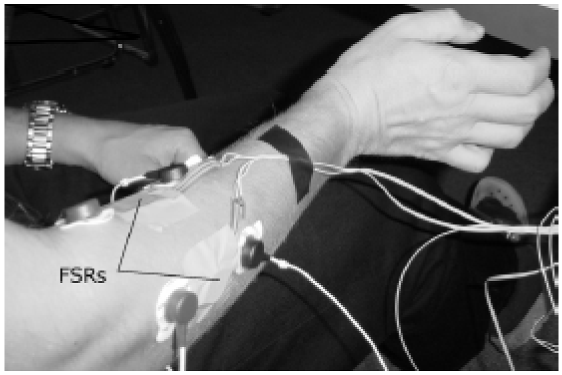


Figure 5-3: FSRs placed on the forearm

FSRs are attached on the skin surface, right in the centre of the muscle as the signal is to be acquired from the muscle belly, whereas the EMG electrodes are usually placed on the ends of the muscle belly. FSRs are placed on the central portion of the muscle due to the fact that the deformation of the muscle is expected to be highest at this particular point.

5.7 Response of FSR

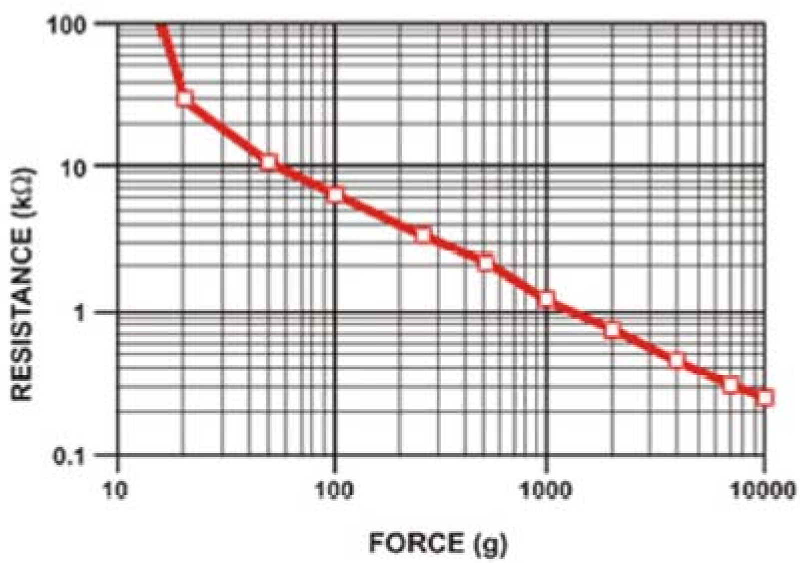


Figure 5-4: Behavior exhibited by FSRs

Behaviour exhibited by an FSR along with increasing force is evident from the above figure. Axes taken in the graph are logarithmic, which means that the response of sensor to force is not that linear as is shown in the graph. Moreover, it must be kept in view that the accuracy range of FSR is from ± 5% to ± 25%, therefore there would be variations in the response exhibited by the sensor in different iterations. In the force-resistance graph above, at the beginning (less force), switch like behaviour can be seen. It is a turn-on threshold, or may be known as ‘break force”, and it swings resistance down from higher than 100 kΩ to approximately 10 kΩ. This is the start of the dynamic range of the sensor, which follows power-law (P = 1/R). This start of dynamic range is dependent on the substrate, overlay thickness and flexibility, also shape and size of actuator, and the thickness of spacer-adhesive. An increase in the break force is experienced with increases in all of the above mentioned variables.

A deviation of the sensor behaviour from power law can be seen towards the high force end of the graph, which reaches a point where very minute or no response is shown by the sensor with increase in the force. This is a saturation point where the resistance remains unchanged with increase in force. Saturation force in the figure seems to be beyond 10 kg. Saturation point is more dependent on pressure than force. A typical FSR has a saturation pressure of the range of 100 to 200 psi.

