AN ELECTROCARDIOGRAM/ ELECTROMYOGRAM WITH AN OPTO-COUPLER CIRCUIT AS A PROTECTION

A report submitted to the School of Engineering and Information Technology, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering (Hons) specializing in Medical and Industrial Computer Systems Engineering.

AUTHOR: ADEESH AUTAR
SUPERVISOR: ASSOCIATE PROFESSOR GRAEME COLE
MURDOCH UNIVERSITY

Declaration

I, Adeesh Autar hereby declare that this thesis, entitled "An Electrocardiogram/ Electromyogram with an optocoupler circuit as a protection" is my own work.

Word counts: 13,875

Acknowledgements

Firstly I would like to thanks the almighty who blessed me by giving me all the things required to make this project happen.

I am grateful to my supervisor, Associate Professor Graeme R Cole, who guided me to the right direction.

I am thankful to Dr. Gregory Crebbin, Dr. Martina Calais and Dr. Sujeewa Hettiwatte who helped me to go through all the issues that I experienced throughout this project.

This project would not have reached at this stage without lafeta "Jeff" Laava. Jeff and I spent hours troubleshooting and finding the fault whenever there was one.

I would definitely like to thank Murdoch University for the support in terms of funding. All the important components were purchased by Murdoch University which contributed towards the making of this project.

This one goes to my friends and housemates who supported, encouraged and guided me throughout the whole project.

Lastly, and most significantly, I would like to thank my family, who no matter what, they have and will always support me. Mom, dad, brothers and sister, this one is for you all.

Thank you all!

Abstract

An Electrocardiogram (ECG or EKG) is an important feature in the medical environment, for instance in a hospital. Since this equipment is critical to the physician looking after the patient, the price of an ECG machine is high. When dealing with healthcare, one important aspect is the safety for both, the physician and the patient. The goal of this project is to produce a substitute, which is a cheaper version of the ECG circuit. Also treating the ECG as an Electromyography (EMG), experiment would be done to verify if the former could serve as a dual purpose circuit.

Operational amplifiers (op-amps) are very useful in electronics and is the reason why they are present in almost all the major industries such as automotive and medical. This project will explore some of the qualities that op-amps can offer to meet the demand of this project. In addition, a safety circuit will be executed to ensure that the safety of the device as well as the operator is respected in all aspects. Murdoch University has an EKG sensor from Vernier, which can be used to demonstrate whether the results achieved through the amplifiers circuit's, matches the readings from Vernier's sensor.

Finally modelling is magic as it opens the creativity mind of people, allowing them to think freely. Using this boon some modelling of muscle types have been done as it is really hard to take the EMG of two muscle types.

Contents

List of figures

List of tables

Abbreviations

O_2 Oxygen

CO_2 Carbon dioxide

LAT   Left atria

RAT   Right atria

LVT   Left ventricle

RVT   Right Ventricle

Kg   Kilogram

V   Volts

F   Farad

Ω Ohms

μ Micro

^oC Degrees Celsius

DB   Decibel

Hz   Hertz

R   Resistor

IC   Internal Circuit

RMS   Root Mean Square

PD   Photodiode

RA   Right arm

LA   Left arm

LL   Left leg

RL   Right leg

ECG   Electrocardiogram

EMG   Electromyogram

CMRR   Common Mode Rejection Ratio

V_{in} Voltage in

V_{out} Voltage out

1.0 Introduction

Heart disease has become a major problem all over the world. Long ago, it was less observed as most of the people were engaged in physical activities or jobs such as labourer, which in turn kept them active. However nowadays this has changed to a greater extent, as everything is available at the touch of a finger. Technology is one of the major causes of this distraction, for example kids prefer to sit and play video games rather than physically playing with children. A study conducted in 2011-2012 showed that there are about 7.9% of the male population and around 7.5% of the female population who have heart disease, in Australia [1].

Heart disease is caused by different factors and just to name a few, heavy smoking, wrong diet and more like diabetes [71]. Regular visit to the doctor's may reveal the condition of the heart but not many people visit the doctor often as they are busy in the daily life. The heart is a very special and important organ and without it, life might be impossible. This project is dedicated to all those who would want to take a forward step to check if their heart is functioning properly. An Electrocardiogram (ECG) would be implemented to help those who are willing to get a cheap one. In previous years there have been a lot of circuits developed to illustrate an ECG circuit, however none of the previous projects put forward at least two different circuits and elaborated on the results [2]. In this project, at least two circuits were built to measure bio-signals and the results have been compared. Depending on the outcome of the comparison, it will be discussed which one is more likely to be built at a larger scale.

The aim of this project is to examine the responses that different circuits would offer. Also these results will be compared to the EKG sensor from Vernier Technology which is a proper sensor. In terms of time for the ECG, this would not be regarded as a huge factor as this project is dedicated to verify the different responses and analyse the results. The body signal would be taken by the aid of the electrolytes 'sticky tape' available. These are specifically designed tapes that stick to the skin and the electrolytic gel that is found on the surface, facilitates the transmission of the electrical signal of the body.

The body is composed of different types of muscles. Muscles have very important functions such that a body without muscles would be simply useless. Muscles can be defined as the mechanism that produces force to push or pull different parts of the body. Depending on their functions and structural characteristics, they can be classified into different types. An Electromyogram (EMG) is used to measure the muscle activity and this project will verify whether an ECG circuit can be used as an EMG circuit. It should be noted that there are three different kinds of muscle groups and not all of them can be measured using EMG hence their response to applied force would be modelled. The three classes of muscles are:

- Skeletal muscle
- Cardiac muscle
- Smooth muscle

The purpose of this project is to build an ECG and to see whether this circuit can act as an EMG. The EMG is a tool to look at the performance of the muscles, so a good overview on how muscles work is essential. Obviously the three sorts of muscles act differently depending on their function and they are described below.

1.1 Skeletal muscle

Skeletal muscles are mainly responsible for movement [1]. This type of muscle can be controlled voluntarily and is extensively distributed throughout the body making about 40% of the total mass [2]. Normally the skeletal muscles are attached to bones and if viewed from a microscope they are found to be striated such that the muscle cells contain interchanging light and dark bands. In addition, this colour depends on the amount of myoglobin [3]. The figure below shows this kind of muscle.
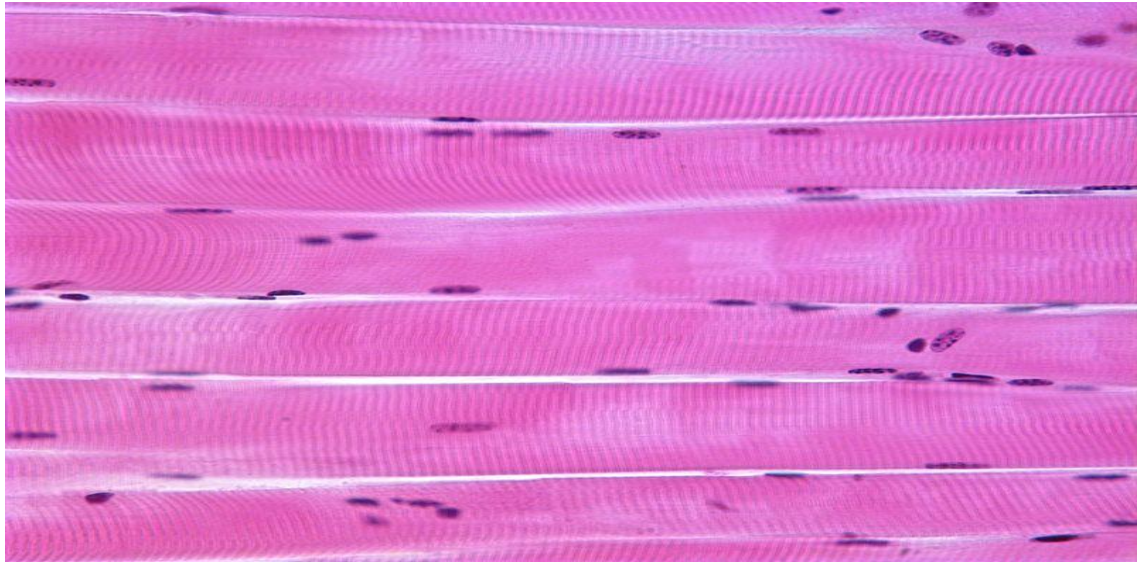
Figure 1 shows the arm muscles, which are skeletal muscles

One key thing to note is that not all the skeletal muscles are the same, as some contract faster than others, which is the result of their capability to break down Adenosine Triphosphate (ATP). Therefore those muscles which can synthesis ATP faster and therefore can contract faster [3]. The muscle types can be further divided into three categories.

1.1.1 Category I Fibres
This one is concerned with slow muscles twitching hence the contractions are slow. These muscle fibres comprise of abundance of mitochondria, which aid the muscle in the oxidative metabolism. Also they have a greater endurance and fatigue resistant [5]. This gives them the ability of working for longer period of time. Some examples are the eye muscles, the pectorals (chest) and more [6].

1.1.2 Category II a: Fast Twitching
This class of muscle fibres provide fast twitching and are responsible for quicker contraction. Also, they have a better ability to release calcium, which is needed for their higher rate of contracting activity that uses both anaerobic and aerobic metabolism. Hence these extraordinary properties help the muscle fibres to provide a sudden burst of power [7]. This tenacity defines the uses of these muscles and they are mostly used during performing sports such as soccer, basketball.

1.1.3 Category II b: Fast Twitching
This set of muscle fibres generate the most amount of force and power but at the same time the most fatigable muscle. In terms of twitching, they are the fastest and hence it allow them to provide an explosive wave of contraction but not for long [8].

1.2 Cardiac muscle
Cardiac muscles are only found in the heart and their function is to pump blood throughout the body. They are generally powerful and efficient as they have to do their task throughout the entire life cycle. Additionally cardiac muscle contract involuntarily and in a rhythmic way to maintain the continuous heartbeats [9]. The muscle fibres have a sole nuclei, normally placed in the centre then the fibres fuses with the adjacent fibres. The figure below shows the cardiac tissues.
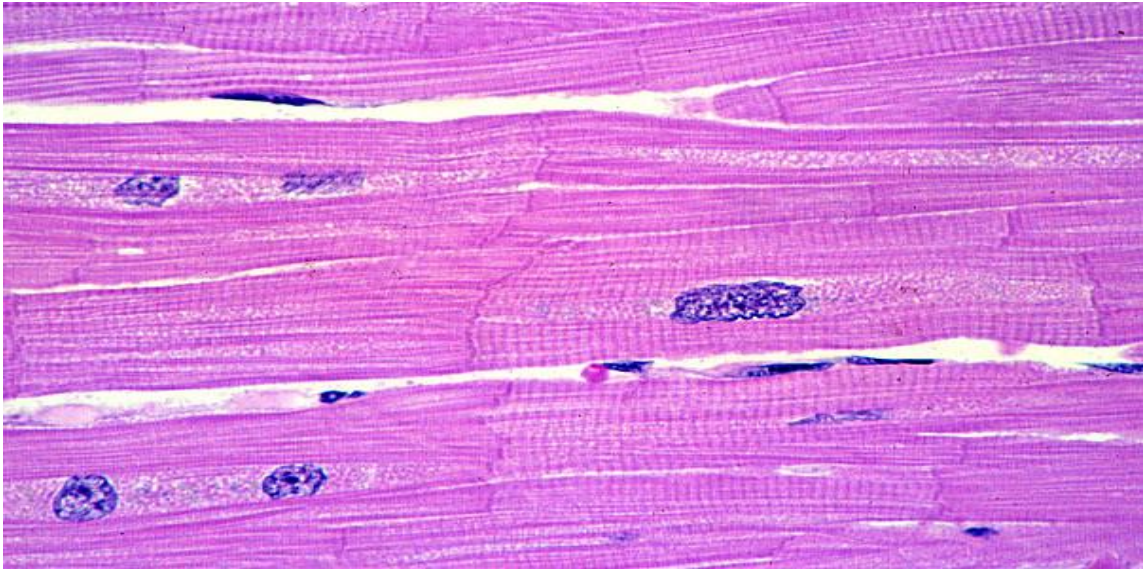
Figure 2 illustrates cardiac muscle fibres where the nucleus are in bluish colour

A length comparison to the skeletal muscles shows that the cardiac fibres are shorter in size, but form a so called network of many branches between the cells. The fibres are found to be striated and the vertical line signifies the end of the fibres. The glue to hold them together is the overlapping of the intercalated disk. The tissues must contain a lot of mitochondria to give them the strength to pump blood throughout the body.

1.3 Smooth muscles

The nature of the muscles is plain, non-striated and contract involuntarily meaning that the conscious mind has no control on the action. The main function is to displace substance from one place to the other, inside the body. As the name states, seen under a microscope the fibres are mostly plain and look 'smooth' [12]. The diagram below shows the structure.
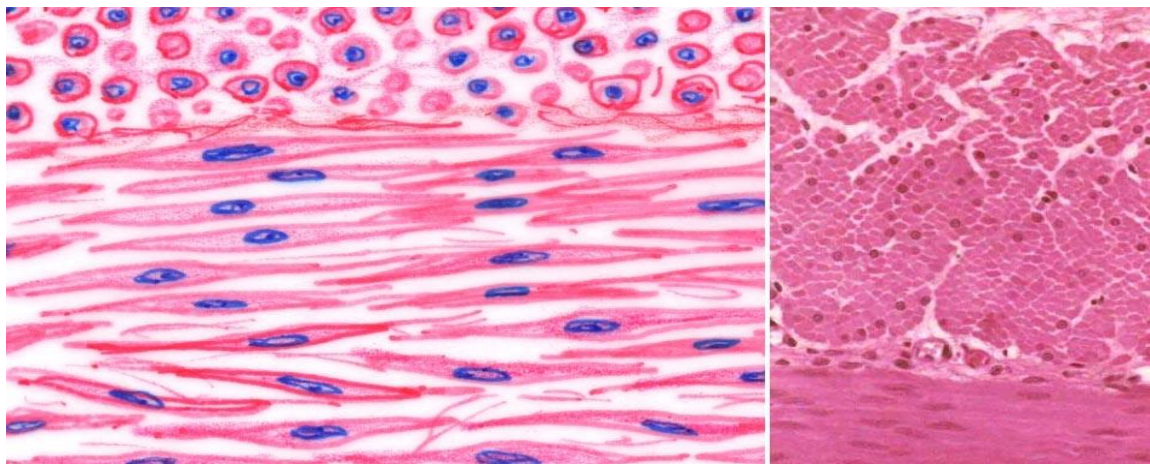
Figure 3 shows the smooth muscle tissues and how simple they are

The fibres are long and thin with a single nucleus in the middle. This type of muscles are very weak in performing their action and require a lot of time to complete their tasks. In fact they work in a rhythmic order similar to the cardiac muscle. Comparing this sort of muscle to the previously shown muscles, this muscle type display very short fibres with almost no striated present. [12]. Just to name a few examples where smooth muscles are present are the stomach walls, bladder, intestines.

2.0 The Circulatory system

Muscles are living tissues hence they need oxygen, nutrients and their waste product need to be taken away. This is a set of works that needs to be completed on a regular basis. The circulatory system also known as the cardiovascular system and this system is termed as an organ system as it contains several organs [13]. In order for the cardiovascular system to exist, three main elements are needed, namely:

- Fluid – blood
- System of tubes – blood vessels
- A pump – the heart

2.1 Blood as a transportation fluid

Blood being the transportation medium of constituents for the survival of the muscles, is a circulating liquid. The flow depends on the pressure gradient generated by the heart. Some vital components that blood contains are [14]:

- Blood cells
- Nutrients and other substances
- Plasma

2.1.1 Blood cells

The blood contains blood cells and with three main types:

- Red blood cells
- White blood cells
- Platelets

2.1.1.1 Red blood cells

Red blood cells also known as erythrocytes, as the name states they are red in colour. These cells contain a high amount of haemoglobin, which is a protein that increases the affinity to bind with the oxygen molecules. Their main function is to carry and feed the tissues with oxygen and partially load some of the carbon dioxide produced by the tissues away, to the lungs [15]. The shape of red blood cells is a biconcave disk which allows the cells to squeeze through blood vessels. These cells are available in abundance, they give the reddish colour of the blood (usually 45% of the total blood volume) [16]. The common site of production of these reddish cells are the bone marrow available in the body. Figure 4 below shows these red blood cells.

[16]

Figure 4 shows the structure of red blood cells

2.1.1.2 White Blood Cell

Also known as leukocytes, these cells are responsible for the defensive action for the body. There are different types of white blood cells present in the blood and if compared to erythrocytes quantity wise, the former are in very less concentration. In addition, leukocytes can be further divided into different types, given below [17]:

- Neutrophils – engulfing of foreign bodies such as bacteria.
- Eosinophils – engulf bacteria by forming the antigen-antibody complex.
- Basophil – secretion of anti-coagulant substance to break down the bacteria.
- Lymphocytes – production of antibodies.
- Monocytes – provide intense phagocytic action with the secretion of bodies that digest some part of the invader.

Different kinds of leukocytes have different shapes and are present in different quantities in the blood. The reason being is that some of them are produced if the body senses that there are attacks from foreign bodies. Additionally the immune system of the body produces cells named as memory cells which remembers the type of bacteria and their properties. These cells keep the record such that if in future there is an attack by the same parasite, the body would not waste time in getting to know the invader, but rather start the cleaning process [17]. The image below illustrates the leukocytes.
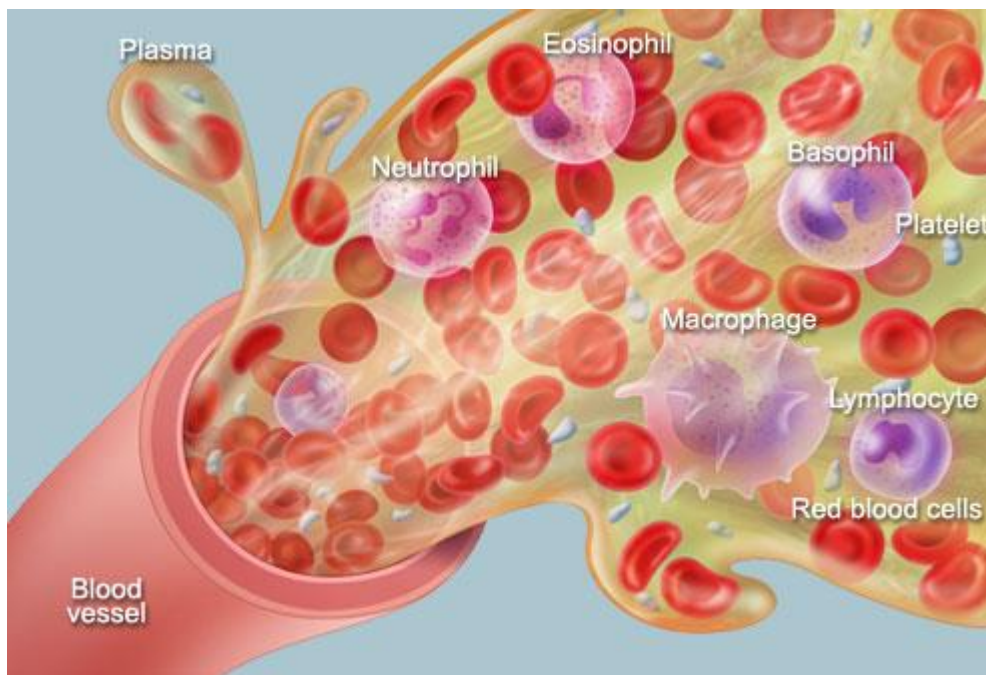
[18]

Figure 5 shows the different types of white blood cells and other components of the blood

2.1.1.3 Platelets

These are small fragments of blood cells found in the blood. Their main objective is to clot blood, given their sticky nature whenever is an injury involving bleeding. This helps prevent bacteria to infest the body, as well as reducing blood leakage [22].

2.1.2 Nutrients in the blood

Along with blood cells, blood has another function which is to feed the tissues by carrying nutrients with it. The origin of the nutrients are from the food that is digested, which is then processed by the digestive system and then put into circulation through the blood. Few of the important nutrients and other substances includes [19]:

- Hormones – released by the endocrine glands, hormones are very imperative substances which the body needs to do different activity, for example thyroid hormones are produced by the thyroid gland and its function is to adjust metabolism and energy production [20].
- Proteins – these substances are usually large in size but important for the body functioning, for instance blood carries albumin which is a protein, manufactured by the liver. The function of albumin is to regulate blood pressure and this is a really serious matter as a failure in maintaining a constant blood pressure might prove to be fatal [21]. (This is also common in blood plasma.)

2.1.3 Blood plasma

Habitually yellowish in colour, plasma contains most of the important body salts such as Sodium Chloride, carbonate ions, glucose and more. The key role is to keep equilibrium of the ions present in the blood. Plasma makes about 55% of the total blood volume. The diagram shows the plasma obtained from the blood after centrifugation.