5.8 Electrical Interface of FSR

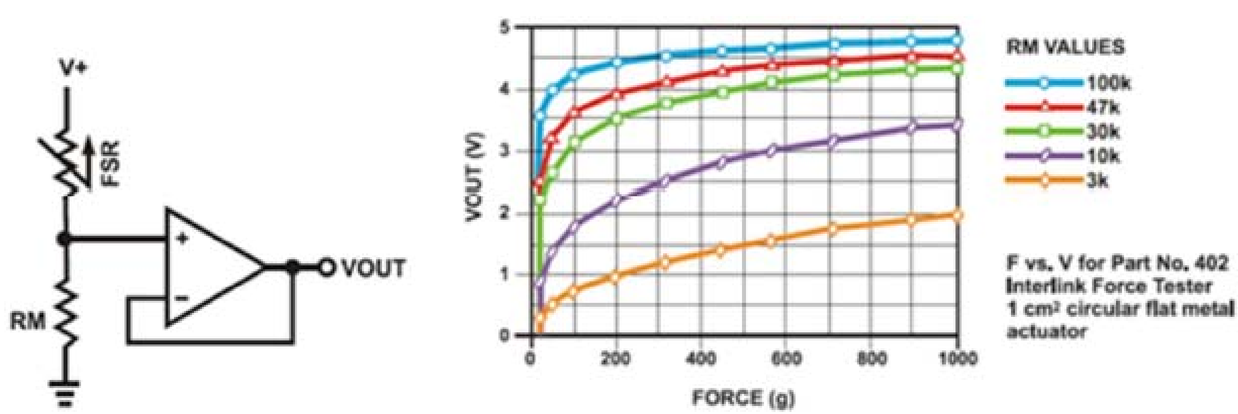


Figure 5-5: Electrical interference of FSRs

Above example configuration has been taken from the data sheet of Interlink Electronics, showing a simple conversion from force to voltage. A measuring resistor having resistance (R_M) is tied with FSR whose resistance is denoted by (R_{FSR}) in the configuration of a voltage divider. The output is obtained by the following equation:

$$V_{OUT} = \frac{(V_+)}{\left(1 + {}^{R_{FSR}}/_{R_M}\right)} \qquad \text{............} \qquad (5.1)$$

In this configuration, an increase in the output (V_{OUT}) is experienced with increase in the force. If the locations of R_M and R_{FSR} are swapped over, then the relationship is inverted and now a decreased output (V_{OUT}) will be exhibited by the device with increase in force. Few graphs of Force Vs Output Voltage have been shown in the above figure with different values of measuring resistance (R_M). The graphs have been obtained with an input of +5V.

5.9 FSR application in Sensorial System

Control system of present prosthetic devices lack feedback, more precisely the only feedback available to the device and the user is the visual feedback, vibration or pressure exetted due to striking or rubbing with any external object. Moreover considerable attention by the user is required to exercise visual feedback control, as he / she has to keep the eyes open to monitor the prosthesis actions, which can become tiring. The purpose is to have a subconscious control as is available in case of natural limbs. As is shown in Figure 5.5.

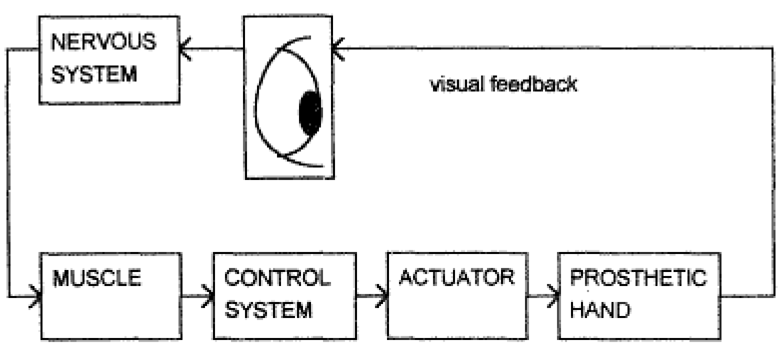


Figure 5-6: Prosthetic device having only visual feedback

This limitation of the prosthetic device can be overcome by the application of FSRs in the palm of the hand which can act like, slippage sensors and strength sensors.

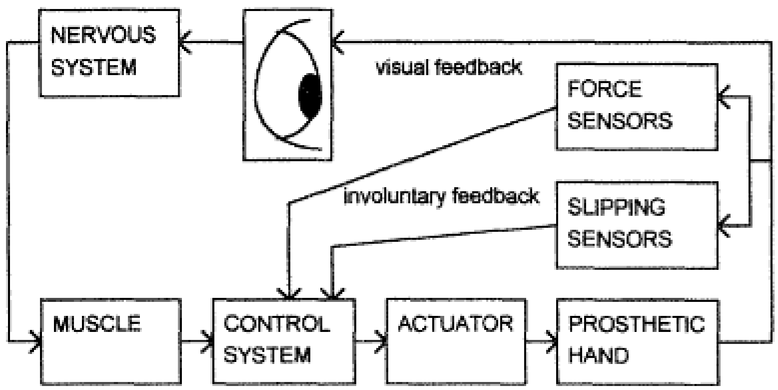


Figure 5-7: FSRs utilized as Feedback source

FSRs can be employed to provide slippage and strength sensors and the feedback may be conveyed separately or jointly to control system, i.e., while some object is being grasped by the hand and enough strength is required to keep the object from slipping these signals can be fed to the controls. If the object starts slipping, the actuators can automatically be controlled by the controlling system due to the feedback from slipping sensor.

5.10 Conclusion

FSRs do provide an alternative method to control the prosthetic device as they can also be a good source for the detection of muscle activities. Availability of muscles of lower arm (forearm) has to be there in the amputees, otherwise FSRs can also be used for controlling the devices. It is evident from the results of researchers [250] that sensing concept of FSRs is more applicable in the monitoring of the activities of individual muscles, just like EMG sensors.