[23]
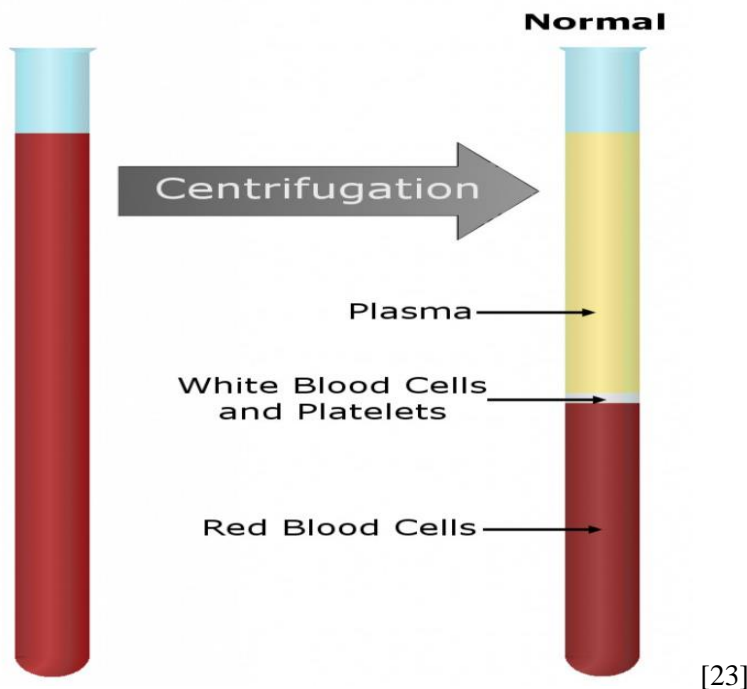
Figure 6 shows the plasma obtained before and after centrifugation of the blood

2.2 Blood vessels as the transportation pathway

Since blood is in liquid form, there should be a transportation medium. This can happen due to the different types of pipes available throughout the body, known as blood vessels. The major function of these vessels is to transport blood throughout the body. The running blood encounters five types of blood vessels, specifically:

- Artery and arterioles,
- Veins and venules,
- Capillary

2.2.1 Artery and Arterioles

An artery is a pipe that carries oxygenated blood away from the heart, except the pulmonary artery which carries deoxygenated blood. The arteries are muscular since they have to support the excessive pressure that the heart exerts [24]. The destination of the blood is usually the muscles where there would be exchange of materials. Arteries can further be branched to arterioles which are the smaller version of artery with relatively thinner muscle.

2.2.2 Vein and Venules

Veins are also blood vessels, however they carry deoxygenated blood, with exception of the pulmonary vein. Unlike artery, they have thin muscle which also contains a valve to prevent backflow [25]. They usually lead the blood to the lungs to be then become oxygenated. Veins further proliferate as venules, which are the smaller version of veins.

2.2.3 Capillaries

These are the smallest blood vessels which link arterioles to venules. Their main function is to allow maximum exchange of materials between the blood and other parts of the body such as muscles [26]. This is possible because of the size and they are usually present in numerous quantities that forms a bed of capillaries. The diagram below illustrates all the blood vessels.
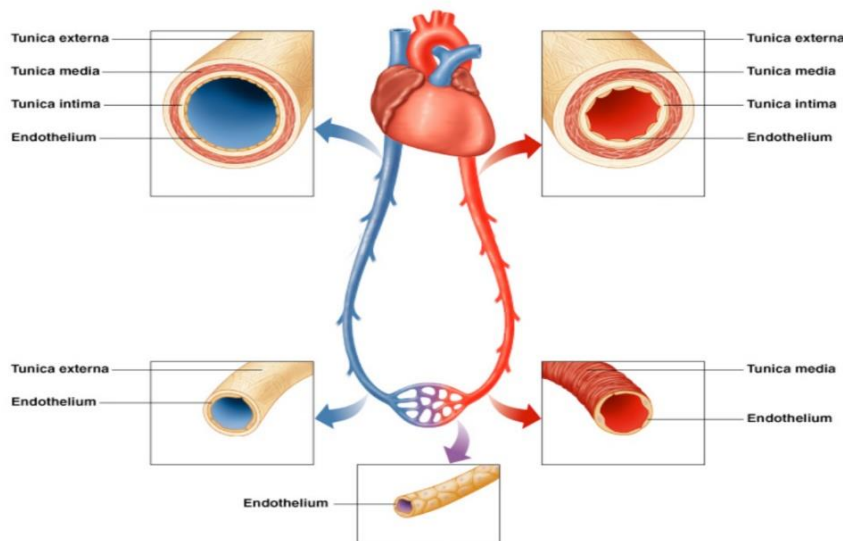
[27]

Figure 7 shows all the blood vessels and their sizes, starting from the top right is the artery then on the left is a vein followed by the right bottom is an arteriole versus the left which is a venule and finally the centre diagram is the capillaries bed.

2.3 The heart as the pump

Often described as the pump, the heart is an important organ for the survival of any living being that incorporates a circulatory system. This organ has muscular walls and its main function is to pump blood to the other parts of the body. From species to species the structure of the heart differs for instance, reptile's heart contains three chambers whereas humans' heart contains four chambers hence they work differently [28]. In this project, the test would be conducted on human as a normal ECG procedure is.

2.3.1 The structure of the heart

Usually the size of a fist, the heart comprises of four chambers namely:

- Two atrium located on the top of the heart
- Two ventricles located on the bottom

The atrium are divided into two separate chambers, the right and the left atria. The walls of the atrium are thin. Similar to the atrium, the ventricles also divide into the right and left parts. Comparative to the atrium, the ventricles have thicker walls given the intense work they perform. The difference in size is due to the amount of force that each chamber needs to provide which can be observed in an ECG. The diagram below shows the structure of the heart [28].
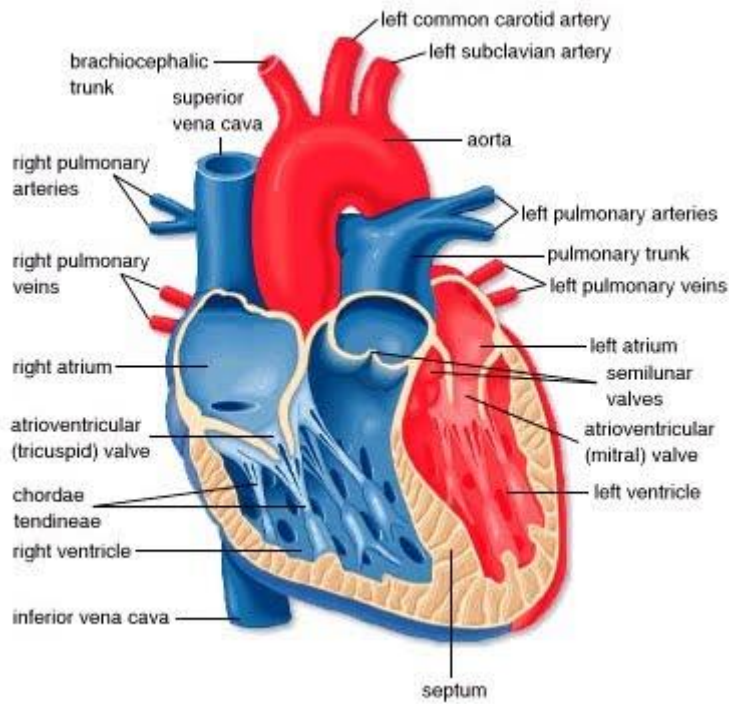
[29]

Figure 8 shows the structure of the heart with the different structures

The function of the heart is to propel blood throughout the body and this is done by the two ventricles as they are responsible for this task. This can be seen from the ventricles' muscles (septum) as it is quite thick which explains the vigorous generation of force. Comparatively, the occupation of atrium is to receive blood from the other parts of the body. The following diagram illustrates the circulatory system present in humans. The circulatory system plays a huge role as it acts as a trigger for the heart to start its electrical activity.
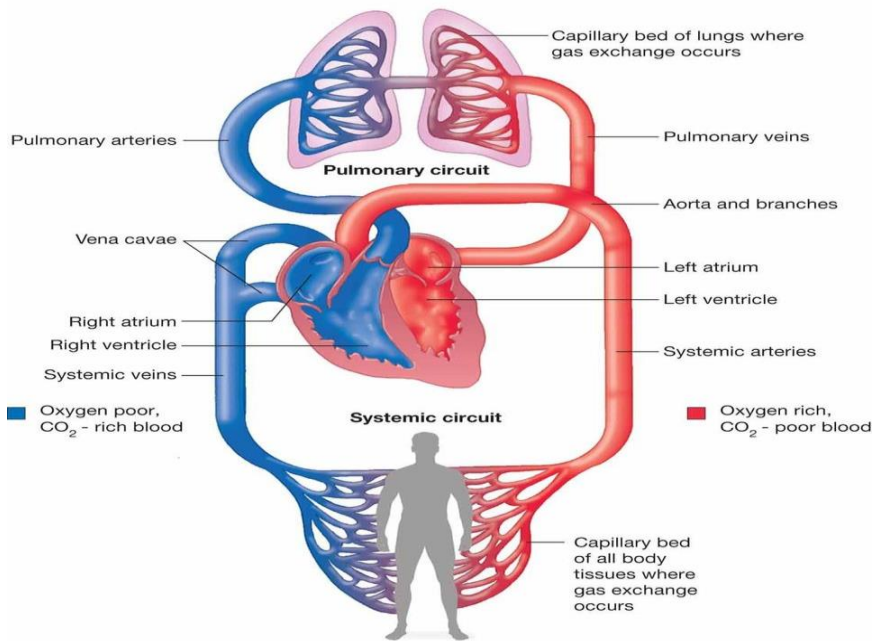
[30]

Figure 9 shows the different pathways that oxygenated and deoxygenated blood takes

Since muscles are living tissues they do need O_2 to survive [31]. The lungs are the main site where gas exchange occurs. Under normal conditions the erythrocytes are infiltrated with O_2 and CO_2 is left out which occurs due to concentration gradient in the blood. Once replenish the oxygenated blood (described as red in colour in figure 9) is directed to the left atrium and the heart keeps the mitral valve closed. This gives the LAT time to fill up. After a short period of time, the valve opens by the contraction of the LAT, letting the blood to flow in the LVT. Once the LAT relaxes, the valve also closes. After few milliseconds, the LVT contracts and gushes out the oxygenated blood collected from the atrium. The function of the valve is to prevent backflow of blood [31]. Leaving the LVT, the blood flows into the aorta which then directs it to the different parts of the body. Once the O_2 is seized from the red blood cells, the blood becomes deoxygenated due to the absence of the respiratory gas (illustrated in blue in figure 9). Blood from different parts of the body are gathered in the vein which finally leads to the right atrium (RAT) through the vena cava [32]. Since the RAT is relaxing, the tricuspid valve is closed and the blood gets stuck in the chamber. After a short period of wait, the RAT contracts, tricuspid valve opens and blood floods the RVT. The RAT relaxes which results in the closing of the valve which will prevent backflow of blood to the RAT. After a small wait, the ventricle squeezes itself and pushes the blood out of the heart to the lungs to be oxygenated through the pulmonary artery. The whole cycle repeats itself all over again [32].

2.3.2 Willem Einthoven and the Electrocardiogram (ECG)

Willem Einthoven took birth in Semarang, Netherland on 21th May, 1860. Unfortunately his father passed away when he was six years of age. Later Willem joined University of Utrecht Medical School where he greatly admired as a physiologist who was involved in studying the electrical activities of the heart [35]. He secured a job as a professor in the physiology field at Leiden. His research were really of a wide range, giving him the opportunity to publish 127 papers. The figure below shows Willem Einthoven.

 [36]

Figure 10 shows Willem Einthoven

Willem interest in anatomy led him to attend an International Congress of Physiology which took place in London where he seized the chance to observe Augustus Waller demonstrating the use of capillary electrometer to record an electro-gram of the heart using pan electrode, which was the first at that time [35]. This experiment involved the dipping of his right hand and left foot in a saline solution.

This idea of using a salty solution sparked in the mind of Willem in the 1890s when he started thinking about recording the electrical activities of the heart using the capillary technique. Due to his adamant nature, Willem was able to record the "P, Q, R, S, T" complex for the electrical signal of the heart [35]. To record his readings, Willem went to develop his own printing method by developing a "string galvanometer", consisting of magnets and quartz thread. His machine would weight about 250kg that occupies two rooms and required 5 individuals to operate. Willem did a lot of works in his field, but this one was exceptional which rewarded him the Nobel Prize [35]. Some of this later work involved the respiratory effect on the electrocardiogram which gave birth to the equilateral triangle theory.

2.3.3 Einthoven and his equilateral triangle theory.

Willem Einthoven's triangle was composed with three leads namely lead I, II and III with each representing a limb. The purpose of these leads (where all the three leads form the triangle) were to help in finding the rhythm of the heart [37]. The assumption was that the leads were bipolar meaning that there is both a positive and a negative pole. Horizontally extended, lead I runs from right arm (RA) to left arm (LA), with the LA bearing the positive pole. Lead II is positioned such that it forms the second side of the triangle but this time placed vertically such that it runs from the RA to the LL and the electrode is located on the left leg (LL) with a positive pole. Lastly the last side of the triangle is completed by running Lead III from the LA to the LL with a negative pole [37]. Since then this is a common practice for the practitioners to connect the leads in the predicted place by Einthoven. The diagram below illustrates Einthoven's triangle.
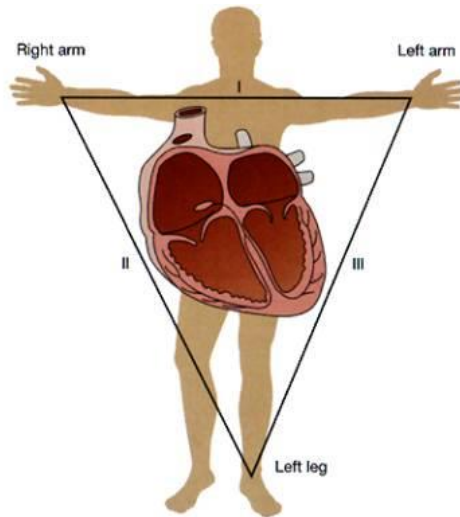
[38]

Figure 11 shows the equilateral triangle theory proposed by Willem Einthoven

This theory is considered to be the base of finding the rhythm. Over the years, scientists have experimented with this model, for instance keeping the leads as it is but instead of using the LL, the RL is used. This gave the physicians a better insight of this theory and a chance of understanding the body to a greater extent.

3.0 The Electrocardiogram (ECG) and Electromyography (EMG)

The heart is a sophisticated organ in many aspects, for example in contracting at the right time depending on the body movement. In order to produce a heartbeat, the heart needs to depolarize to start the contraction of the chambers of the heart.

3.1 Electrical Signal of the heart and the recording of the ECG

Unlike different organs the body has, the heart is quite special since it produces its own electrical signal therefore directing all the events that occur during a heartbeat. Each heartbeat is initiated by an electrical signal from within the heart muscle. A heartbeat can be described as the heart's chambers contract and relax to rush blood out of the heart [32]. In a heartbeat there are two phases namely systole and diastole. In the systole phase the ventricles and the atrium contract in contrast to the diastole phase where it is the vice versa situation. An Electrocardiogram (ECG or EKG) is used to track the different actions of the heart.

Under normal conditions, the electrical signal is commenced in the Sino Atrium node (SA node), located in the RAT. The heart rate is defined as the number of times the SA node fires the electrical signal per minutes. When the atrium is full, the electrical signal is generated which causes the atrium to contract. The pressure causes the tricuspid valve to open and the tightening of the atrium forces blood to flow into the ventricle. This is called the P wave on the ECG.

The released signal arrives to the Atrioventricular node (AV node) where it waits for a while, letting the ventricles to fill. From there the signal moves to the Bundle of His (muscles separating the two ventricles) which is a pair of muscle for each ventricle [33]. The signal is divided into the right and left bundle

11

branches moving slowly across the septum which contains the Purkinje fibres which is located at the bottom of the heart. This permits the ventricles to fill and is recorded as the Q wave.

At this stage, the signal moves swiftly across the ventricles walls. This then triggers an array of events. The dissociation of the signal causes the ventricles to contract. After contracting, the blood follows the pathway such that the blood in the RVT opens the pulmonary valve to go to the lungs whereas the blood in the LVT unlocks the aortic valve to rush to the tissues. It should be noted that the LVT is bigger by a minor fraction that the RVT so the two do not contract at the same time. This is registered as the RS complex on an ECG [33]

After contraction, there is repolarisation of the ventricle which means that the ventricles are back to the relaxing state. This is noted as the Q wave. The diagram below shows the illustration of the theory explained above.
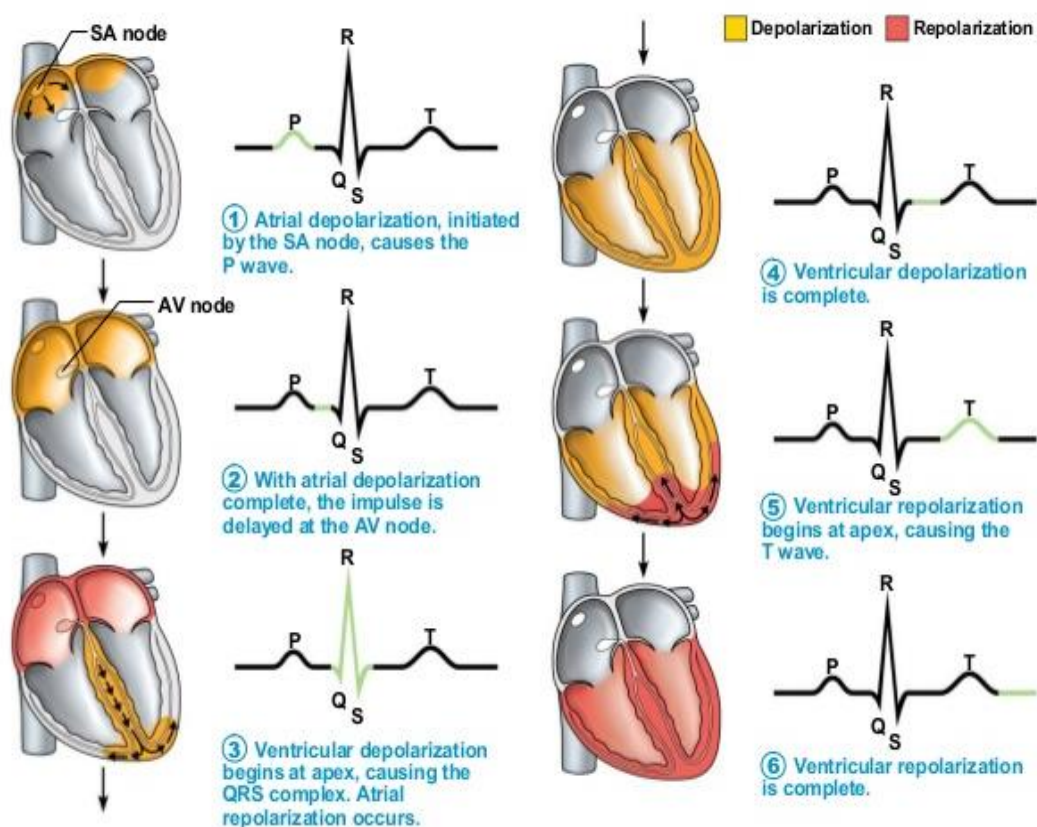
[34]

Figure 12 shows the stages that the heart undertakes to produce a heartbeat

Similar to other parts of the body, the heart is made up of muscles. Depending on the types of muscle, the muscle activity can be measured by the aid of an EMG.

3.2 Muscle activity and the EMG recording

As of recently, EMG has introduced itself as a powerful tool in the medical world. EMG is utilized to determine the electrical activities or muscles response to a nerve's stimulation of the muscle. This allows the practitioner (normally neurologist) to detect neuromuscular irregularities. Other uses may include the study of biomechanics of the muscle such as injury biomechanics and more.

The procedure to start an EMG process is one or more small needles (also called electrodes) are inserted through the skin into the desired muscle. The acquired result obtained from the muscle activities is then projected on a monitor that shows the response in the form of waves. Some advance equipment provide

an audio-amplifier which aids in hearing the muscle activities. Normally using the EMG, measurement for the muscle activities are taken at rest, followed by a slight contraction and finally vigorous contraction. Muscle tissue does not normally produce electrical signals during rest (where potential is around -70 mV) [39].

When an electrode is inserted, a brief period of activity can be seen on the oscilloscope, but after that, no signal should be present. [39]. The diagram below shows an example of an EMG being recorded.
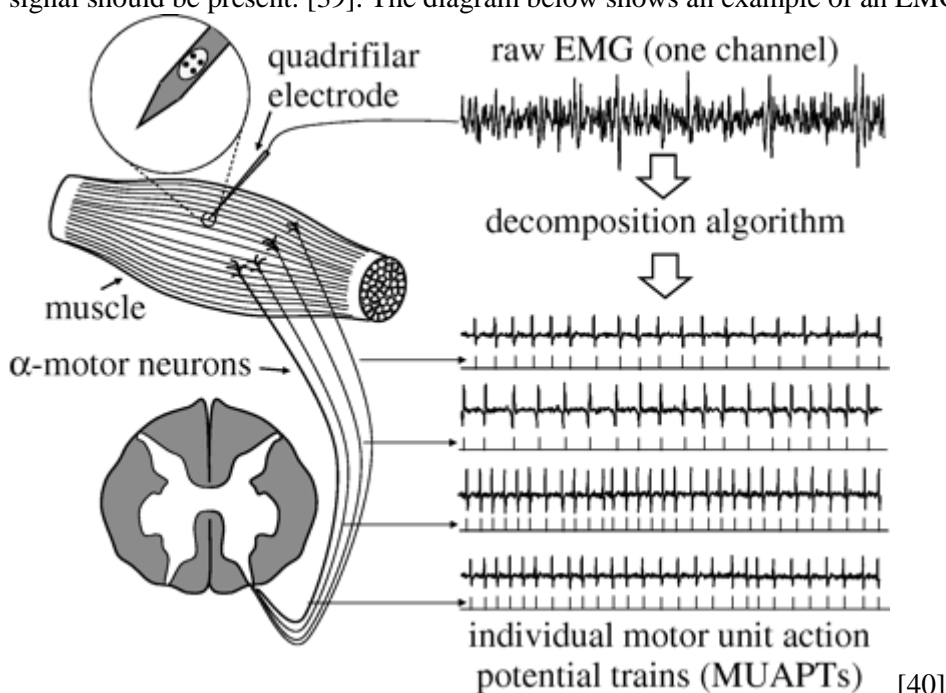
Figure 13 shows an EMG with the readings obtained

After an electrode has been injected, the patient can or may be asked to contract the muscle, for example, moving their leg in different poses. The action potential (size and shape of the wave) that this creates on the screen provides information about the ability of the muscle to react when the nerves are stimulated [40]. As the muscle is contracted more forcefully, more and more muscle fibres are activated, producing action potentials hence more force.