In case of EMG signal from other muscles may be source of noise, however, is case of FSRs it can be a supportive element. If some heavy object is lifted, it will not only have its effects on the selected near-surface muscles, but deeper body layer muscles will also be affected. Therefore activity observed by the FSR from the observed muscle would be a combined effect of bothe the muscles and thus will be a higher value. However as the muscle properties are dependent on age, sex and usage, hence the results should be validated through larger studies.

Sensory usage of FSRs is highly important, the same has been developed by Otto Bock hand prosthesis [245]. Two basic functions are performed in it:

a. touch sensing: Automatically searches for the objects in the environment and feedback as soon as the contact is established

b. It detects the grasped object slippage from the grip

First function, on the basis of FSR sensors, is already in working condition, however the cost effect is very much and it must be tried to develop it locally. Moreover an improvement in it is still possible, silicon cosmetic glove with an inbuilt FSR sensor may be manufactured. This way, an automatic more delicate touch sensing will become a part of the prosthetic device, which is not present, presently. As presently holding a paper cup without damaging it is not possible.

Advantages that the automatic touch will give can be summarized as follows:

a. User become relaxed from controlling the device visually during operation.

b. The risk of damage to the delicate device is reduced (this risk is more in new users, despite of the fact that the visual feedback is present).

c. Gripping speed is increased: as the grasping operation becomes automatic, hence maximum power can be used to operate the actuators, thereby getting maximum speed.

CHAPTER VI: CONCLUSION AND RECOMMENDATIONS

6.1 Electromyography

A lot of advancement has been experienced in the field of Surface electromyography (SEMG). All the professionals working in the field of muscles are attracted towards this field of study, main reason for this attraction is non-invasiveness involved. It works in the same manner as an electronic stethoscope of muscles. Researches from engineering background prefer SEMG due to the fact that muscle function is studied through it with non-invasive techniques. The technology of surface EMG has advanced from the time when it used to be conducted through copper cages. And now it has reached the level of scientific inquest regarding the function of muscles. Certain recommendations about the placement and size of electrodes as well as about the EMG processing circuitry are enlisted below.

6.1.1 Recommendations For Electromyography

a.	Size of Electrode	-	Diameter < 10 mm
b.	Interelectrode Distance (IED)	-	< 20 mm, or < ¼ the muscle length, which ever is smaller
c.	Electrode Location	-	Between the most distal innervation zone and the distal tendon. Between the most proximal innervation zone and the proximal tendon; not over an innervation zone
d.	Reference Electrode Location	-	Wrist, ankle or other electrically inactive area
e.	Preamplifier	-	Must have highest CMRR
f.	High Pass Filter	-	~ 20Hz
g.	Low Pass Filter	-	~ 600 - 650 Hz (sampling

			frequency >1000 samples/s)
h.	Gain	-	Suitable to bring the signal into the input range of the A/D converter with desired input resolution

6.2 Neuroelectric Signal

Neuroelectric control, i.e. controlling a prosthetic arm through nerve impulses, yields a device which is closest to the physiological hand and this technique is the most natural control approach in the field of prosthetic devices. Scientists have been working for controlling the artificial devices through nerves and neurons but the functionality of human-machine interface is problematic. Sensitivity of nerve tissue to mechanical stresses is a hindrance in the progress.

6.2.1 Recommendations for Neuroelectric Sensing Technique

It is suggested that the students may be given a project and they work in coordination of the doctors present in the Armed Forces Institute of Rehabilitation (AFIRM) and work on designing a prosthetic device based on neuroelectric sensing technique.

6.3 Brain Machine Interface

Researchers are working since last 40 years to control the devices or to interact with the environment by mere thought process instead of manual control. However, the success in this field has been achieved in recent past. This is a multidisciplinary field which is experiencing rapid emergence and is known as brain–machine interface (BMI). Latest trends and the modern technology in the field of robotics, like mechatronic design procedures, miniature actuators having better weight to power ratio, micro position sensors and tactile \ force sensors, have enabled the scientists to develop a compact, multi fingered and yet light-weight hand prostheses, which incorporates embedded systems and having the facility of actively grasping control and capable to carry out dexterous manipulative tasks, by having proper interfacing with human brain.

EEG is the easiest and simplest way to record reflection of the activity of our brain. It requires only some surface electrodes along with signal processing circuit which is not that expensive.

Moreover EEG is a safe and convenient method of recording electrical signals, which makes it a popular BMI technique. Electrical activity is detected at the scalp. Due to these characteristics, EEG is gaining a lot of attention by the researchers to control the neuromotor prosthetic device.

6.3.1 Recommendations in EEG

It is suggested that in the first phase the projects for development of translational algorithm of inputs of EEG signal into its outputs may be got developed for the prosthetic devices, and in the later part physical control of prosthetic device through EEG signals may be worked upon as it is an emerging field and does not involve any kind of invasiveness.