4.0 Building the ECG circuit

The ECG circuit consists of different parts that should be built. This section will describe different techniques that will contribute towards building the ECG circuit.

4.1 A differential amplifier

Differential amplifier is a category of amplifier that takes the difference between two voltages and amplifies the difference. Also it neglects any voltages that are common between the two readings [41]. From the body, two different voltages can be acquired hence a differential amplifier can be used to measure them. The diagram below shows a differential amplifier.
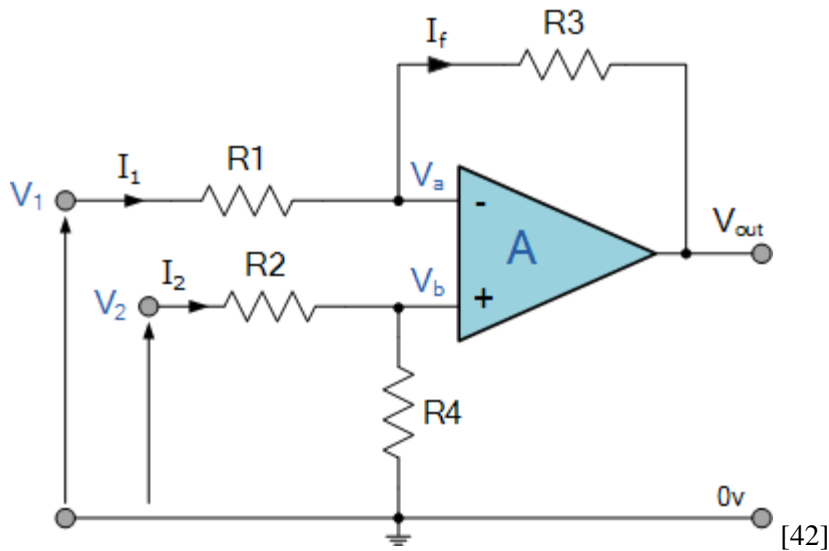
Figure 14 shows a differential amplifier with two different inputs, V1 and V2

From calculation and derivation (refer to appendix 9A):

$$Vout = \left(\frac{R3}{R1}\right)(V2 - V1)$$

If all the resistors are of identical values:

$$Vout = (V1 - V2)$$

However the differential amplifier is not often productive when dealing with small voltages. The other issue is what op-amp would be used for example an all-purpose amplifier is used like LM741, the reading would be not that accurate since this opamp is not designed to measure small changes. So a more accurate amplification circuit would be an instrumentation amplifier (ins-amp).

4.2 An instrumentation amplifier

A common mode signal can be defined as the mean of the input voltages. In order to provide a more robust circuit that can register minor changes in voltage drops, a more complex circuit needs to be implemented. One circuit in particular is the instrumentation amplifier circuit which can attempt to be more accurate to read small changes [43]. An instrumentation amplifier is another type of differential amplifier which is able to amplify small differential signals. In addition, an ins-amp has a very worthy common mode rejection ratio (CMRR), where the latter has the capability to amplify differential signal while rejecting common mode signal [44]. One of the most popular arrangements is using three op-amps, and this is shows in the diagram below.

14
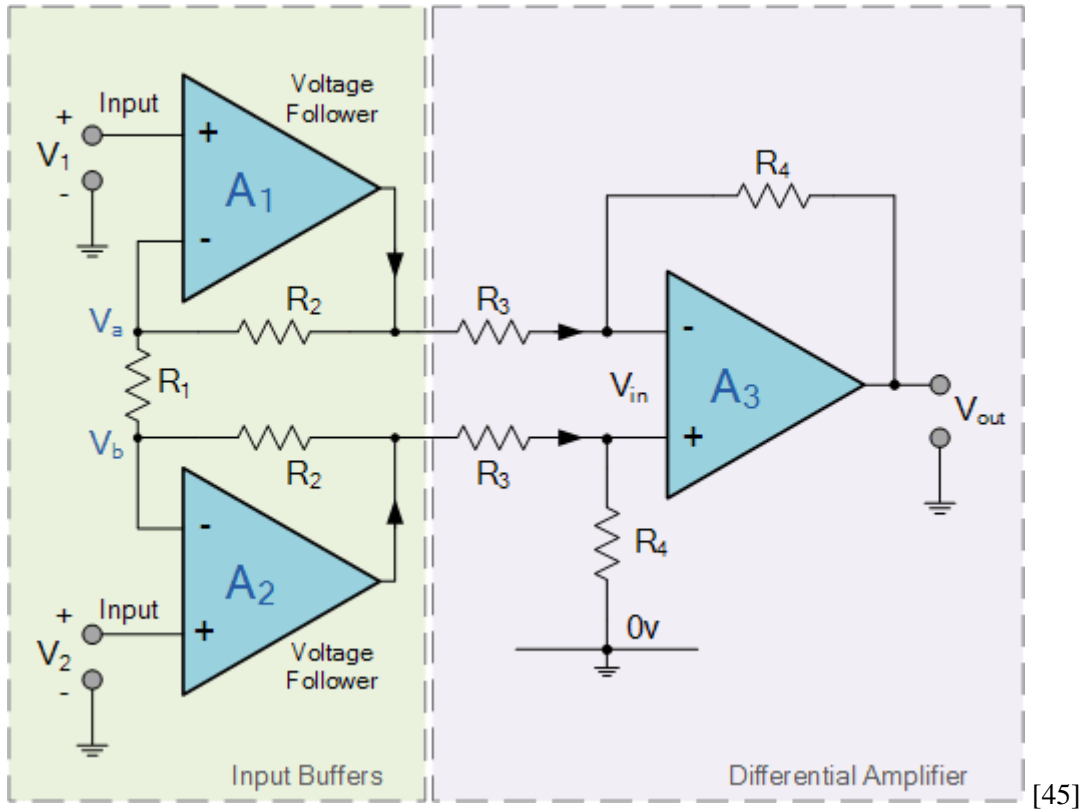
Figure 15 shows the three op-amps arrangement which will form the instrumentation amplifier

From derivation (see appendix) [46]:

$$Vout = (V2 - V1)[1 + \frac{2R2}{R1}](\frac{R4}{R3})$$

This circuit will form the base of the ECG circuit where V1 and V2 would be the inputs received from the body. However a third input would be implemented by simply connecting the ground of the system to the body which will act as a reference point. Using this diagram as a template, the circuit can be designed using the suited components values.

4.3 A simple ECG

A simple ECG circuit could be designed using the idea of a differential amplifier. To make it even simpler, it should be battery operated instead of using a power supply which will make it easy to carry around. Figure 16 below shows a circuit designed using the differential method.
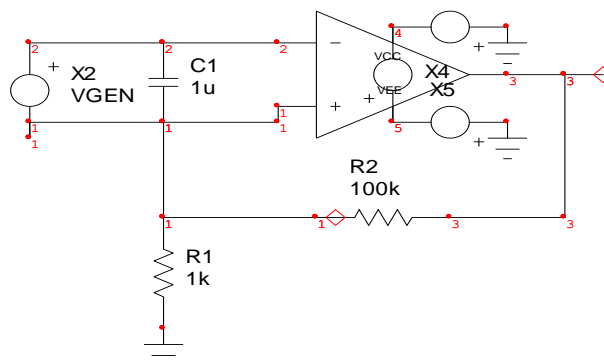
Figure 16 shows a simple ECG circuit powered by a 9V battery

15

The primary choice of the op-amp was to use LM358N as it fulfils all the requirements of the circuit. However this was not possible as this op-amp was not available from Murdoch University, so the other alternative was to use another op-amp, which has approximately the same characteristics as the original. Few of the qualities that are of particular interest include:

- Low voltage powered.
- Wide bandwidth.
- DC voltage gain.

Through research a series suitable op-amps were found [47]:

- LM2904N1
- LM158N
- LM258N
- LM386N

The top three were not used as they were not available in store and were required to order them, which will take about a three to four days to reach. Also, since the budget was being controlled, this would be another expense while another alternative is available. This lead to use the fourth option, which was LM386N. Comparing the latter with LM358N, there is not much difference in the concerned properties although there are minor differences but are not significant enough to be worried about such as biased current/voltage and so on.

4.4 An ECG using the Instrumentation amplifier technique – Circuit 1

While this is not a new system, some of the project available on the Internet consists of this three op-amps configuration where it has been used to perform such operations. In most bio-signal taken from the body, there should be a pre-amplifier circuit, followed by a filtering circuit and lastly an amplification circuit to amplify the filtered signal. The aim is to produce an ECG with the components that are available in the lab. This will also fulfil the desire of the product being cheap. The op-amp is probably the most used internationally due to its cheap price is LM741. As this op-amp was available, the LM741 forms part of the project. The easiest way is to search on the Internet for an existing circuit which can accelerate the progress instead of creating a new design. Additionally, this is an excellent chance to prove whether all the sources are reliable or not. Also dependant on the result, analysis would be made which will involve a more critical point of view rather than taking a circuit that is known to work and experimenting with the latter. The following diagram has been selected from one online source [48]:
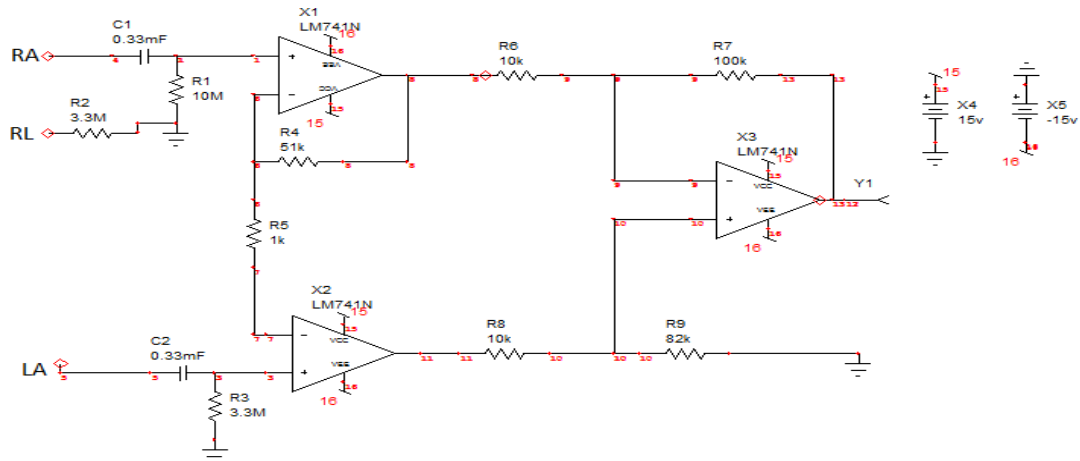
[49]

Figure 17 shows the ECG circuit ready-made obtained from an online source

16

From the above figure, lead RA will be attached to right arm, lead RL to right leg whereas LA to left arm. The output Y1 would be displayed on the digital oscilloscope. Notice the capacitors attached to LA and RA respectively, these are meant to stabilise the waveform. The RL small circuitry is implemented so that it acts as a reference point [49].

4.5 Circuit 2

Using an instrumentation amplifier as the foundation, a new circuit is designed. Of course this circuit will consist of the same arrangement and depending on the output, different resistors value would be used. The gain of the system is not preferred to be high as in later section other circuit will be added and the total gain would be really high hence the gain is to be kept at a moderate level. The other issue with a high gain circuit is of course the saturation of the op-amps. The diagram below shows the circuit to be used [50].
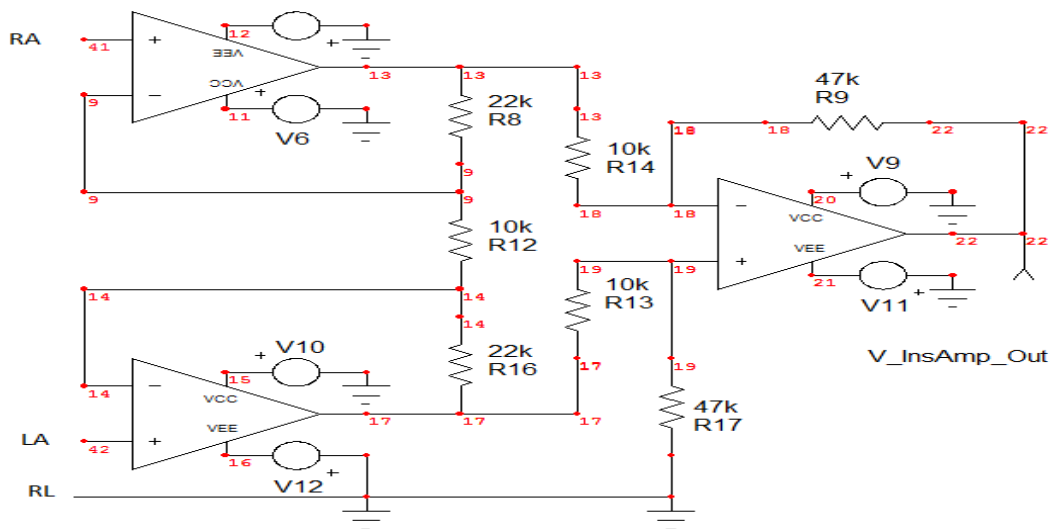
Figure 18 shows the newly designed circuit

The use of this instrumentation amplifier is to provide a very high input impedance as the body has a relatively high impedance. As explained in Circuit 1, different leads go to diverse parts of the body. In the figure above the resistor R17 (47 KΩ) is in fact a potentiometer of 100KΩ but the value is set to be at 47Ω as the latter allows the circuit to have a high CMRR. Also the gain of the system is kept at 25 because the electrodes often produce an offset thus helping in inhibition of saturation [51].

4.6 Circuit 3

All thanks to technology, nowadays instead of using three op-amps, other op-amps are available which consist of an instrumentation amplifier in a chip of the size of an eight pins LM741. One such op-amp is the INA12XN where the letter X represents different the number of 1 to 9 and the latter defined different qualities such as greater bandwidth or high cut-off frequency. More precisely, the op-amp that would be used in this part of the project is the INA128N. This is a general purpose amplifier that offers outstanding accuracy and they are normally low powered for energy savings. Moreover their small size makes the op-amp more versatile when it comes to space preservation. In addition the desired gain can be achieved easily by varying the resistor R_G and the rest of the circuit stays the same. The following diagram shows the arrangement of op-amps inside the INA128.

INA128:

$$G = 1 + \frac{50k\Omega}{R_G}$$

INA129:

$$G = 1 + \frac{49.4k\Omega}{R_G}$$

NOTE: (1) INA129: 24.7kΩ
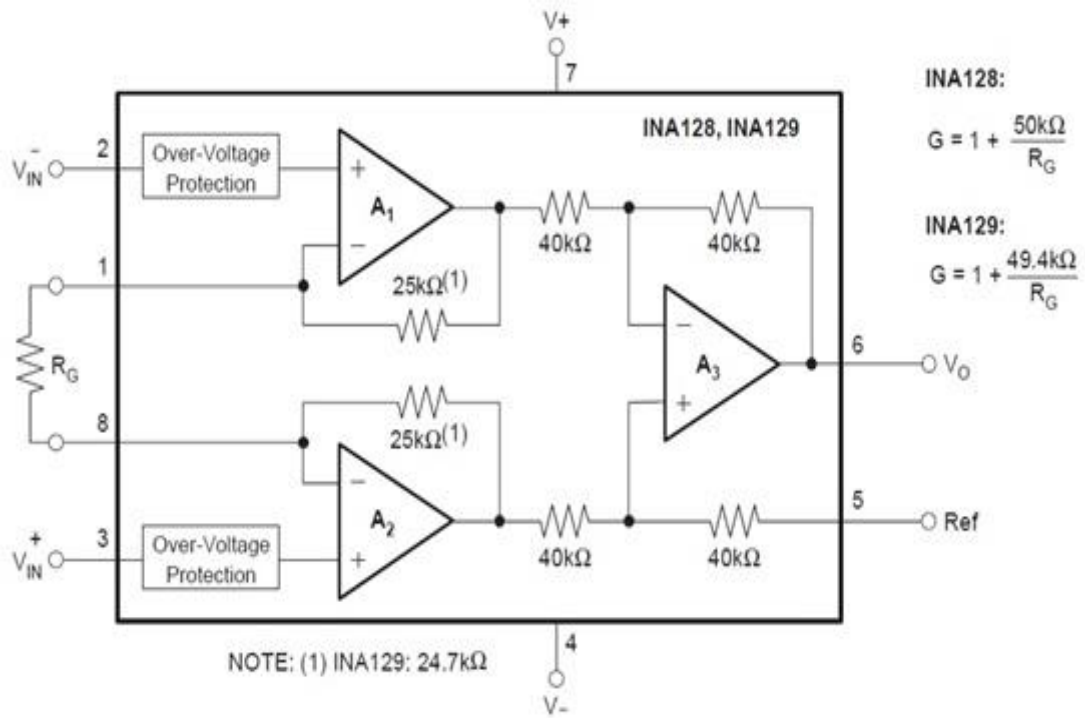
[55]

Figure 19 shows the structure of amplifier INA128/129

The other plus point of this op-amp is the ability of handling a high gain of, 1 to 10,000 in contrast to the LM741 which has a gain of about 1-1000. Slew rate of an op-amp is the aptitude of the latter to track rapid changes in the signal so the higher the slew rate, the faster changes can be measured [52]. Assuming under favourable condition, where temperature is about 25 ^{0}C, the figure below shows few of the comparison that are essential between these amplifiers [53], [54].

Properties	LM741	INA128
Number of chips to create an instrumentation amplifier	3	1
Offset voltage	50 μV	15Mv
Slew rate	0.5 V/μs	4 V/μs
Gain handling	1-1000	1-10,000
Common mode rejection ratio	95 dB	120 dB
Power to operate	Minimum: 2.25V	Minimum: 10V
Protection within the chip	No protection	Over-voltage
Price (AUD)	Less than $1	About $7

Table 1 shows the difference between LM741 and INA128

4.7 Noise – Problems and their solutions

In theory while dealing with signal, it is assumed that the signal is not mixed with noise, but with experimental measurements this is not the case. . Noise is defined as the unwanted signal that forms part of the normal signal [56]. No matter how sophisticated the measuring instrument is, there is always some particular type of undesired noise present

4.7.1 Problems with noise related ECG waveform

When it comes to the ECG measurement, the signal is infiltrated with different types of noise given below [58]:

- Power line interference – this noise can be induced due to contaminations from power lines
- Noise from power supply – the other noise that can affect the signal is the fluctuations coming from power supply which is very small.
- Muscle contraction – since the leads are connected on the wrist of the subject, noise from other parts of the body will be present which would be from the contractions of other muscles.
- Respiration noise – sometimes due to heavy breath, much pressure is exerted on the lungs. Since the heart is located near to the lungs, the heartbeat signal is contaminated with the respiratory one.

4.7.2 Solutions of how to combat noise

The easiest way to neutralise noise is the use of filters. However the tricky bit is to find the frequency or magnitude of the undesirable signal. One way to do so is to use the Fast Fourier Transform (FFT) function that the digital oscilloscope provides and find the magnitude of the noise. The next step is to check if the FFT reading giving a good approximation and this can be done by using the feature that LabView provides under the bio-medical section. The way it works is that LabView has an in-built ECG signal, which can be used to experiment with and is shown in the figure below.
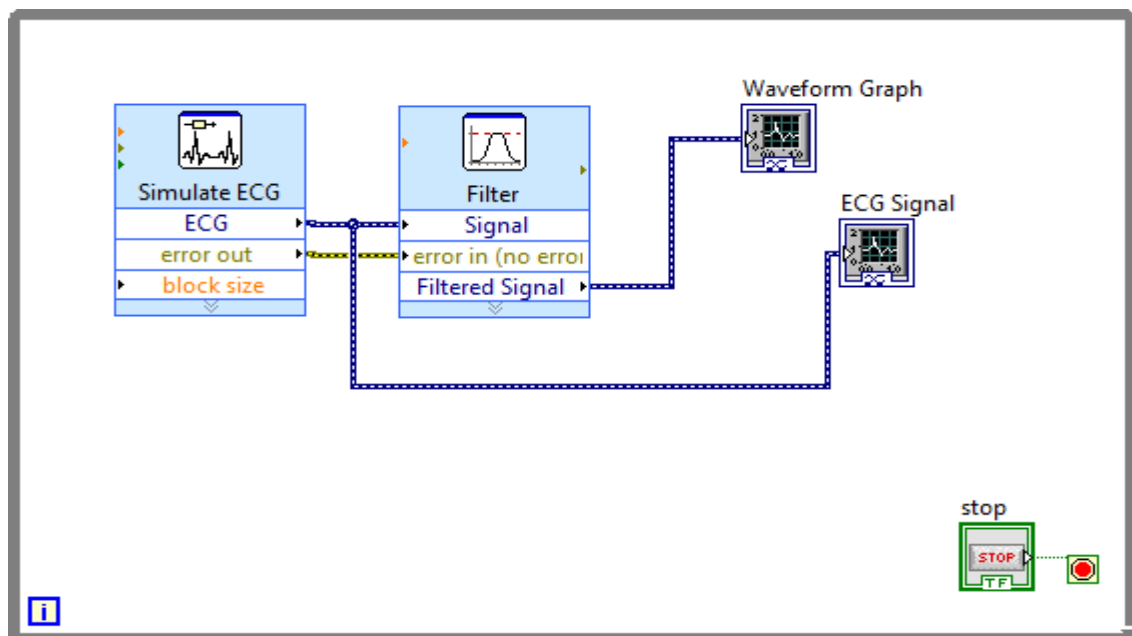
Figure 20 shows the ECG waveform simulation block from LabView

Once this block has been selected and dragged to the workspace, LabView will automatically open the window where parameters such as heart rate, frequency of noise and so on, can be change. This window is given in the figure below:
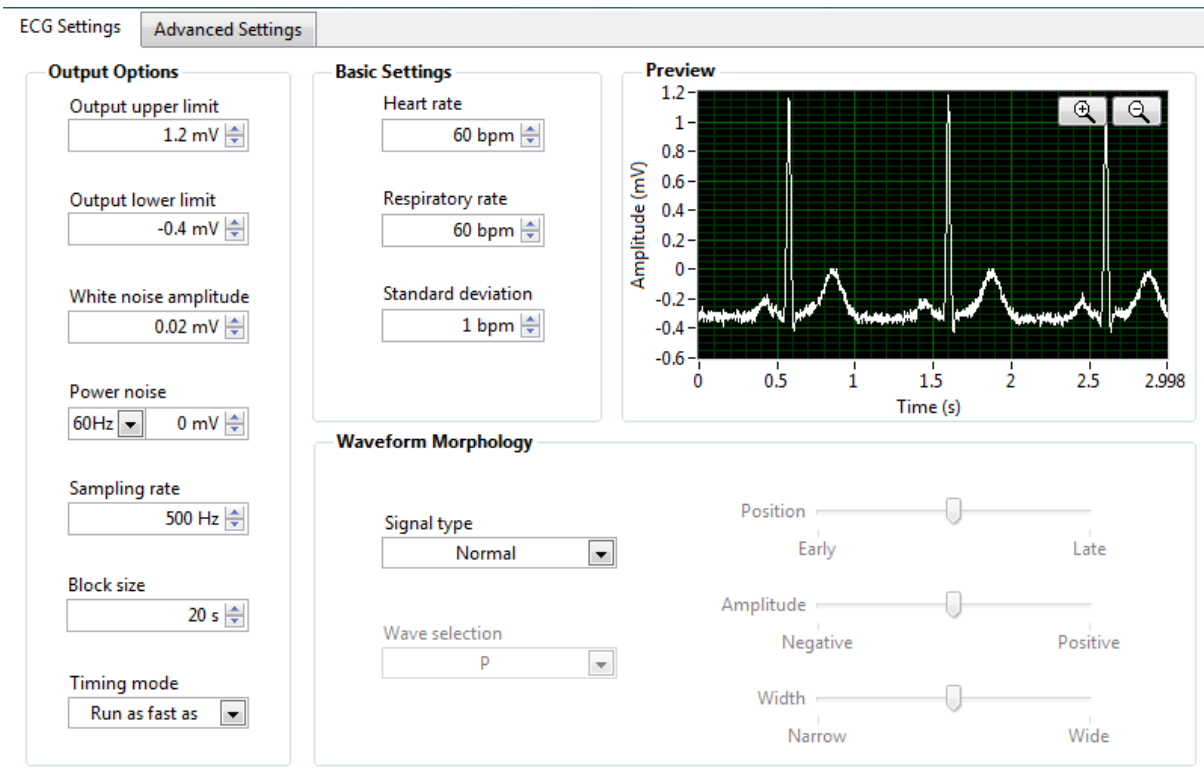
Figure 21 illustrates the properties that LabView allows the user to choose from

Once this setup is accomplished then the next step is to implement a filter. The aim of this is to experiment the behaviour of different filters on the system. The diagram above shows the filtering block and below is the window that opens when double clicked on the filtering block.

Figure 22 shows the filtering block with the options of different types of filters with different cut-off frequencies

4.8 The Opto-isolator Circuit

When it comes to medical equipment, safety is an issue that has the first priority. Although hospitals have the safety feature of a "Cardiac Protected" unit in the wards, it is vital to implement a safety circuit to ensure that the patient is adequately protected. The Cardiac Protected unit contains Residual Current Device (RCDs) which limits the amount of current flowing through that unit [57]. This gives rise for the urge to design an Opto-isolator circuit which works by lighting LEDs to transmit the voltage around. Although there are plenty of these sorts of circuits available, there is one in particular published on Silicon Chip's website [57]. Furthermore this circuit that Silicon Chip put forward has not been used in any other project, since this is a new circuit which might act as a sense of insecurity such that there are no reviews about it. The following diagram below shows the Opto-isolator circuit (in the original form):

[57]
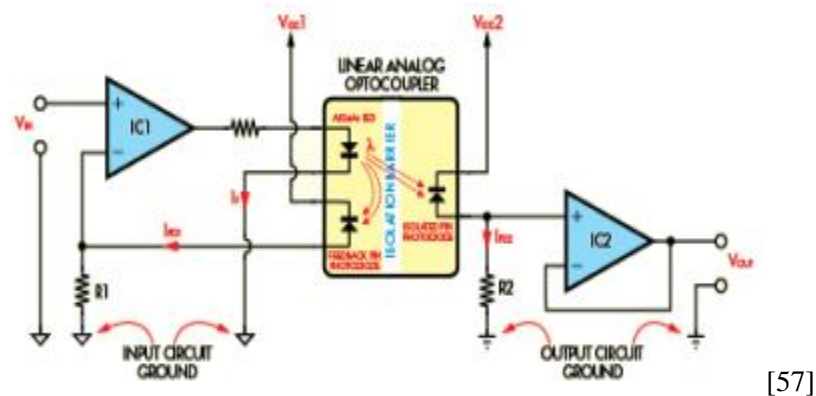
Figure 23 shows the Opto-isolator with all its associated components

The circuit above is designed to isolate high voltages and is shown in a brief manner. One key feature of this circuit is that the opto isolator (HCNR201) is a high linear analogue opto-coupler. Notice that there are two photodiodes in the opto isolator chip, which receive the infrared radiation discharged by the LED. The photodiodes are thoroughly equal in terms of their linearity and capability of sensing the optical emission [57].

One of the photodiode (PD2) is located opposite to the other one (PD1) (on the LED side) and the reason is to provide a linear feedback circuit. When the LED is on, it supplies current I_F hence radiation to both PD1 and PD2 which in turn produces current I_{PD1} and I_{PD2}. A proportional voltage is produced when PD1 passes through resistor 1 (R1) where this voltage can be used for amplification, if needed. The conversion of the input voltage (V_{in}) to the I_F is linearized by this operation of R1. Since the photodiodes are "twin" I_{PD1} is nearly equal to I_{PD2} and R2 is used to return I_{PD2} to a voltage (V_{out}) which would be proportional to V_{in}. The diagram below shows the complete circuit that would be used for this project (the circuit has been modified and adapted to suit this project).
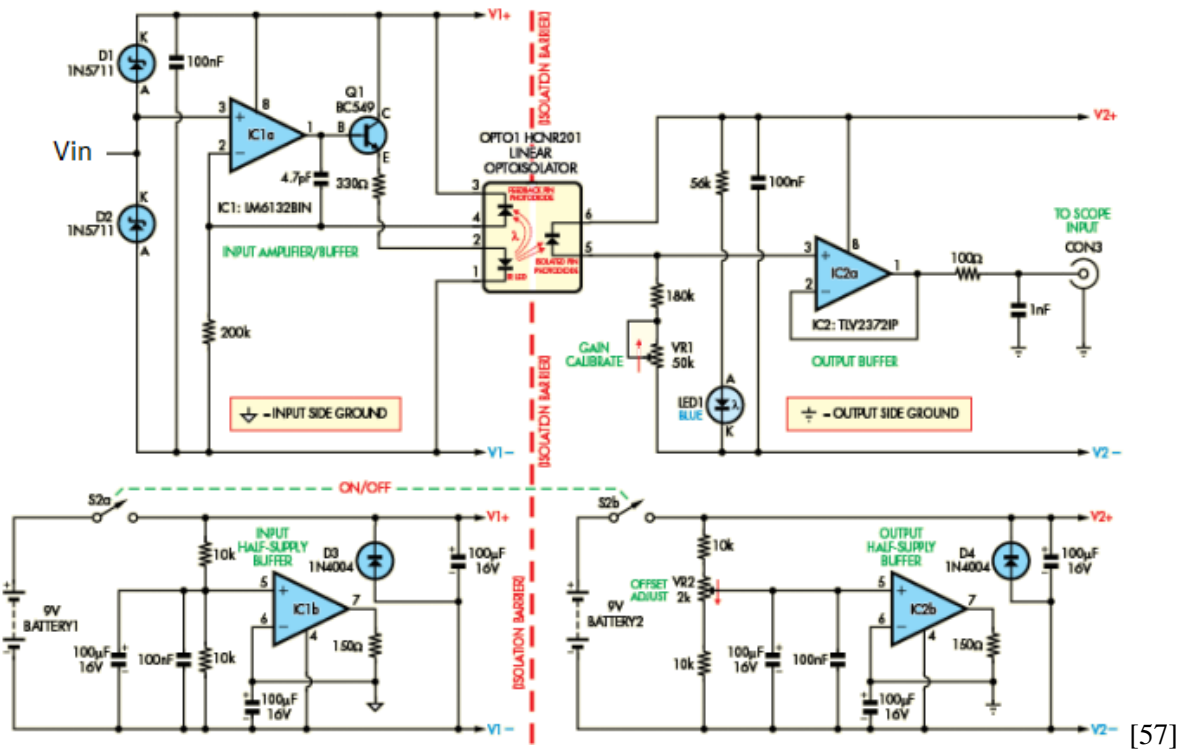
Figure 24 shows the full opto-isolator circuit in detail.

This is a very sophisticated diagram which incorporated a lot of considerations about safety to ensure that there is total isolation. Some of the crucial features are listed below:

- The isolation barrier (not necessary if dealing with small voltages) – this provides total isolation from the input to the output. Should there be any fault in V_{in}, the main line of defence is the barrier. This circuit is designed to protect extreme high voltages, but since this project is dealing with low voltages, having no protection barrier is acceptable.

- The Op-amps (IC1 and IC2) used are low powered, requiring a minimum of 1.8V and 2.7V respectively *(Texas Instrument)* [59] [60]. Both of the chips are dual amplifiers based meaning they contain two op-amps inside. Also they are very precise, offering an offset of 0.25mV and 4.5mV correspondingly. Silicon Chip used the different amplifiers (IC1 and IC2) because of the different properties that matched this project and this choice has been respected hence will remain unchanged in this project.

- The diodes D1 and D2 are to ensure that current is flowing in the right direction. They also act as a protection shield to IC1 preventing an overvoltage situation.

- The transistor, Q1 is used to ensure that the current is enough to switch the LED in the opto-coupler as IC1 is a low powered amplifier.

- The purpose of IC2 is to act as a buffer, assuring that the linearity is preserved. There is also a resistor of 100Ω fitted in the output of IC2 to guarantee that this circuit is well isolated from any capacitance resulting from the wire to the scope. This 100Ω and a 1nF forms a low pass filter which compensate for a peak in frequency that surrounds the opto-coupler [61].

- In addition, the bottom two circuits are for delivering power to both the ICs as they are separated by an isolation barrier. Both, the input and the output side has their own power supply which is a 9v battery. As mentioned before, both chips contain two op-amps and one of them (IC1b and IC2b) is used to divide the 9v into +4.5V and -4.5V as well as creating the reference point by the two 10KΩ. The purpose of the resistor of 150Ω at pin 7 of each IC's and the capacitor of 100μF at pin 6 are used to certify the stability of the voltage follower and stop any short term fluctuation of the voltage as current is drawn out of the op-amp respectively. Following on pin 5 there is a

100μF capacitor in parallel to a 100nF one and of course the question that arises is why to do so? Often this arrangement is used in electronics to ensure that both, short term and long term fluctuations in frequency change is managed where the 100nF due to its size copes with short term whereas 100μF manages the long term variation.

- The LED1 is implemented in this circuit to create the sense of awareness that the circuit is still on and needs to be switch off to save the batteries from draining. The diodes D3 and D4 are incorporated in the circuit in a reverse- biased manner which is harmless to the performance of the circuit. Their function is to protect IC1 and IC2 in case if the battery is positioned in the reverse direction [61].
- There are two potentiometers in the output circuit which serve as the gain calibrator and the offset settler.

4.9 Vernier EKG Sensor

Murdoch University has an EKG sensor purchased from Vernier Sensors. This sensor is a ready-made ECG simulator which is a plug and play device. Associated with it is a Data Acquisition Card (DAQ) from National Instrument. While not much information is available on this sensor, it is relatively simple to use. Figure 25 shows the sensor and DAQ.

(a)   (b)
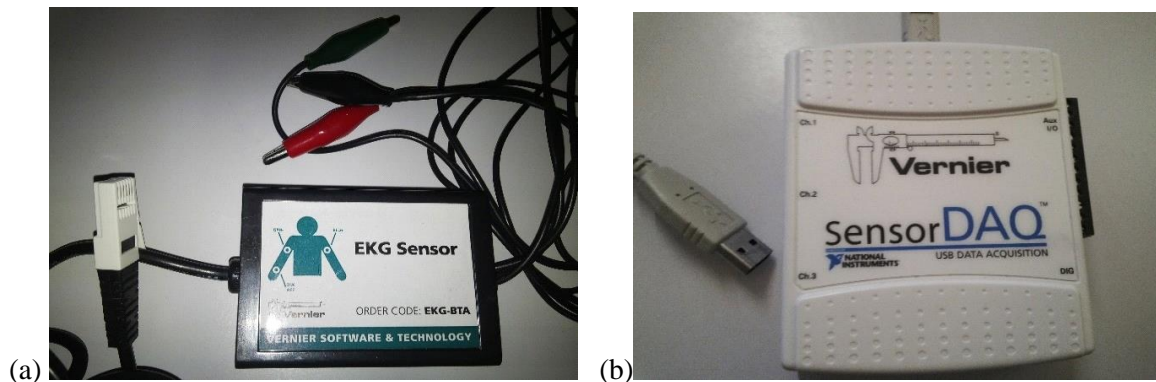
Figure 25(a) shows the EKG sensor and (b) show the DAQ card required to read from the sensor

From figure 25(a), the white plug is the input to the DAQ card. The latter consists of three input channels which can be used to acquire three different kinds of data. The DAQ needs to be connected to the PC. Once connected, the PC will install the software required to run the device. One way to know that the DAQ is being powered is to look for the flashing LED signalling that the Sensor DAQ is recognised by the PC. To check if the device is operating, the use of NI Max from LabView is required where there are parameters which can be change to verify if the intended change is happening. The DAQ card also requires a 5V supply with which it will power the EKG sensor. The diagram below illustrate the different pins configuration.

Terminal	Signal Name	Reference	Direction	Description
5,8,10	GND	—	—	**Ground**: Reference point for single-ended AI measurements, bias current return point for differential mode measurements, AO voltages, digital signals at the I/O connector, +5 VDC supply, and the +2.5 VDC reference.
11,12	AI <0..1>	Varies	Input	**Analog Input Channels 0 and 1**: For single-ended measurements, each signal is an analog input voltage channel. For differential measurements, AI 0 and AI 1 are the positive and negative inputs, respectfully, of differential analog input channel 0.
9	AO 0	GND	Output	**Analog Output Channel 0**: Supplies the voltage output of AO channel 0 from 0-5V with an output current drive value of 5 mA. The maximum update rate is 150 Hz, software timed.
1-4	P0.<0.3	GND	Input or Output	**Digital I/O Signals**: You can individually configure each signal as an input or output.
6	+5 V	GND	Output	**+5 V Power Source**: Provides +5 V power.
7	PFI 0	GND	Input	**PFI 0**: This pin is configurable as either a digital trigger, an event counter input, pulse generation output, or as a period, semi-period, two edge separation timer.

[62]

Table 2 shows the pinouts of the Sensor DAQ

5.0 Results

Before the final circuit was made on the breadboard, some simulation was done to see what should be expected from the circuit.

5.1 Simulation Result

Using Spice ICAP from Intusoft as a simulation tool, the designed circuits were simulated. Starting from the input, the signal that is taken from the body is in terms of voltages so the input of the circuit is two different voltage generators. In this simulation, circuit 2 would be simulated. The figure below shows what is observed if only the input is to be simulated.
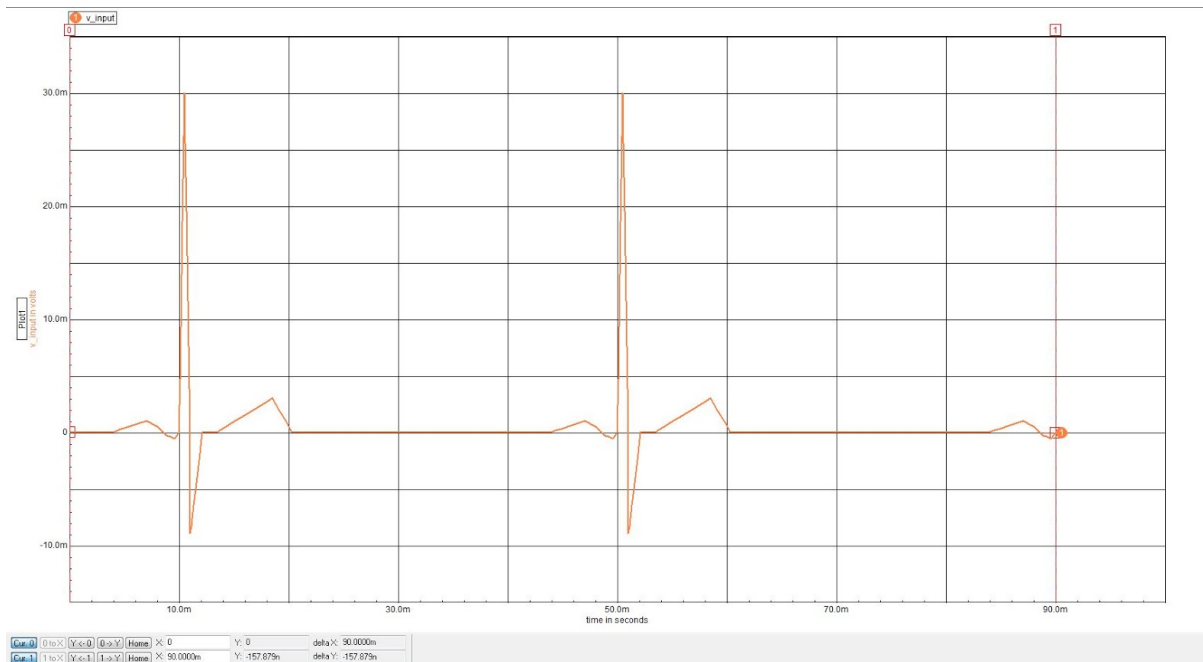
Figure 26 shows the voltage that leaves the body and the input for the ins-amp

Now that the input is giving a difference in voltage, the ins-amp would easily pick up the difference in the signal and do the rest of the operations such as readjusting the gain of the signal as the bio signal is really small, in order of mV. The input as shown above is assumed to contain no noise so even if a filter is attached to the output of the ins-amp, not much effect would be seen. Most likely the gain will change as the filter has some gain, but comparing the waveform that will leave the ins-amp and the filter would be nearly the same. Figure 27, shows the output of the ins-amp with the filter attached to it.
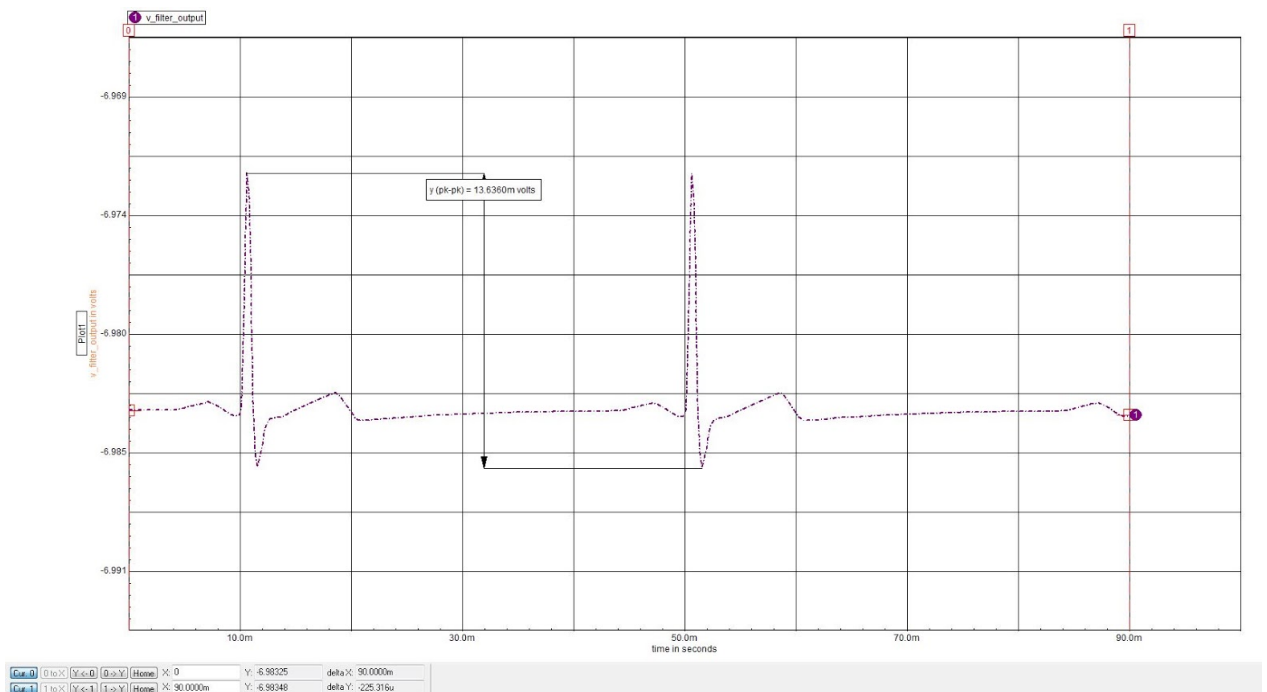
Figure 27 describes the output of the system that comes out of the filter