6.4 Force Sensitive Resistors

During the past years, advancement in the field of robotic hands, have materialized different concepts having the capability to show various movements, which can be applied in the field of prosthetic devices. Controlling such like sophisticated prosthetic devices has always been an issue for the researches. Although the functionality and versatility of a device is not established only on the basis of its mechanical complexity, i.e., the DOF it provides, there is another very significant question, that whether it provides the sensorial system, which optimizes the grip and the increases the efficiency and speed of the tasks performed by the device.

Force sensitive resistors can be utilized in this field for the getting the signals from the residual portion of the amputees hand but also to provide a proprioceptive feedback to the user, which would provide an increased functionality to the device.

6.4.1 Recommendations regarding FSRs

FSRs do provide an alternative method to control the prosthetic device as they can also be a good source for the detection of muscle activities. Hence it is recommended that prosthetic devices based on FSRs may be made and such like projects may be given to the students of UG class.

Moreover sensory usage of FSRs is highly important, the same has been developed by Otto Bock hand prosthesis. Two basic functions are performed in it:

a. touch sensing: Automatically searches for the objects in the environment and feedback as soon as the contact is established

b. It detects the grasped object slippage from the grip

It is recommended that sensory usage of FSRs for sensory feedback from the finger tips may be explored as it is not very difficult, the block diagram has already been included in the previous chaptersAdvantages that the automatic touch will give can be summarized as follows:

a. User become relaxed from controlling the device visually during operation.

b. The risk of damage to the delicate device is reduced (this risk is more in new users, despite of the fact that the visual feedback is present).

c. Gripping speed is increased: as the grasping operation becomes automatic, hence maximum power can be used to operate the actuators, thereby getting maximum speed.

6.5 Amputee's Feedback

Survey regarding the treatment conducted by the AFIRM for the amputee's in last 4 years have been conducted and included in this research work, the same is attached as per Annexure 'A' to this chapter. Summary of the same is as under:

Table: 6.1 **Summary of Patients Treated at AFIRM**

Ser	Year	Upper Extremity	Lower Extremity	Total	Upper Extremity %age
1.	2008	7	22	29	24 %
2.	2009	4	58	62	6 %
3.	2010	8	115	123	6 %
4.	2011	0	22	22	0 %
TOTAL		19	217	236	8 %

Out of the 19 patients of upper extremity, 9 were interviewed and a gist of the feedback obtained is as under:

a. Most of the patients need a device which provides proprioceptive feedback

b. Below elbow patients:

(1) 2 x patients asked a permanent fixture, which would facilitate their job requirements.

(2) 2 x patients have asked state of the art prosthetic device, however their education level does not commensurate with those devices.

c. The demand of each patient is unique as the situation, amputation level, state of residual muscles in each case is unique

Basing on above facts it is recommended that:

a. 92 % of patients have amputations in their lower extremity, hence some research work must be done in this field.

b. FSR based systems may be got developed by the students to give sensorial feedback to the prosthetic device

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Annexure 'A'

List of Amputees Treated by AFIRM During Last 4 Years

Ser	Rank and name	Army Number	Unit	Name of Prosthesis
Year 2008				
1.	Sep M Asghar	6466897	603 AD Cor Asc	T.F.P Rt
2.	Sep Zia-ul-Rahman	3358404	15 FF	T.F.P Rt
3.	Sub Abdul Rahman	102807	Kuram Malitia	T.T.P Bil
4.	Sep Habib-ur-Rahman	4110025	645 Mjd BTN	Sym Prost Lt
5.	Capt Samia	PA 104680	Cmh Rwp	T.T.P Rt
6.	Sep M Naeem	3741133	14 Bloch Regt	T.F.P Rt
7.	Sep Nawab Ali	3462766	25 Sindh Regt	Cosmatic Glove+T.T.P Bil
8.	Sep Imran Iqbal	4321128	17 AK	T.K.P Rt
9.	L.Nk Pahlwan Shah	503187	Khyber Agecy	T.F.P Lt
10.	Sep Irshad Hussain	4323624	36 AK	T.F.P Rt
11.	L.Nk Shafiq-ur-Rahman	3267529	SD 11 POL GHQ	T.F.P Lt
12.	Sep Moin Gul	106130	Kuram Malitia	T.T.P Lt
13.	Sep M Riaz	3850112	Karrar Coy SSG	T.F.P Lt
14.	Hav Abdullah	3052155	180 MRI	T.F.P Rt
15.	L.Nk M Iqbal	7767525	4 MP	Cosmatic Glove Lt
16.	L.Nk M Ishaq	2847346	7 NLI	T.T.P Lt
17.	Hav Dost Muhammad	11127	HQ Bamboor Riffles	T.R.P Lt
18.	L.Nk Allah Jani	3332689	34 FF	T.H.P Lt
19.	CFN M Ashraf	4402384	90 EME Btn	Cosmatic Glove Rt
20.	Sep Shaukat Ali	33738	HQ Bamboor Riffles	T.T.P Rt
21.	2nd Lt Wajahat	44601	177 Br Bn	T.R.P Lt
22.	N/Sub M Akram	Pjo 224664	14 Eng Btn	T.H.P Rt
23.	Sep M Azam	2411037	6 Punjab Regt	T.T.P Lt
24.	ALD Ansar Abbas	1076335	11 Cav	Sym Prost Rt +T.F.P Lt
25.	Sig/Man Haq Nawaz	3676533	23 Sign Bn	T.FP Lt+ T.R.P Rt
26.	Nk M. Raees	3670784	49 sig Bn	T.K.P Rt
27.	Nk Nazakat	1715164	53 IFCE	T.T.P Lt