Since the output of the system is obtained, the output shown above can be subjected to the opto-isolator circuit. The job of linear opto-coupler is to isolate the patient and the whole circuitry operation hence the

25

input and output should be similar should be expected and again the gain would differ. The output is shown in the figure below.
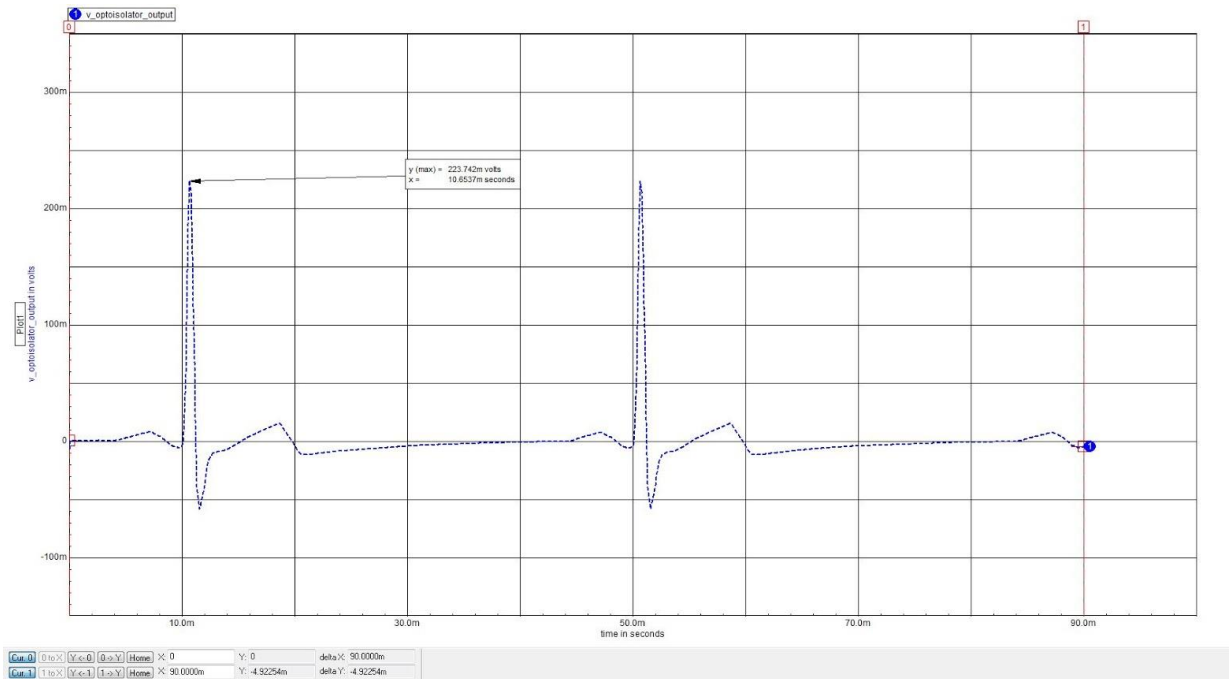
Figure 28 shows the final output of the circuit that would be observed by the physician

If all these waveforms were to be compared, not much differences would be observed as the system would behave like a perfect system which means that there is no intrusion of noise in the waveform. This could be identified from the figure given below.
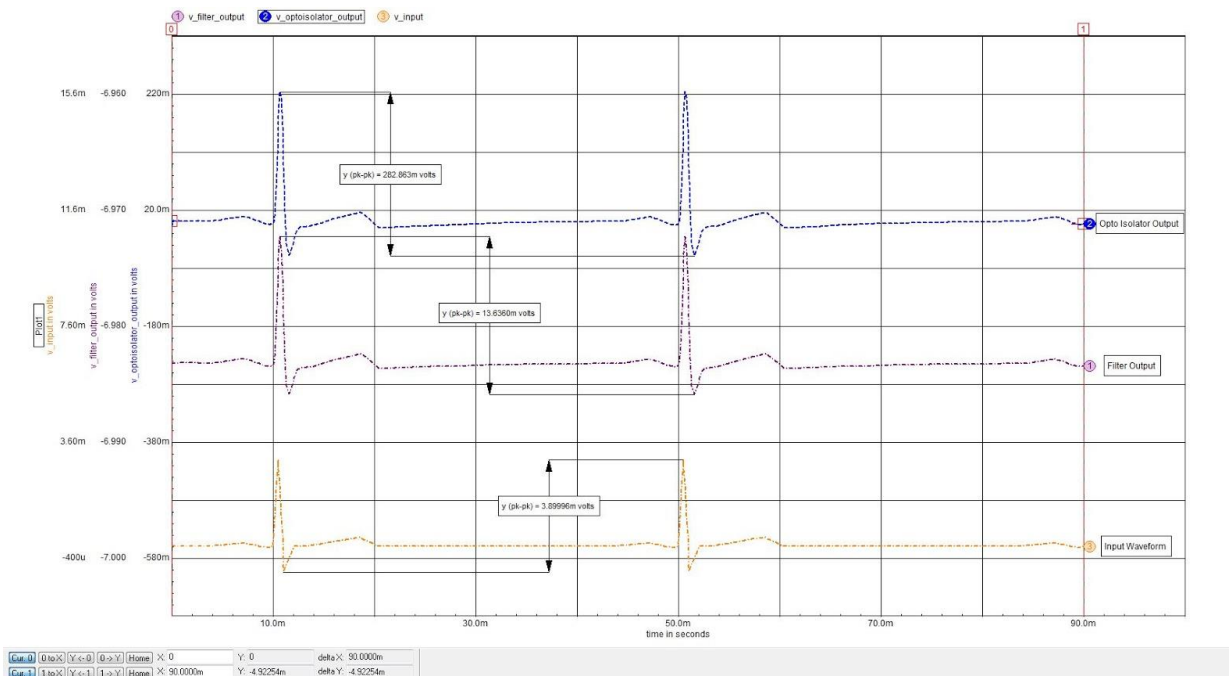
Figure 29 is comparing the different waveforms at once and the key of the graph is on the right hand side

The diagram below shows the complete circuit on the simulation:

26
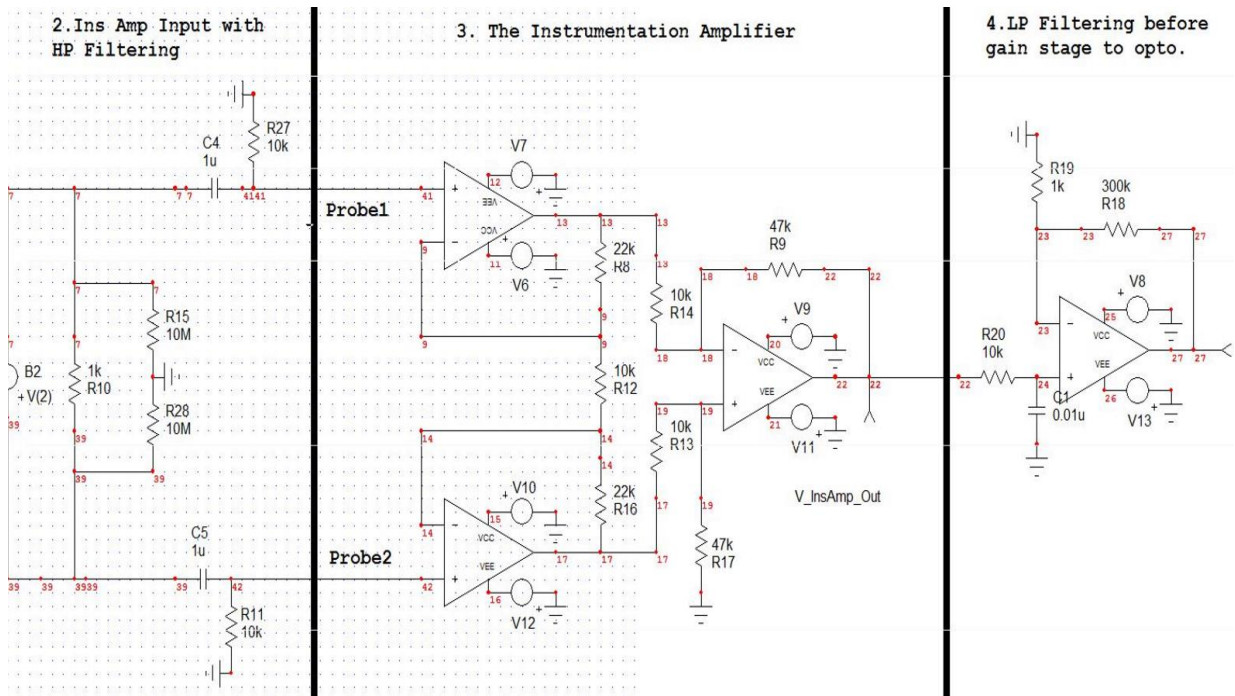
Figure 30 describes the complete circuit with the different parts such as the filters

Also the performance of the filters are tested and is shown in the diagram below:
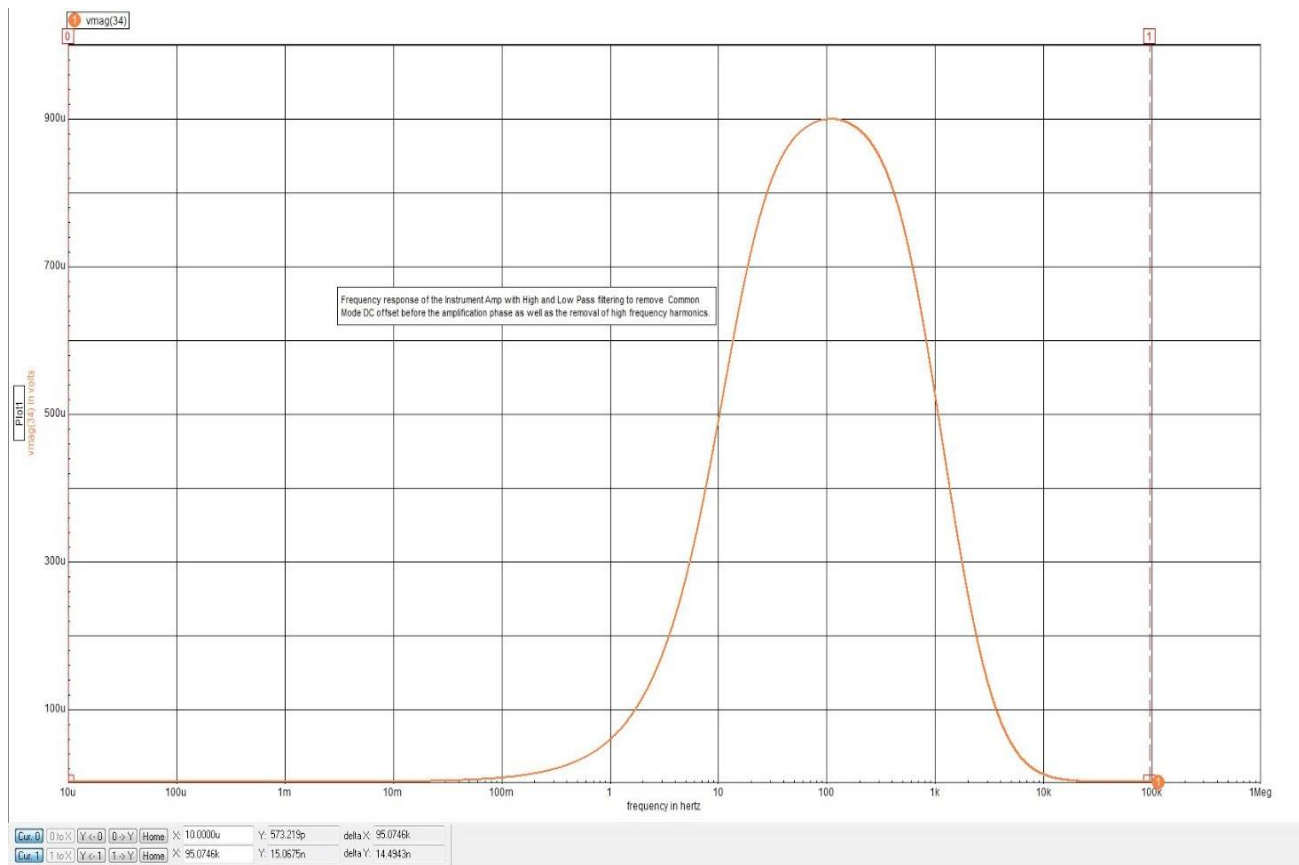
Figure 31 describes the frequency response of the filters

The following diagram shows the isolator diagram used to simulate the waveform:

5.Opto Isolation between the patient and the high voltage output side of the machine.
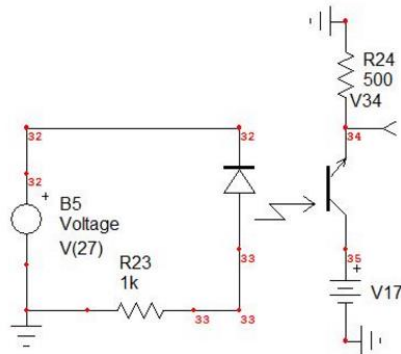
Opto isolator output with capacitor for HPF
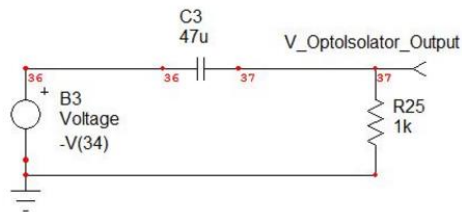
Figure 32 shows the optocoupler circuit with the filter to remove DC offset

In addition, the complete analysis is shown below:
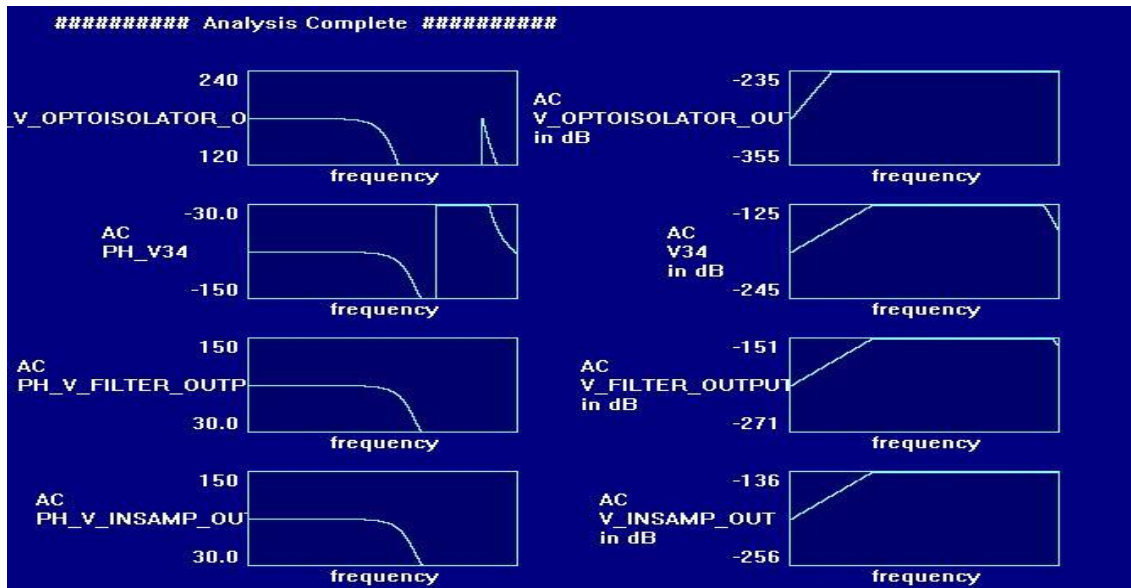
Figure 33 illustrates the complete analysis of the simulations done

5.2 Actual circuit result

Having done all the simulations, the circuit is ready to be built. The graph given in figure 12 would be considered as the reference diagram which would be used to measure the quality of the results acquired.

28

Starting with the 'simple ECG', the primary choice of the op-amp was to use LM358N as it fulfils all the requirements of the circuit. However this op-amp was not available so the other alternative was to use another op-amp which has approximately the same characteristics as the nominated one.

Comparing the LM368N with LM358N, there is not much difference in the concerned properties although there are minor differences but are not significant enough to be worried about. Below is the actual circuit and the result.
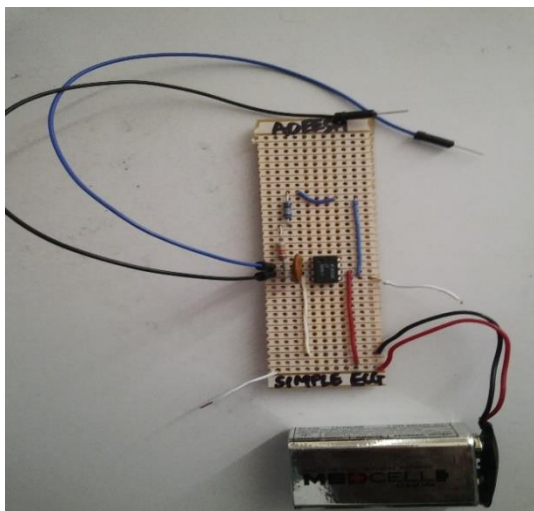
Figure 34 displays the differential amplifier circuit of the simple ECG
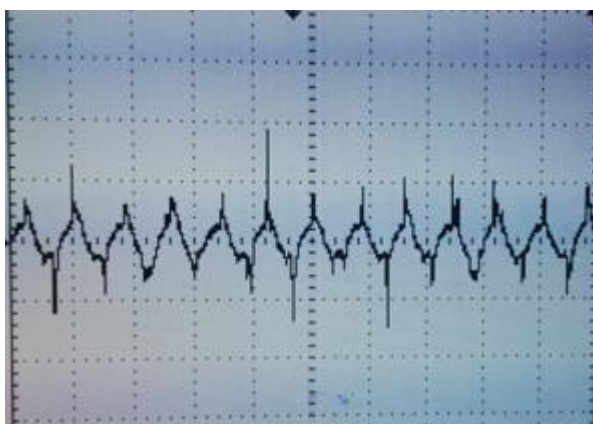
Figure 35 shows the result of the circuit given above

Moving on to Circuit 1, all the components used are identical to diagram given in figure 17. For all the following circuits, a body signal will be used instead of a signal generated by a signal generator. This will give a better insight of the actual signal being taken rather than a 'made' signal. Normally a cardiac simulator is used but in this case there were none. The circuit is shown below:
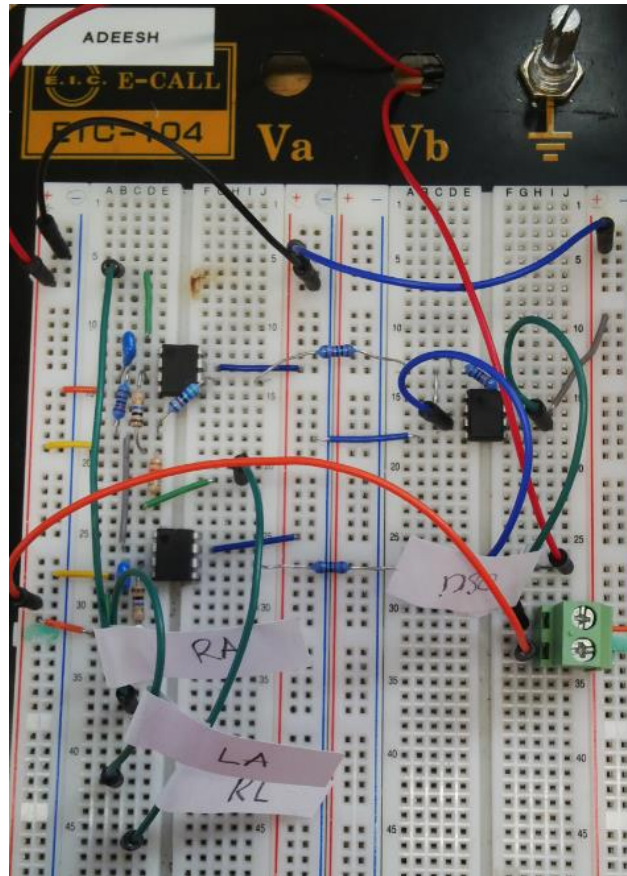
Figure 36 shows Circuit 1 with the instrumentation amplifier in use

From the figure above RA signifies Right Arm, LA means Left Arm whereas RL denotes Right Leg. Using the available ECG electrodes the connections are made to the body to the specific places named above. The next graph displays the result of the circuit (a different oscilloscopes is used to display the graphs to get a better contrast where all the individual point can be identify easily rather than black and white display.)
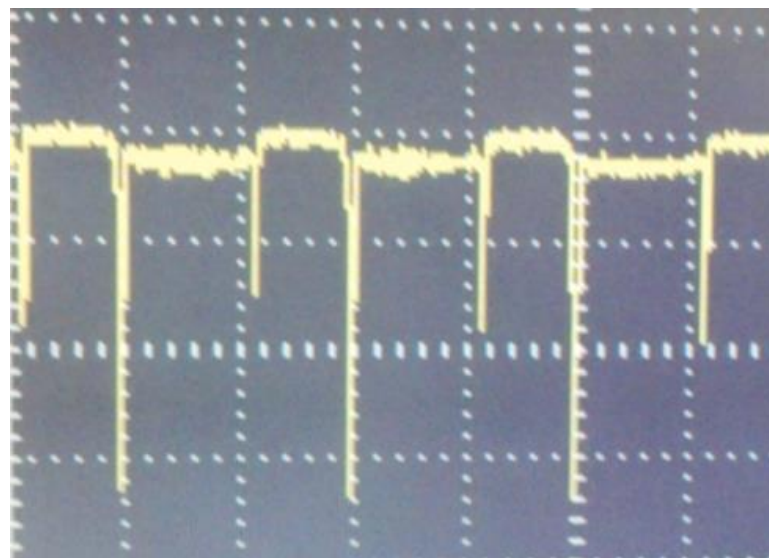
Figure 37 shows the result of Circuit 1 displayed on the oscilloscope

After Circuit 1's completion, Circuit 2 is ready to be built and is shown below.
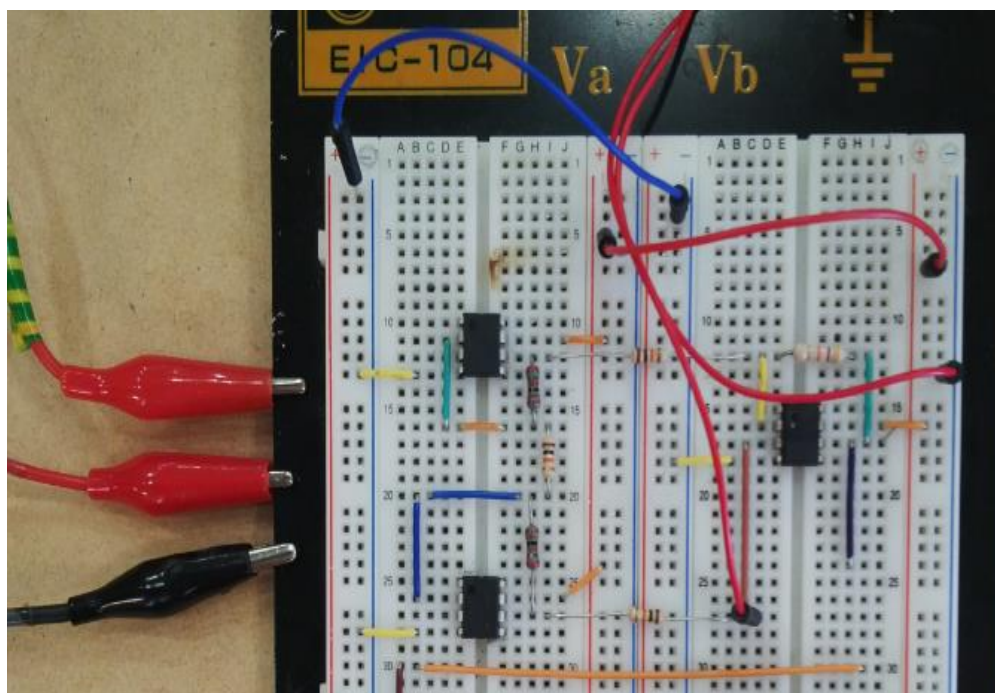
Figure 38 displays Circuit 2 with the different leads

From the left bottom corner, these are the leads that will go onto the body. The green goes to RA, red lead goes to LA whereas black lead also known as the reference lead will on the RL the blue wire on the right, next to the op-amp is the output and is shown in figure 35:

Figure 39 displays the result of Circuit 2 as observed on the digital oscilloscope

The last ins-amp circuit to be implemented is the INA128 op-amp which contains the ins-amp inside the chip and is shown in the diagram below:
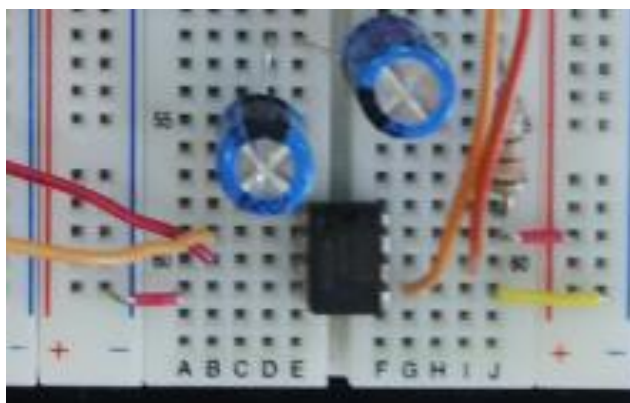
Figure 40 shows the INA128 instrumentation amplifier chip

Starting from left are the inputs of the bio signals. The capacitors and resistor are used to create a high pass filter of 0.5Hz and the orange and red wire on the right go to the digital oscilloscope. Below is the waveform observed on the oscilloscope.
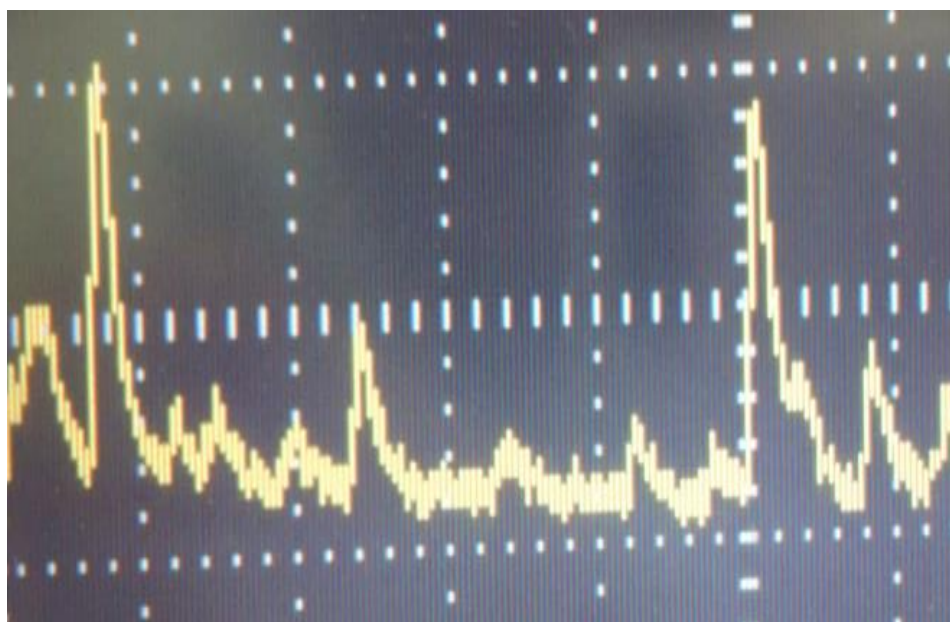
Figure 41 displays the output of the INA128 amplifier

Since these results are noisy, a filter is implemented that has a cut-off frequency of 50HZ. The filtering circuit is shown below:
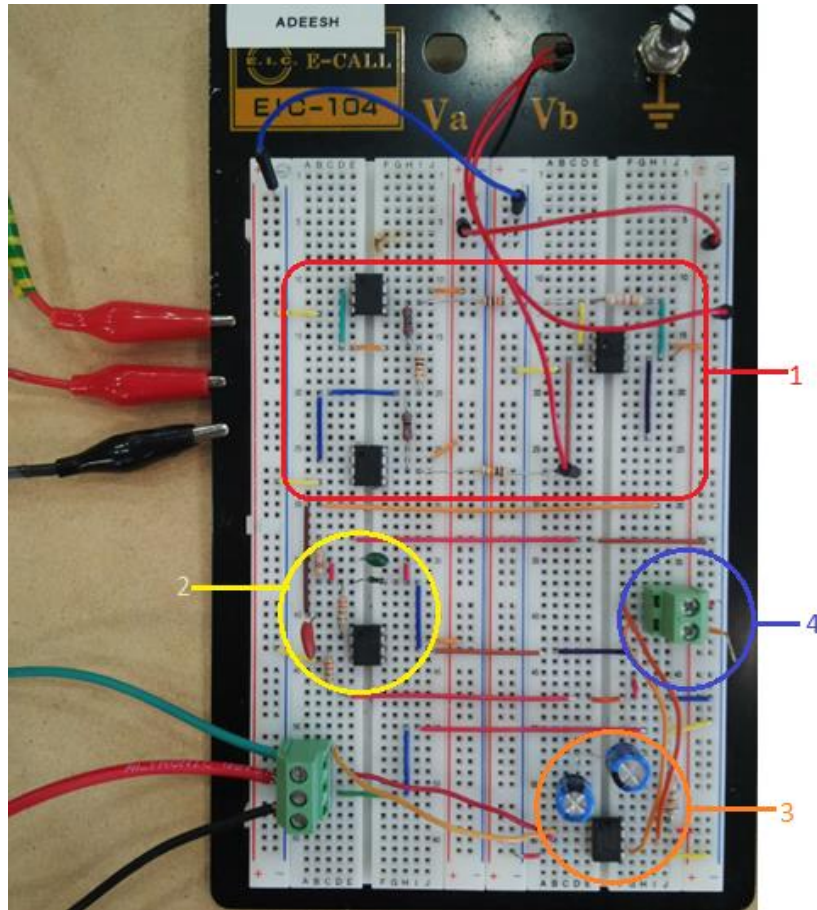
Figure 42 displays the full circuit of the instrumentation amplifier

From the diagram above, the red rectangle dubbed as number 1 illustrates Circuit 2 whereas encircled in orange and numbered 3 is the INA128 circuit with the 0.5Hz high pass filter. Also the yellow circle which is called 2 is the low pass filter. Both Circuit 2 and 3 share the filter depending on which one is in use and can be done by simply changing the wire which results from the ins-amp. Below are the result after filtering has been done (the data could not be captured since the oscilloscope uses a different memory card that the usual one, which was not available):

Figure 43 displays the three op-amps configuration filtered signal

Figure 44 illustrates the INA128 filtered signal

The ECG circuits are completed hence a safety circuit needs to be implemented. One particular design is the opto-coupler circuit since it has just been published in one of the famous engineering catalogue. The isolator should be able to show the linearity between the input and the output, however it does not and will be discussed later. A sine wave of about 100HZ (about the same frequency that a bio-signal will be) is served as the input of the opto-isolator circuit. The figure below shows to build photo isolator circuit.
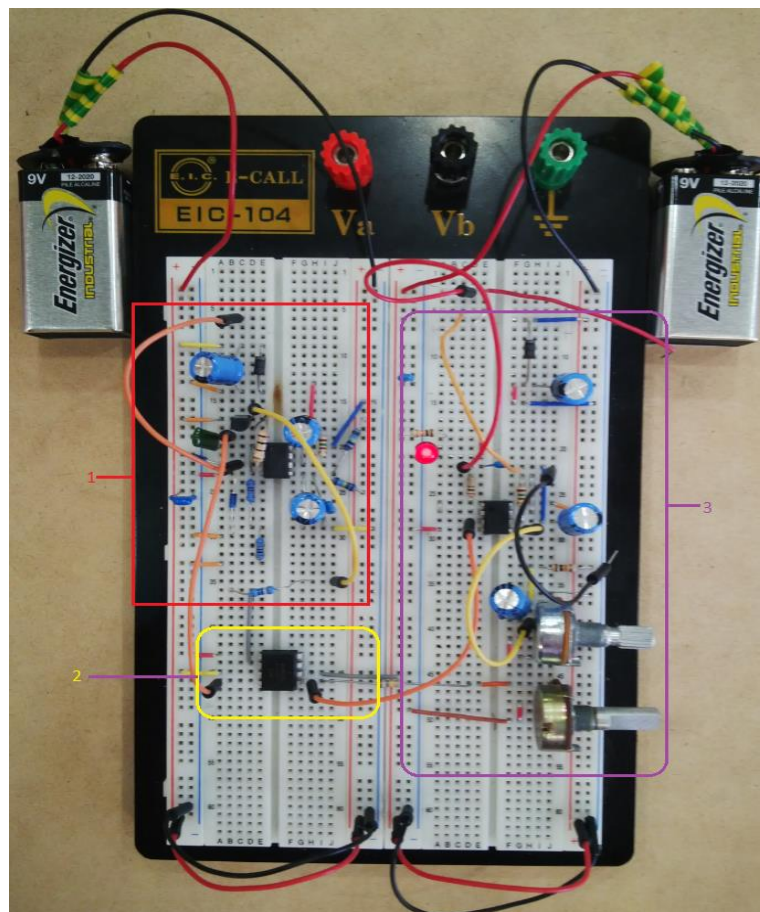
Figure 45 demonstrates the circuit which will act as a safety barrier

From figure 41 the red rectangle numbered 1 is the input amplifier circuitry, number 2 illustrates the opto-coupler whereas the rectangle in purple in the right side which is numbered 3 shows the output op-amp circuitry. The output of the system is taken from the red and orange wire on the right top and the result is shown below:
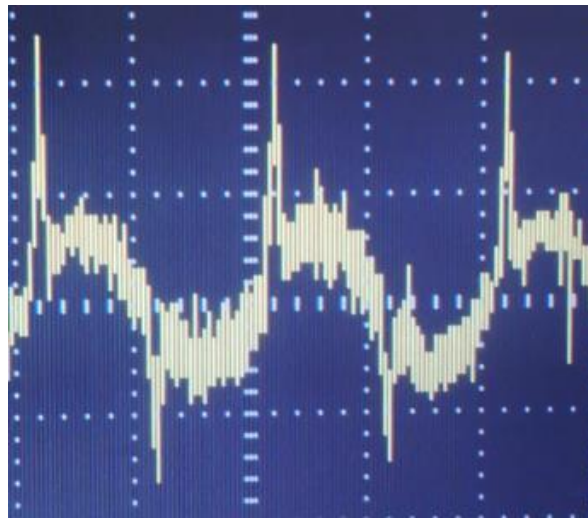
Figure 46 shows the output of the optocoupler

Lastly is the EKG sensor acquired from Vernier Technology. It should be noted that the final signal is acquired through LabView. The diagram below shows the LabView program developed to acquire the signal.
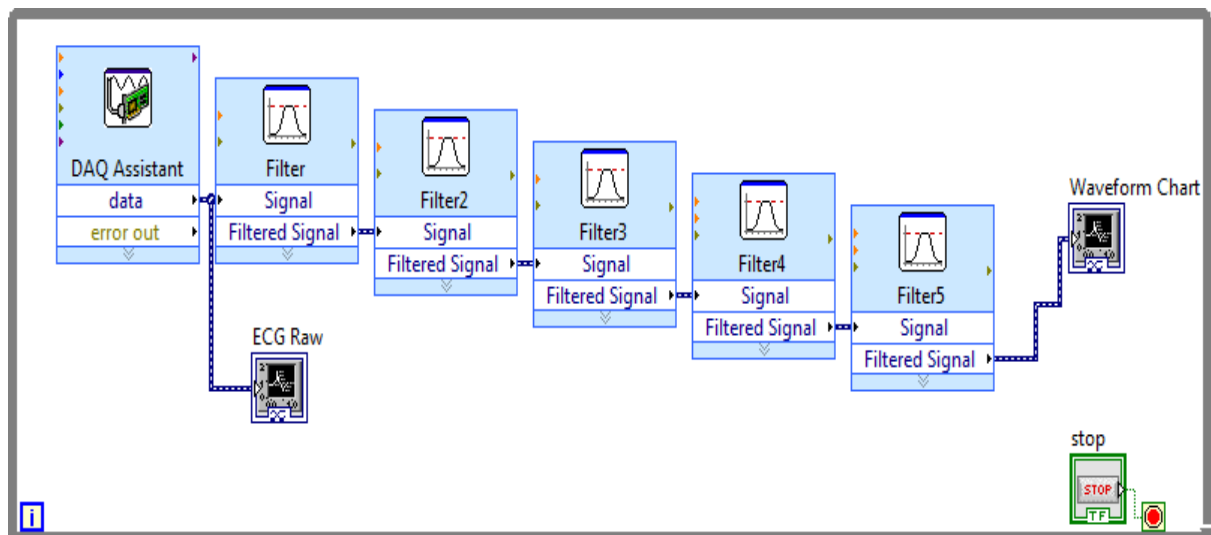
Figure 47 display the LabView program that has been developed to acquire data from the sensor

Once this device is detected and recognised as an external LabView DAQ card, operations such as communicating with the card can be executed. The DAQ Assistant block is used to collect the data collected by the sensor. Once this block is selected, a window will open asking for more information on the DAQ card for example which input is to be used, what kind of signal is being acquired and so on. After this is setup, the other actions such as filtering can be performed. Note that many filters are used to get a smooth reading. The figure 43 below, show the results:
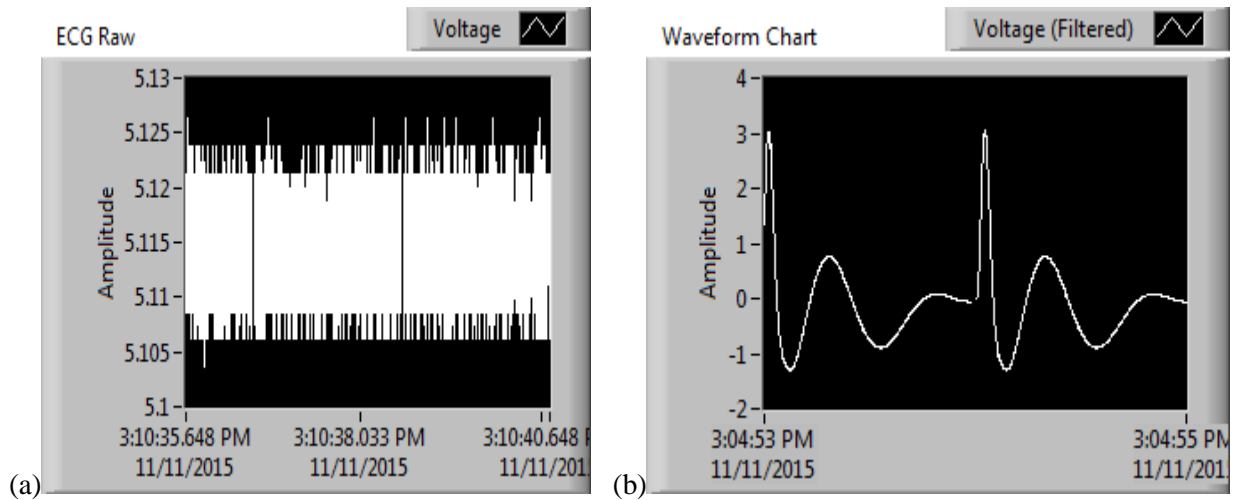
Figure 48(a) shows the raw ECG signal compared to (b) which is the filtered signal

Another objective was to verify whether an ECG circuit can be used as an EMG circuit. The figure below shows the tested EMG signal, where both leads connected to the muscle belly, about 5cm apart and the reference lead would be sticked on a nonconductive part such as a bone. So suppose an EMG of the bicep muscle is taken, then the two leads are fixed on the bicep belly (equally apart from the middle of the muscle) and the reference sensor is fixed on the joint of the elbow. The figure below shows the response observed:
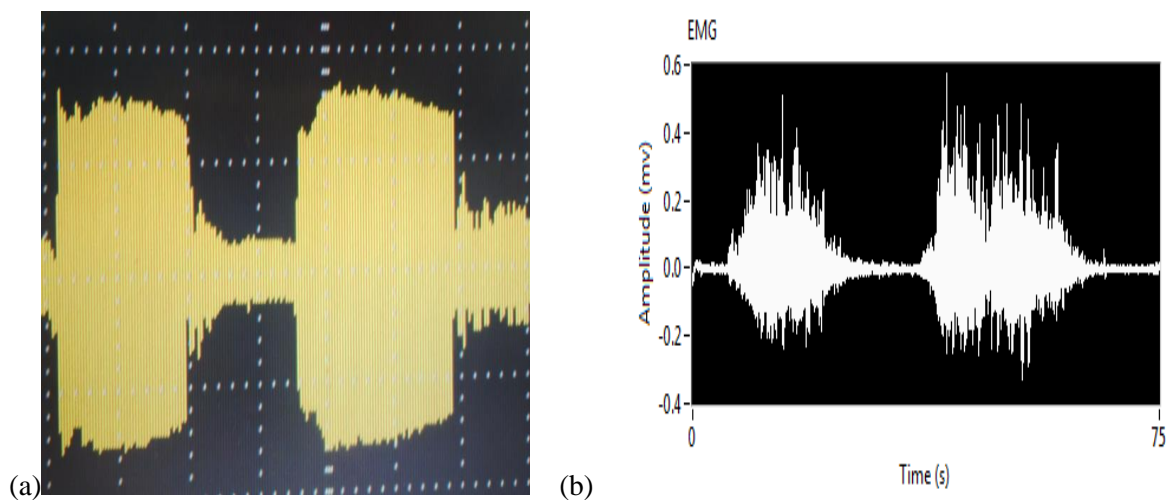
Figure 49(a) shows the EMG recorded by the oscilloscope using the INA128 op-amp whereas (b) shows the EMG recorded by the EKG sensor

Some precautions that need to be taken during the construction of the circuit are:

- Wearing an electrostatic band to prevent any building of charge as the amplifiers are quite sensitive and might get damaged,
- The amplifiers are really soft devices so being harsh on them would damage the IC for instance the pins of the amplifier,
- A multimeter that can measure true RMS is used,
- The testing should be done in a remote area where there is not much electrical equipment in the surrounding to avoid the mixing of noise induction.