28.	Sep Sayed Zafar	3468162	1 Sind Regt	T.T.P Lt
29.	Capt Shakeel	PA 39146	139 SPMed Regt	Partial foot prosth Bil
Year 2009				
1.	Sep Dilawar Khan	603180	Thall scout	T.K.P Lt
2.	Sep Fahim Ahmed	4319582	26 AK Regt	T.T.A Bil
3.	Hav M. Amin	7137669	50 Signal bn	T.T.P Bil
4.	CFN M.Arshad	7124914	58 S&T Bn	T.F.P Rt
5.	Rect M. Abdullah	924086	Baloch Regt Ctr	T.F.P Rt
6.	Nk Ali Sher	4407221	1 sindh Regt	T.T.P Rt
7.	Rect Rab Nawaz	65462	EME Ctr	T.T.P Lt
8.	Lt Col Zahid	PA 28767	MS Branch GHQ	T.T.P Rt
9.	Hav Muh Arif	7127396	1CDO Bn	T.R.P Rt
10.	Lnk M. Ishaq	2847346	7 NLI	T.T.P Lt
11.	Sep Asbar Khan	4321210	10 AK Regt	T.F.P Lt
12.	Sep M. Asif	3272490	46 S&T Bn	T.F.P Lt
13.	Sub Abdul Majeed	177584	34 Baloch Regt	T.T.P Lt
14.	Sep M Jahangir	2390680	1 Punjab Regt	T.T.P Rt
15.	Sub M. Zahoor	17678	60 Baloch Regt	T.F.P Lt
16.	Capt Shahid Ghafar	MO 10638	816 Mjd Bn	T.T.P Rt
17.	Capt Fahad	PA 38607	AMF Kamra	Chopart Prostheses
18.	Cpl/Tech Rab Nawaz	1719773	760 CTE	T.F.P Rt
19.	Sep Wajid Fayaz	4516965	815 Mjd bn	T.T.P Lt
20.	LNK Said Mali	4369	HQ MRFC	T.T.P Bil
21.	J/T Abdul Hameed	498935	No 486 MCC PAF	T.T.P Lt
22.	LNK Rab Nawaz			T.F.P Lt
23.	Sep Irfan Haider	2415411	8 Punjab Regt	T.T.P Rt
24.	Nk Rehmat Ali	1724517	69 Baloch Regt	T.T.P Lt
25.	Sep Qamar Zaman	2408966	16 punjab Regt	T.T.P Lt

26.	Sep M. Ajmal	3472666	3 Sindh Regt	T.T.P Rt
27.	Sep Imtiaz Ahmed	4324356	03 AK Regt	T.F.P Lt
28.	Sep Rizwan Ali	922971	60 Baloch Regt	T.F.P Lt
29.	Sep Gul Baz	498935	33 Baloch Regt	T.F.P Bil
30.	Hav Allah Bachaio		7 Sindh Regt	T.R.P Rt
31.	L/Hav M. Khurshid	2415411	4 CDO	T.T.P Lt
32.	Sep Samiullah	1724517	Touchi Scout	T.T.P Rt
33.	Sep Nazakat Husain	2408966	18 AK Regt	T.F.P Rt
34.	Sep Hashim Taj	3472666	Bajour Scout	T.H.P Lt
35.	Hav Iran Gul	4324356	Muhmand Rifle	Symes Prostheses Rt
36.	Sep Fazal e Rabi	1201616	Swat Scout	T.T.P Rt
37.	Hav Amir Faizullah	3342577	4 F F Regt	T.T.P Rt
38.	Hav Zarshahdain	1075416	52 CAV	T.F.P Lt
40.	Sep Wajib Hussain	41119018	655 Mjd Bn	T.T.P Lt
41.	Sep Nojawan	37727	Mohmand Rifle	T.T.P Rt
42.	Sep Imran Younas	55779	PRC mardan	T.F.P Lt
43.	Sep M.Abbas	4318938	08 AK Regt	T.T.P Rt
44.	Rect Shah Khalid	55390	PRC	T.F.P Rt
45.	Sep Javed qbal	3131463	165 Fd Regt	T.T.P Rt
46.	Sep Majhar Iqbal	4117493	641 Mjd Bn	Syme Prostheses Lt
47.	Sep Syed Ibrahem	27532	Mohmand Rifle	Syme Prostheses Rt
48.	Nk M.Ikram	6684864	SSD Hyd	T.T.P Lt
49.	Lt/col Raza Abbas	Pa 28580	HQ 4 CORPS NG	T.F.P Bil
50.	L/Nk M.Iqbal	4116933	658 Mjd Bn	T.F.P Rt
51.	L/Nk Nazar Muhammad	25640	MR(FC)	Syme prostheses Rt
52.	Maj sajid Ali	PA 33475	MT Dte GHQ	T.F.P Rt
53.	Sep Yasir	4117711	646 Mjd Bn	T.T.P Lt
54.	N/Sub M.Ismail	Pjo158269	29 Panjab Regt	T.T.P Rt
55.	Rect M.Asif	55810	PRC	T.H.P Lt
56.	Sep Basit Nawaz	4119870	646 Mjd Bn	T.T.P Lt