5.3 Analysis of the result

This section will discuss the result whether they were expected or if not, what were the measures taken.

5.3.1 The Simple ECG circuit

Consider the first circuit also known as the 'simple ECG' circuit. What the physicians normally look at is the P, Q, R, S, T complex, which enables them to understand the heart activity. The result given below is good such that some segments of the graph tally with the referenced one (figure 12). However it can also be observed that the other segments are barely visible, for instance the P interval. The diagram below shows a section of the graph taken and analysed.
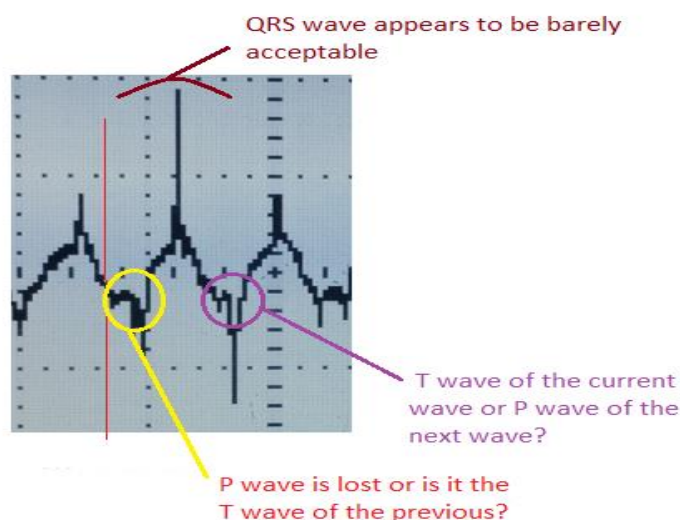
Figure 50 shows the analysed waveform of the simple ECG circuit

From the figure above, it is a bit confusing as there seems to be an overlap of waveforms as shown in the figure. Some of the reasons that might have caused this distortions are:

- The amplifier is an all-purpose one so its usage might not be appropriate as it can be used everywhere but not good for a particular measurement.
- A differential amplifier might not be the best configuration when dealing with signal in millivolts (mV) [17].
- The amount of noise present in the waveform is enormous so some of the intervals must have been lost. Noises is mixed with the original signal by different means such as the contraction of other muscles like the palmaris longus (arm muscle) since the electrodes are placed on the arms [12]. Regarding noise, there are other means of transferring the latter such as fluctuation of the power coming from the source which is the power supply.
- The uncertainty values of the components such as resistors' value might have caused a small disturbance in the reading.

5.3.2 Analysis of Circuit 2's result

As mentioned before, the three leads circuit was taken from an existing design and was modified as desired. Obviously to check the performance of a circuit, it should be analyse, built and then compare the result with the result that is meaningful. If the result does not matched the referenced result or differs from the other results, this means that something is wrong probably with the circuit or the way the readings were taken. The diagram below show an analysis of this particular circuit.

Figure 51 illustrates the identifiable waveform from circuit 2's result

From the figure above, the result seems to be meaningless. It appears to be only noise in the system and no actual ECG signal really. This might be caused by:

- The configuration of the circuit. It is unnoticed that this circuit attempts to use an ins-amp configuration, however there is no feedback resistor at the inverting node in the second op-amp (highlighted by the blue rectangle). Also normally the resistor R7 is equal to resistor R9 but in this circuit it does not. Technically this does not classify the circuit as an ins-amp.
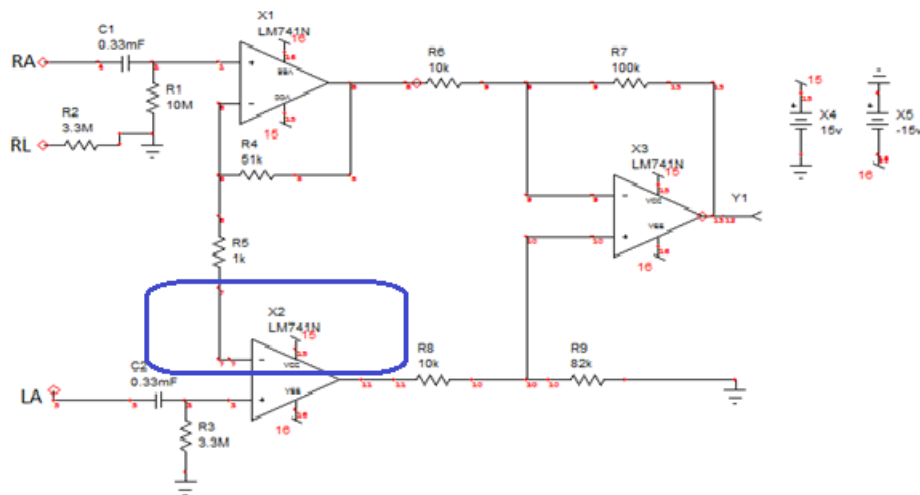
Figure 52 gives a hint where there is no resistor associated to form the classic instrumentation amplifier

- So an attempt was made to make this resemble an ins-amp by inserting a 51KΩ resistor to the missing link and the result is given below:
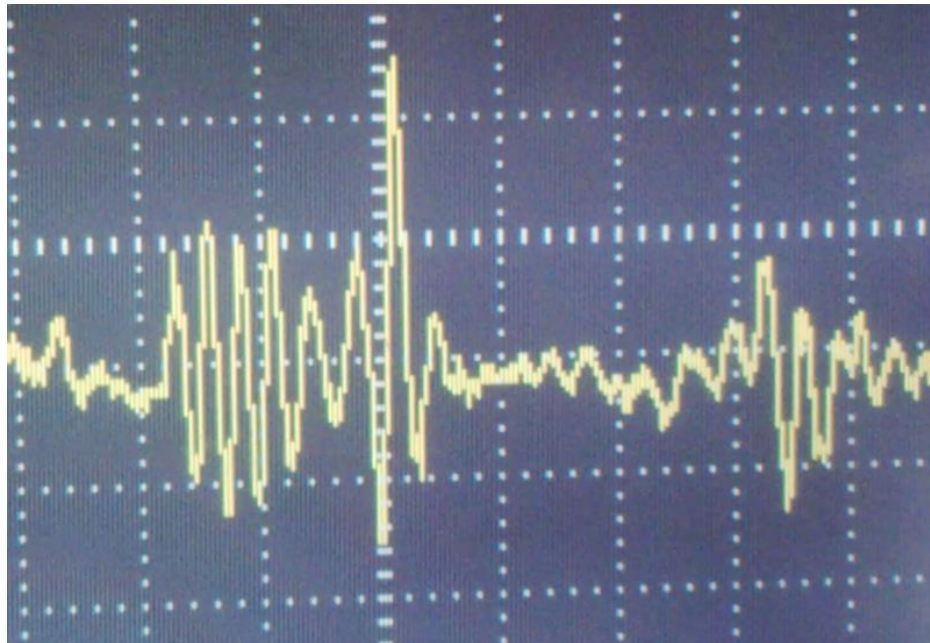
Figure 53 shows the result of the modified circuit by the addition of an extra resistor

The rectified version seems to be more meaningful compared to the previous one. However there are still some issues, even troubleshooting is hard to find hence it would a waste of time if more time would be invested in investigating the cause. So having the basic knowledge an ins-amp, a new circuit was designed.

5.3.3 Analysis of Circuit 3's result

Since this design was taken from a book and modified, this one was bound to give the best of answers [50]. The circuit matches closely the configuration of an ins-amp so at least some part of the waveform should be observed. Furthermore, this circuit has been simulated and the result was equal to the referenced one. This means that the circuit should behave the same if built and the following diagram gives the analysis of the result.
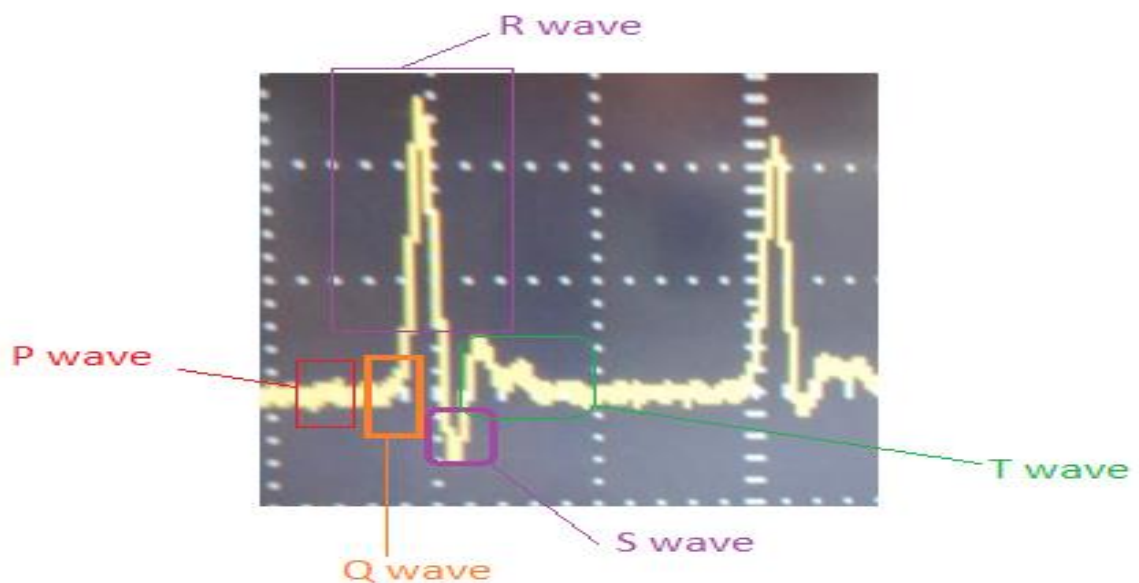
Figure 54 displays the graph obtained and the different segments of the graph is related to the referenced one

This result is much better compared to previous one and as it matches the wavefront of an ECG wave. It can be observed that the signal is noisy, and it should be filtered to get a more defined wave, where all segments can be seen and appreciated.

Using the FFT function provided by the oscilloscope, the noise is found out to be about after 50HZ and a bit of noises can be found around 0.5Hz and below. So two filters are built to combat this such that one high pass, allowing all the frequencies above 0.5Hz to go through and neglecting all frequencies above 50Hz. The result which can be seen in figure 54 is a much cleaner graph that the one in figure 39.

5.3.4 Analysis of INA128's result

Since INA128 is a ready-made ins-amplifier and R_G is calculated to be at the same gain, there is less excuse that this circuit would behave badly. The diagram below shows an analysis of the waveform:
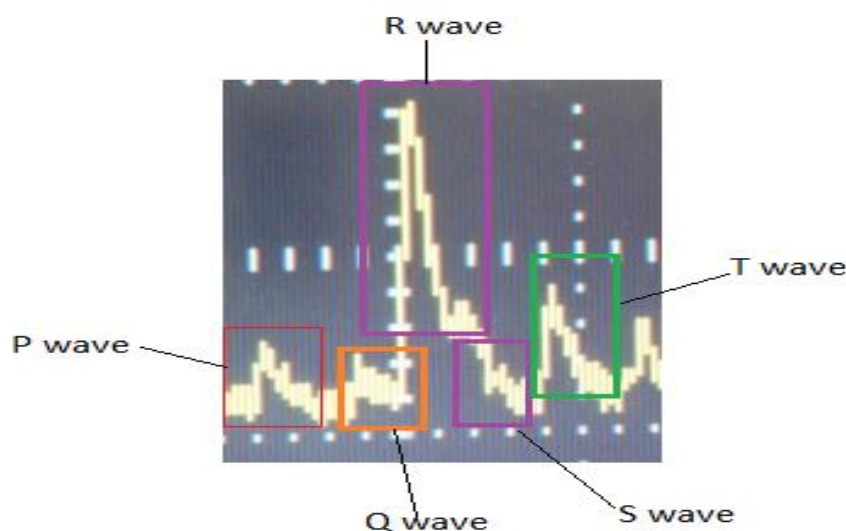
Figure 55 shows the identifiable wave segment from the result of INA128

The important waves can easily be identified when the figure is compared to the referenced one. It should also be appreciated that an op-amp of the size of other 8 pins amplifiers like LM741, is capable of processing such important information. INA128 is a very sophisticated op-amp such as it has many features which would be needed to get an accurate value like low offset. This is probably why not much of an effect can be seen from the filtered signal given in figure 40. Overall if figure 41 was to be compared with 39, not much difference would be spotted except that the LM741 configuration contains a lot of noise hence filtering them gives a much smooth, well-defined graph whereas with INA128, the response is already clean and filtering does not affect it that much. So here there is no primary choice of which system to be used, as the total cost of both the circuits would be more or less the same.

5.3.5 Analysis of optocoupler's result

This optocoupler is meant to replicate its input as an output as its job is just to isolate the circuit. However during testing the circuit alone when a sine wave from the signal generator is fed to the input, a noisy waveform is observed. This creates the doubt that something is not functioning as it should be. To verify where the problem is, a point to point analysis is done. Starting from the input circuitry the signal is checked at the op-amp IC1a. If a sine wave is the input, a sine wave should also be the output which in this case it was. The diagram below shows the response of IC1a:
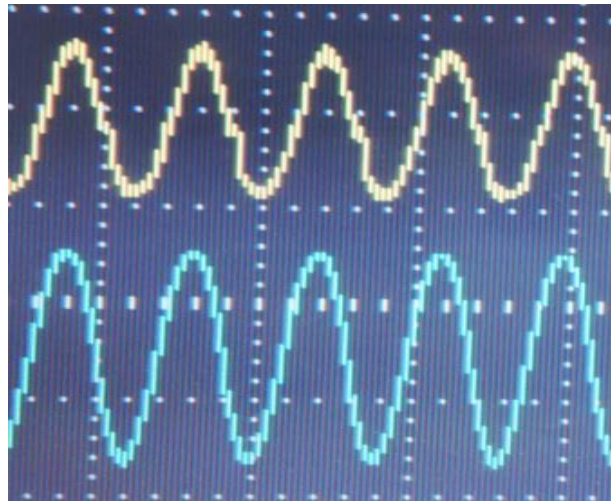
Figure 56 describes the input (blue) and the output (yellow) of IC1a

The input is shown in blue compared to the output shown in yellow. As long as there was something, the circuit was termed as acceptable.

Same procedure was done to the output and the result is shown below:
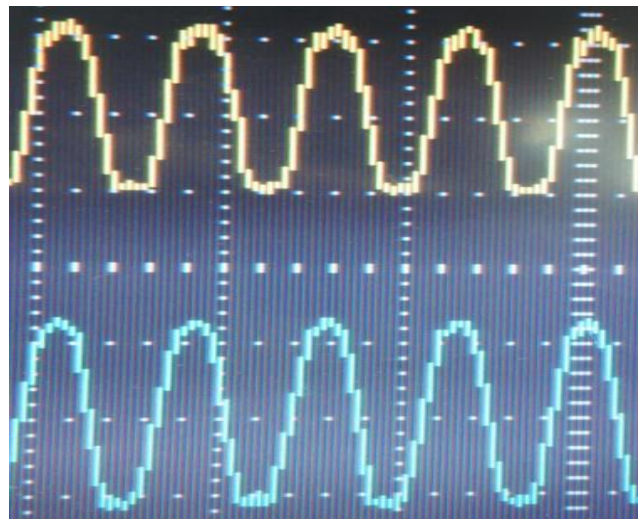
Figure 57 shows the input (blue) and the output (yellow) of op-amp IC2a

This result was satisfactory as both of the graphs are nearly the same.

However when it comes to the optocoupler circuit, that's where there is a problem. So to diagnose the circuit, a sine wave is generated by a function generator and is used to test the circuit. The amplitude is kept in the range of about 30mV which is a fair approximation of the body signal. To start with, the signal is fed to the input of the optoisolator and a point to point analysis is made. The diagnostic test is divided into three parts namely IC1a, optocoupler and IC2a.

 Measuring the input and the output of IC1a, there is a sine wave coming through the emitter of the transistor which is good. This means that till the transistor the circuit is still working fine. When the signal reaches the optocoupler, the latter does not react to it which it should. This then creates the doubt that something might be wrong with this part of the circuit. In fact, it cannot be concluded that the optocoupler chip is gone till the complete process of testing is not completed. To complete the test, the signal generated by the function generator is fed directly to the input of circuit IC2a, bypassing the optocoupler's circuit. Then the problem comes down to the optocoupler chip. The chip contains an LED internally which vary its intensity accordingly to the input. This explains the execution of its linear performance. To check if the suspected chip is really faulty, it is replaced with an external, general purpose LED. Surprisingly the

41

external LED does behave correctly such that its intensity changes according to the sine wave. This confirmed that there is a problem with the optocoupler.

In addition, during the testing phase there was a doubt that the breadboard is faulty since at different times, different readings was obtained raising the question whether everything is connected correctly. So components such as resistors were moved around and this might have been the period where a wrong resistor was in the wrong place, connected to the optocoupler. There is a high probability that there was an excess of current flow which resulted in the damage to the opto isolator chip. During ordering the chip, there was only one in store so only one was bought. This optocoupler chip is not used in many circuits hence its availability is a bit rare and if a new chip was to be ordered, it takes about 4-5 business days to reach as shipping was done from the main warehouse. The time delay was a bit of an issue as this part of the circuit was done in the last week of the project. This was the disappointing bit of the project, nevertheless if there was a bit more time to order the optocoupler, which might solve the problem.

5.3.6 The EKG sensor result analysis

If figure 43(a) was to be analysed, one would say that this is only noise. The raw signal is so noisy that it is impossible to find the expected reading. For noise reduction, different types of filters have been used. The objective of course is to obtain a clean signal so other parameters such as how many filters are being used is ignored.

Also different types of filters were used such as Bessel's or Butterworth and different filters give different performances. Much like controllers in a control system tuning a controller could be done by using different tuning rules, for instance one company can use Cohen-Coon, while others may choose to use Ziegler-Nichols, depending on the type of response they want. Here also it is the same concept about the different filters [73]. In fact this is good as it gives the user the experience of how different filters acts on a system which would create a greater understanding about filters and signal conditioning. An analysis of the ECG is showed on the graph below:
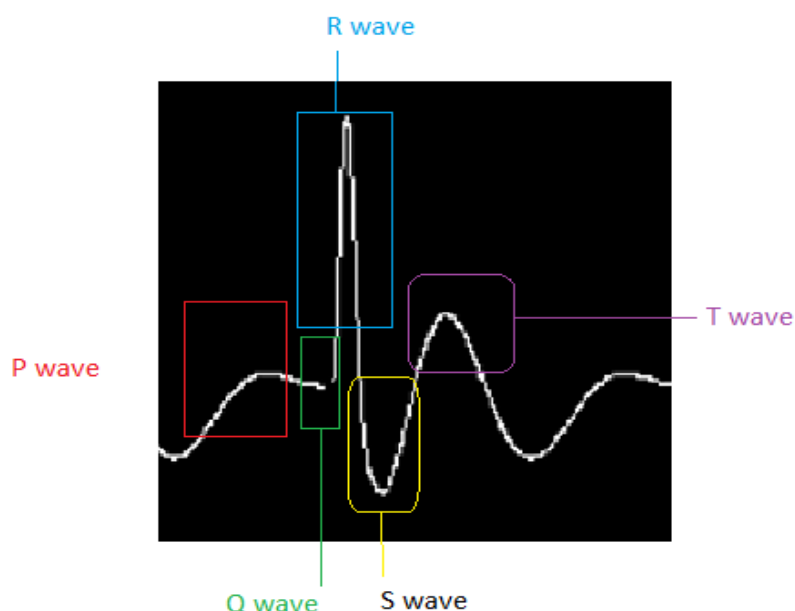

Figure 58 shows the identified sections of the ECG from the EKG sensor

If the result given above is compared to the result of Circuit 2 and 3 (figure 54 and 55 respectively), less differences can be spotted which might be because of the different characteristic. This means that the circuits designed are working as they should as the results match each other.

Comparing the result of Circuit 2, Circuit 3 and the EKG sensor, more or less they all look alike which points towards the success of this project. Obviously there are some differences such as gain or time factor but overall the all have the same waveform structure. The results of all the graphs cannot be displayed on the same screen as the gain of the system is not the same hence the amplitude of the graph would not be similar. Additionally the EKG sensor's graph can only be display on the PC since it is powered by a USB cable. Hence the best way to compare the result is to check visually.