57.	Sep M.syed	4517987	648Mjd Bn	T.T.P Lt
58.	Hav M.Younas	4305335	1 AK Regt	T.T.P Rt
59.	Sep Mahrtab Amwar	915519	20 Baloch Regt	T.T.P Lt
60.	Capt Fahad Abbasi	PA 38607	Cod Khanawal	Partial foot prosthesis Rt
61.	Sep jan Muhammad	3357420	47 FF Regt	T.T.P Bil
62.	Sep Badshah Gul	7366376	64 Med Bn	T.T.P Rt
Yea. 2010				
1.	Hav Ibrar hussain	3065610	158 LT AD	T.K.P Rt
2.	N.Sub Gul Nabi	701782	Mahsood Regt	T.T.P Lt
3.	Sep Waseem Ahmed	3754799	24 Baloch Regt	T.H.P RT
4.	Nk Mushtaq	3739133	1 SSG	T.H.P LT
5.	Sep Umer Khatab	105285	Kurram Militia	T.T.P Rt
6.	Sep Arif hussain	3759124	54 Baloch Regt	sym pros lt
7.	Hav Sajjad Haider	7122701	15 Lancer	T.T.P Bil
8.	Lt Sadaat	PA 42344	4 NLI Regt	T.F.P Lt
9.	CFN M. Umer	4425754	53 EME Bn	T.R.P Rt
10.	Lt Col Umer	PA 29794	15 Lancer	T.T.P Rt
11.	L/Nk Altaf Hussain	1001748	Shwal Rifle	Sym Prosthesis Lt
12.	Sep Naseer-ul Hassan	924952	69 Baloch Regt	T.T.P Lt
13.	Capt Rizwan Ahmed	PA 42541	2 NLI Regt	Sym Prosthe Rt
14.	Hav M. Afzal	3456681	21 Sind Regt	T.T.P Rt
15.	Sep Shakeel Ahmed	3741665	29 Baloch Regt	T.T.P Lt
16.	Nk M. Afzal	3463278	7 Sind Regt	T.T.P Lt
17.	Lnk Gul Mohammad	3458258	09 Sind Regt	T.T.P Lt
18.	Sep M. Ashraf	3375521	43 FF	T.T.P Lt
19.	Sep Amir	3473819	1 Sind Regt	T.T.P Lt
20.	Hav Saleem Sharif	1706769	24 Baloch Regt	T.T.P Rt
21.	Nk M. Riaz	3739818	29 Baloch Regt	T.T.P Lt
22.	L.Nk Khalil ur Rehman	1002466	Shwal Rifle	T.T.P Rt
23.	SPR Christopher	1748471	100 eng Bn	T.T.P Rt

24.	Sep Manzoor Elahi	2858875	2 NLI	T.T.P Lt
25.	SWPR Asghar Masih	2406771	11 Punjab Regt	T.T.P Lt
26.	Nk M. Khan	1709361	02 Sind Regt	Chopart Prosthe Rt
27.	SPR Sajeeb	1747333	25 Eng Bn	T.T.P Rt
28.	L.Nk Israr ud Din	1743963	100 Eng Bn	T.T.P Lt
29.	Sep Haider Ali	3475125	1 Sind Regt	T.F.P Lt
30.	L.Nk Ejaz Ali	6399021	59 S&T ASC	Sym Prosthesis Lt
31.	Hav Zulfiqar Ali	1708416	11 Eng Bn	T.T.P Lt
32.	L.Nk Iftikhar	3749514	35 Baloch Regt	T.T.P Lt
33.	Sep Roman Gul	802931	Bajour Scout	T.T.P Lt
34.	Sep Sayed Ali	2860844	10 NLI Regt	T.T.P Lt
35.	ALD Rab Nawaz	1080484	26 Mechanical Div	T.T.P Lt
36.	Sep Ghulam Rasool	2403434	69 Punjab Regt	T.T.P Lt
37.	Maj Syed Ali	35767	01 Punjab Regt	T.T.P Rt
38.	Hav Fayyaz Hussain	3097813	49 Fd Arty	Cosmetic Glove
39.	L.Nk Arman Shah	1102700	M.Rifle (FC)	T.T.P Lt
40.	Maj Mujtaba	39402	31 Baloch Regt	Cometic Glove
41.	L.Nk Tariq Bin Bashir	1721045	173 Eng Bn	T.T.P Lt
42.	Sub M.Arif	PJO 224059	11 Eng Bn	T.T.P Rt
43.	L.Nk Allah Baksh	1724645	107 Eng Bn	Partial Foot Orthosis Rt
44.	Sep M. Aslam	931665	21 Baloch Regt	T.T.P Rt
45.	Hav fazal ur Rehman	3749325	69 Baloch Regt	Cosmetic glove
46.	Sep Falak Sher	2858271	10 NLI	T.T.P Lt
47.	Sep Mubarik Ali	2406353	57 Punjab Regt	T.T.P Rt
48.	Sep Abbas	1202835	swat scout	T.T.P Rt
49.	Sep M. Ejaz	2421693	32 Punjab Regt	T .F P Lt
50.	Hav Mehar Imtiaz	3462990	01 Sind Regt	T.T.P Rt
51.	Hav Niaz Mir	4308996	20 AK Regt	T.T.P Lt
52.	L.Nk Javed	303969	wazirastan Scout	T.T.P Lt

53.	Sep Zaheer Abbas	75842	Eng Centre	T.T.P
54.	L.Nk Noor Gul	104176	swat scout (FC)	AFO with toe filler Lt
55.	Sep Umer Farooq	206224	Touchi Scout	T.F.P Lt
56.	Sub M. Ashraf	PJO 1101560	M. Rifle	T.T.P Lt
57.	Hav Liaquat Ali	2374381	41 punjab Regt	T.T.P Rt
58.	Sep Zawar Khan	305401	south Wazirastan	T.T.P Rt
59.	Sep Ghulam Haider	PJO 157030	25 Punjab Regt	T.F.P Lt
60.	Sep M. Niaz	37578	24 Baloch regt	T.T.P Lt
61.	Sep Ghulam Haider	E 11-9-10	PJO 157030	25 Punjab Regt
62.	L.Nk Shadi Khan	3102991	46 FD Arty	T.T.P Bil
63.	Sep Sayed Zafar	3468162	1 Sind Regt	T.T.P Lt
64.	Sep M. Shafique	5858	603 Fd bamboot rifle	T.T.P Lt
65.	Nk Wazir Ali	345919	18 sind Regt	AFO with toe filler
66.	L/Nk Said Umer	1103441	M.Rifle	T.F.P Rt
67.	Sep Nisar Hussain	4317884	21 AK Regt	Cosmetic Glove
68.	Sep Sartaj Khan	1105335	M.Rifle	T.F.P Rt
69.	Sep Meraj	304183	south wazirastan	T.T.P Lt
70.	Sep Baksh Ali	2425597	27 Punjab Regt	T.T.P Rt
71.	Sep Ali Raza	PR 64624	11 punjab regt	T.R.P Lt
72.	Nk M. Jamal	203242	swat scouts	T.T.P Rt
73.	Hav Nasir Zaman	423817	642 Mjd Btn	T.T.P Rt
74.	Hav Israr Ahmed	4317586	2 AK Regt	Partial Foot prosth Lt
75.	Sep M. Khalid	2600899	18 pujab regt	Partial Foot Orthoses
76.	Sep Noor Shad Ali	1105003	M.Rifle	T.T.P Lt
77.	Sep Barkat ullah	1003556	shawal Rifle	T.T.P Rt
78.	Sep Zaheer Ahmed	3370174	38 FF regt	T.T.P Rt + T.K.P Lt
79.	Sep M. Sharif	2411614	1 punjab regt	Syme Prostheses lt
80.	Sep M. Shafique	5858	603 Fd bamboot rifle	T.T.P Lt
81.	Nk Wazir Ali	345919	18 sind Regt	AFO with toe filler

82.	L/Nk Said Umer	1103441	M.Rifle	T.F.P Rt
83.	Sep Nisar Hussain	4317884	21 AK Regt	Cosmetic Glove
84.	Sep Sartaj Khan	1105335	M.Rifle	T.F.P Rt
85.	Sep Gul tab	31470	AM FC 65 wing	T.T.P Rt
86.	Sep M. Maqbool	65372	32 Punjab Regt	Cosmetic Glove
87.	Sep Jalil Khan	1104648	M.Rifle	T.T.P Rt
88.	Sep Habib ur Rehman	2419192	32 Punjab Regt	T.F.P Lt
89.	Sep wazir Gul	1105866	M.Rifle	T.T.P Lt
90.	Nk.Yaqoob	3839388	144 LT AD Sp	T.K.P Rt
91.	Nk M. Shoukat	4309972	2 AK regt	T.T.P Lt
92.	Sep Ashfaq Ali	3131115	27 army aviation sqn	T.F .P Rt
93.	Hav Tariq	1727942	69 Baloch Regt	AFO with Toe filler Rt
94.	Sep M. Ibrahim	3378644	04 FF	T.T.P Rt
95.	Signal Man Naseer	3678821	27 signal btn	T.T.P Rt
96.	Sep M.Yamin	1106046	MR (FC)	T.T.P Rt
97.	Se Muhammad Rasheed	2426200	4 Punjab Regt	T.T.P Rt
98.	SWP sabir Masih	17335	516 M.Rifle	FRO Rt
99.	Sig/mn M. Bilal	3686389	45 AD Regt	WHO Rt
101.	L/Nk Noor Gul	104176	Swat Scout	AFO with Toe Filler Lt
102.	Nk Faisal Nadeem	2404119	18 punjab Regt	AFO Rt
103.	Sep Irfan Haider	2415411	8 Punjab Regt	T.T.P Rt
104.	Lt Col Zahid	PA 28767	MS Branch GHQ	T.T.P Rt Silicon gel liner
105.	Lt Col Umer	PA 29794	15 Lancer	T.T.P Rt
106.	ALD Rab Nawaz	1080484	26 Mechanical Div	T.T.P Lt
107.	Sep Manzoor Elahi	2858875	2 NLI	T.T.P Lt
108.	Hav Saleem Sharif	1706769	24 Baloch Regt	T.T.P Rt
109.	Sep Ghulam Rasool	2403434	69 Punjab Regt	T.T.P Lt
110.	Sep M. Ashraf	3375521	43 FF	T.T.P Lt

111.	Sep M. Ejaz	2421693	32 Punjab Regt	T .F P Lt
112.	Sep Gul Baz	931071	33 Baloch Regt	T.F.P Bil
113.	Capt Shahid Ghafar	MO 10638	816 Mjd Bn	T.T.P bil
114.	Hav Niaz Mir	4308996	20 AK Regt	T.T.P Lt
115.	Nk Mushtaq	3739133	1 SSG	T.H.P LT
116.	L.Nk Shadi Khan	3102991	46 FD Arty	T.T.P Bil
117.	Sep Ejaz Haider Ali	3475125	1 Sind Regt	T.F.P Lt
118.	Sep Irfan Ali	3146851	47 Fd Arty	T.T.P Lt
119.	J/T Abdul Hameed	498935	No 486 MCC PAF	T.T.P Lt
120.	LNK Rab Nawaz	1719773	760 CTE	T.F.P Lt
121.	Sep M Jahangir	2390680	1 Punjab regt	T.T.P Rt
122.	Sub M. Zahoor	17678	60 Baloch Regt	T.F.P Lt
123.	N/Sub M Akram	Pjo 224664	14 Eng Btn	T.H.P Rt
Year 2011				
1.	Sep M.Imran	347588	11 Sind Regt	T.T.P Rt
2.	Sep Mansoor Ali	347514	6 Sind Regt	T.T.P Rt
3.	Sep Habibullah	28557180	12 NLI	T.T.P Lt
4.	Nk Sawal Baig	1001723	Shawal rifle (FC)	T.T.P Lt
5.	Sep Khalid Din	1105268	M.Rifle	T.T.P Lt
6.	Sep Ab Salam	4337235	35 AK	T.T.P Lt
7.	Sep M. Imran	92362	2 Baloch Regt	T.T.P Rt
8.	Sep Ali Akhter	2853950	01 NLI	Sym Prosth
9.	Sep Noor Azam	901593	Dir Scout	Cosmetic Glove AFO ē Toe filler
10.	L/Nk M. Irfan	3684133	92 Sig Bn	Cosmetic Glove
11.	Lt Jamshed	PA 45025	17 Sindh Regt	T.T.P Rt
12.	Sep Mamraiz Khan	3767076	12 Baloch Regt	T.R.P Rt
13.	SPR Hafeezullah	1735617	11 Eng Bn	T.T.P Lt
14.	Sep Raheem Khan	1105739	MR FC (1)	T.T.P Lt
15.	Hav Naveed Illyas	3095518	10 Med Bn	AFO ē toe filler Bil

16.	L/Nk M. Altaf	3461117	17 Sind Regt	T.T.P Lt
17.	N/Sub Riaz Hussain	PJO 122451	10 med Regt Arty	AFO ē toe filler Bil
18.	Sep Irfan Ali	3146851	47 Fd Arty	T.T.P Lt
19.	Sep Basharat Abbas	3274702	22 S&T Bn	Cosmetic Glove with silicon finger filler Lt
20.	Sep Jahanzeb	3757102	11 Punjab Regt	Figer orthoses
21.	Sep Irfan Ali	3146851	47 Fd Arty	T.F.B Rt
22.	Sep Bakht Raj	3362357	31 FF Regt	Silicon Insole