Regarding the EMG, INA128 op-amp was chosen as it does not really need a filter due to its properties as an EMG is expected to be a noisy signal. On the other hand filters had to be in place as the EKG sensor would give a very noisy signal. Notice that the EKG sensor is using 5 filters so the output is expected to be really smooth compared to the INA128 circuit which is using only 2. The analysis would be performed on the EKG sensor as a much clearer picture is detected.
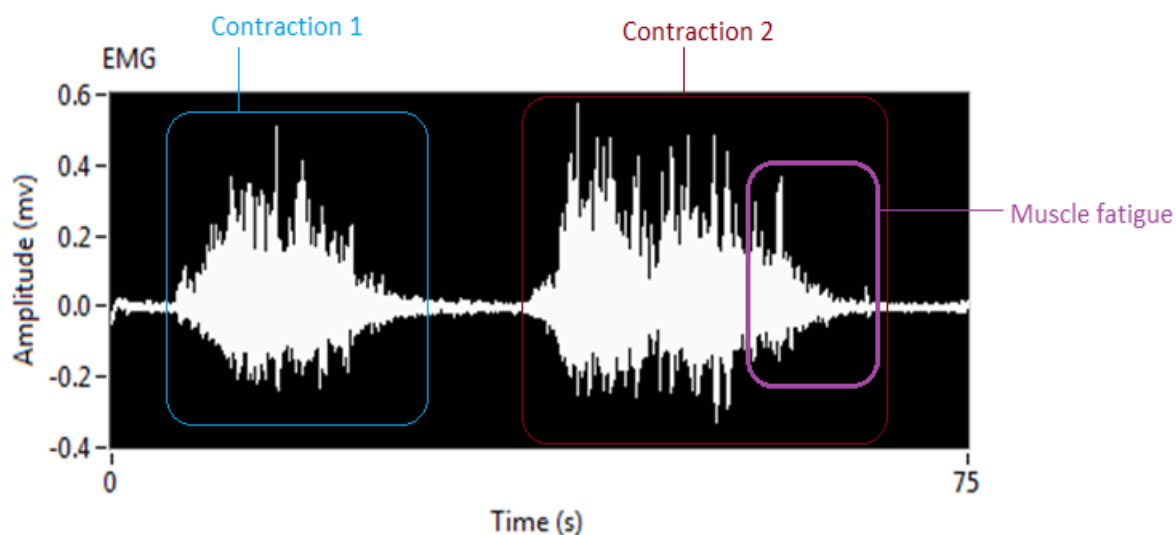
Figure 59 describes when the bicep is contracted and when relaxed

Figure 54 shows the contraction and relaxation of the bicep. When a straight line is observed, the muscle fibres are relaxing whereas during a contraction the signal grows in magnitude and can be observed from above, named contraction 1 and contraction 2. There is another phenomena called muscle fatigue which occurs when the muscle is tired but still manages to contract but not for long. More spikes means the more the muscle is electrically active. Muscle fatigue is caused when all the energy are being depleted and there is an increase in waste collection in the muscle. So the brain starts to stop the functioning of the muscle and allow exchange of material [65]. What is missing with the sensor is a hand dynamometer that will measure the amount of force the muscle will produce, and unfortunately it is not economical to purchase. Using simulation tools, the force and the response of an EMG of other muscles can be explained.

6.0 EMG Modelling
In this part of the project, some modelling will be done for different system and the result will be explained.

6.1 Skeletal modelling
As described before, skeletal muscle are the muscles that are attached to the body. Muscles can only be pulled and cannot be pushed. This would be a problem if a joint is controlled by just one muscle. As soon as the muscle contracts and it pulls the bone. Following this, there is no way to move the bone back again. The problem is solved by having muscles in pairs, called antagonistic muscles. A good example is biceps and triceps. The mechanism behind the working of the latter is that as one contracts, the other relaxes and

vice-versa [66]. A common example can be seen in the gym, where a muscle builder exercises their forearm. The elbow joint lets the forearm move up or down. It is controlled by two muscles, the biceps on the front of the upper arm, and the triceps on the back of the upper arm. The biceps and the triceps are antagonistic muscles.

- When the biceps muscle contracts, the forearm moves up
- When the triceps muscle contracts, the forearm moves down.

This solves the problem. To lift the forearm, the biceps contracts and the triceps relaxes. To lower the forearm again, the triceps contracts and the biceps relaxes. It can also be found in other parts of the body such as in the legs. The figure below illustrates the theory explained above.

[67]
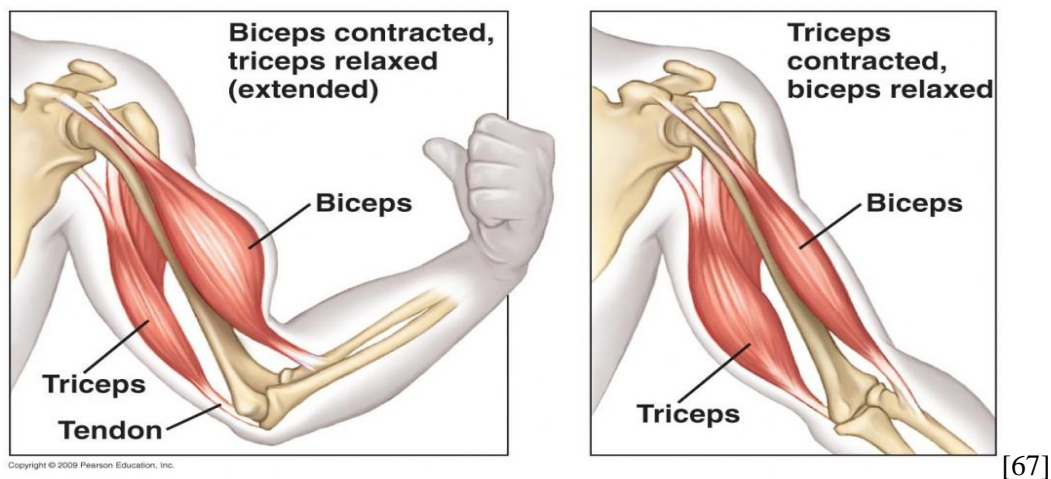
Figure 60 shows the different muscle actions for different postures

6.1.1 Modelling of Antagonistic Muscle – Skeletal Muscle

While modelling this mechanism, it should be highlighted that the model should feature the two muscles such that as one contracts, the other relaxes. It should be also noted that this report is more concerned about how the muscle works in a dynamic state. Quite a few model equations from the Internet were found, however they were too complex to implement in Matlab/Simulink, whereby most of the models were plotted and examined in some other special programs. Therefore based on the results, other techniques may be used to acquire the same or nearly the same result. One of the method used to model this is using harmonics of sine wave up to 11th cycles and each term is divided with their respective harmonics number. Obviously as this part is concerned with antagonistic muscles, two sets of data would be required to demonstrate the workings of the muscles (for example, weight lifting). Since the actions of the muscles are known (opposite response), the method of trial and error is used by approximating the force. This part of the project is devoted to modelling so the answer is not expected to be exact. (The equations would be in the appendix)
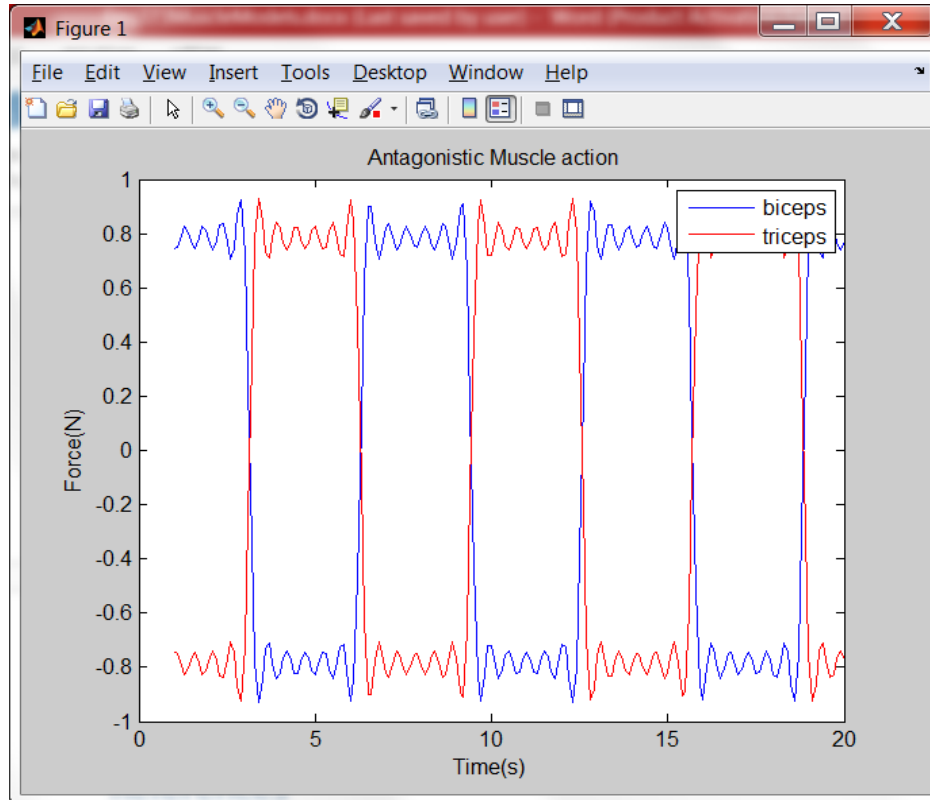
Figure 61 shows how the an antagonist pair of muscle would react during weight lifting

In the figure above, notice the spikes that each of the graphs offer. This is known as Gibb's phenomena and this is due to muscle twitching and depending on the muscle type, twitching can be fast or slow as explained in the introduction. Since this is an antagonistic pair, for instance the bicep and triceps, it can as one of them contracts, the other relaxes.

6.1.2 Muscle Fatigue

As mentioned in while taking the EMG of the muscle that a hand dynamometer was not available, modelling can do just that, that is producing a graph that can explain how the muscle will react if muscle fatigue is experienced. Mostly skeletal muscles are the ones to experience fatigue as they can contract vigorously while the other muscle types do take their time. Figure 57 shows the muscle fatigue:

Figure 62 describes the muscle action with fatigue

45

If the graph was to be analysed, at the start there is a rise in force which means that the muscle is contracting. As time passes, the value is still high, implying that there is still contraction until the highlighted part in red where the action starts to calm, nearly giving a straight line. This looks realistic as the muscle will be tired after a good, long contraction.

6.2 Smooth muscle modelling

An EMG of smooth muscles are really difficult as they are present in organs which is internal of the body. So modelling them is the best as the basic knowledge of how smooth muscles react is known. In this section, there will be an analysis of the airway system of the body. The figure below shows the path air takes to finally reach the lungs.

[68]
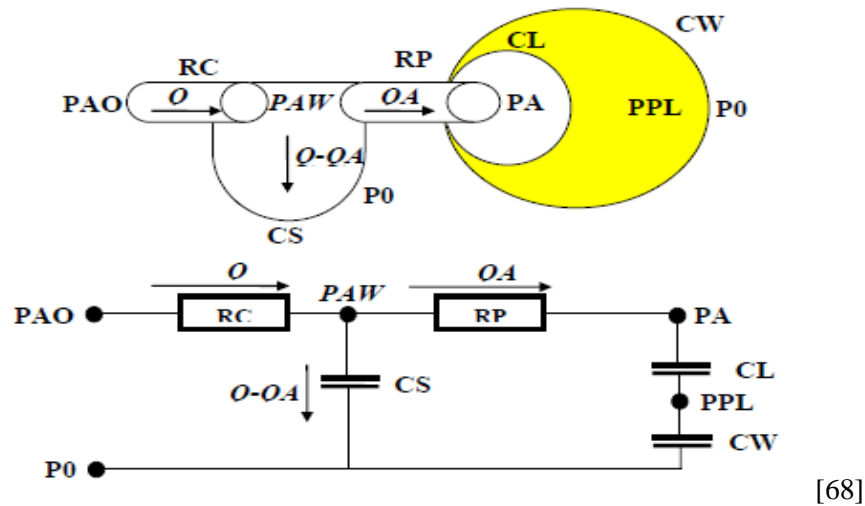
Figure 63 describes how air from the atmosphere reaches the lungs

The lungs are associated to the ventilator of a simulated pulmonary ventilation, which blows air intermittently in the lungs, with pressure *PAO*. *P0* is the pressure of surrounding atmosphere. The air flow *Q* flows through the upper respiratory tract which has a resistance of RC. From the higher respiratory tract, air fights through the lower respiratory tract into the in lungs, more precisely in the alveoli. The lower respiratory tract resistance can be described as *RP*, the pressure in middle part of the respiratory zone is named *PAW*, and alveoli pressure is *PA* [69]. The air inflates alveoli which is elastic in nature and the elasticity is *CL*. The interpleural cavity is the thin layer that is found between the lungs and the chest and the pressure in the chest can be described as *PPL*. Normally as the volume of the lungs increases, the volume of the chest must expand hence the chest elasticity is *CW*. A minor portion of air, which is not able to make it to the alveoli, only expands the respiratory tract resulting in the creation of the expansion of the respiratory tract with its elasticity is *CS* [69]. (See appendix for analysis of the electrical circuit). The diagram below shows the response of the system.
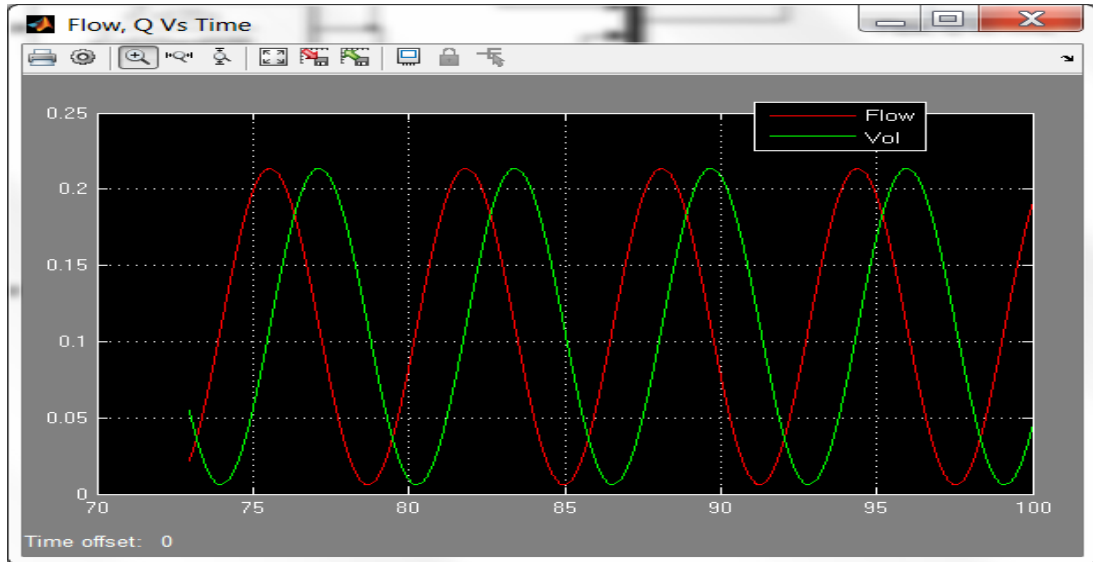
Figure 64 shows the volume of the lungs (green) and the flow of air in and out of the lungs (red)

If the pressure gradient is less in the lungs, then air flows through to fill it up and to main a levelled gradient. In red is the volume of air that flows to the body as the pressure in the lungs drops (green). Once filled the pressure of the air drops which creates an imbalance in pressure gradient again hence the lungs pressure drops and the cycle continues.

6.3 Cardiac muscle modelling

The heart produces its own electrical signal so it the heart is taken out of the body, it will be able to live for few minutes. But it is hard to take an ECG as needles needs to be inserted (rather than electrodes stuck on the heart) which might puncture the heart chambers. Again in these cases, modelling is the best way to understand how the muscles of the heart contracts to give a constant rhythm.

The heart beat rhythm is an involuntary action that normally occurs once per second. Modelling of cardiac muscles is often difficult, because not many models are available. All the obtainable models are for the rhythm rather than the muscle models. In this case as the cardiac rhythm is known, which is the PQRST state, model of the functioning muscles can be derived. This part of the report depends on the PQRST state of art. Bearing the knowledge of the latter tells that there should be at least two muscles in general, that is one for the atrium and the other for the ventricle. Again this is where the uniqueness of modelling plays a role whereby all kinds of ideas can be used to form the model which in this case is the use of transfer function and constants to make the lowest reading at zero mark. The diagram below shows the Simulink model result (see appendix for equations). The result is shown:
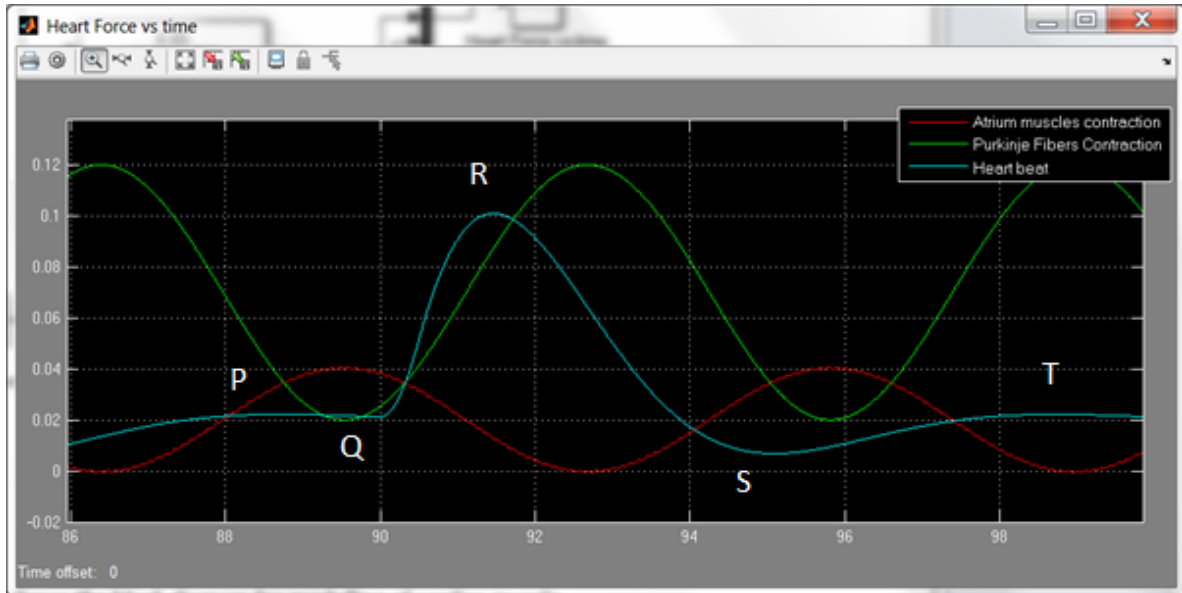
Figure 65 displays the muscle that acts on the behalf of the heart to produce a heartbeat

As P the atrium depolarises hence it contracts and this can be demonstrated by the red line. At Q, the atrium relax hence the force also goes down. At stage R, there is depolarisation of the ventricle hence the latter pushes blood out of the heart. This means that the force of the ventricles should contract to abbey this action which they does (green line). At S, as the ventricles relax, the force also goes down. At stage T, the force of the ventricle should remain down as it is on repolarisation state, however it does not do that as it was hard to implement this change in the simulation. It should be noted that the amplitude of the atrium and ventricle forces are not the same because the ventricles are more powerful since they have to gush the blood all around the body hence a greater force is needed. The only problem with this diagram is that for the cardiac rhythm, the PQ wave could not be properly done as it is difficult to disturb the graph and if done, it mess up the whole graph.

If all the graph shown in figure 61 were to add up and give a single waveform, it should reflect a normal heart beat. This can be seen in the next figure.
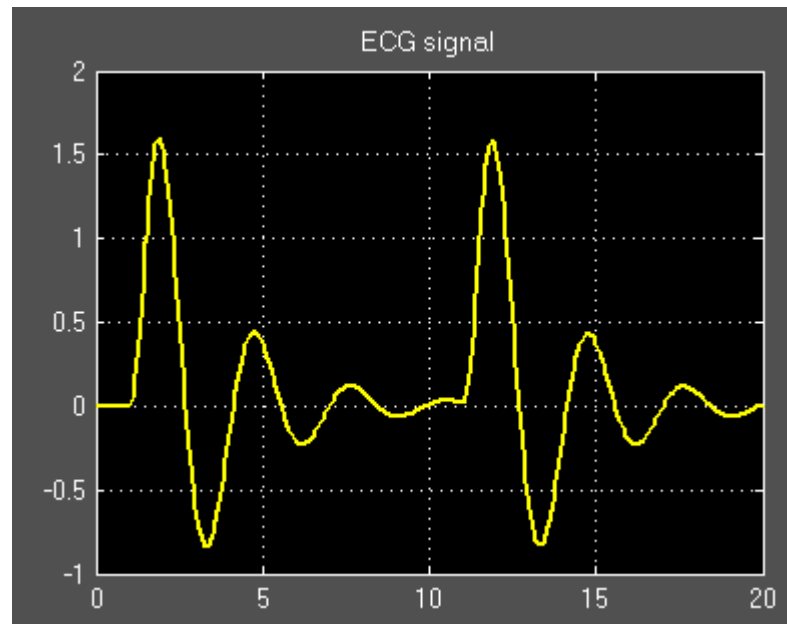
Figure 66 shows a couple of heartbeats

48

From figure 62, the PQRST complex can be observed quite easily. Also notice the vertical scale as it goes to the negative which in fact the normal body signal does and is known as the atrium repolarisation.

7.0 Budget

While this is a new project, much of the money were spent on the components such as op-amps. Also one of the objective was to keep the cost as minimal as possible. The issue that arise was whether three optocoupler circuits should be implemented which will be separating the leads and the rest of the circuit. As the bio signal is not huge at all, there is no point of placing three isolation circuits. On top of that, the ins-amp circuit is made up of op-amps that are really cheap. So investing on the optocoupler would be a waste of money and time as well as they have to be constructed. The table below shows the cost of this project.

| Item	Quantity	Price per unit / $	Total
Opto-isolator (HCNR201)	1	8.38	8.38
Op amp (TLV2372IP)	1	3.93	3.93
Diode (1N5711)	1	0.361	0.361
Op amp (LM6132BIN)	1	4.31	4.31
INA128	1	7.89	7.89
Other components	1	10	10
TOTAL			35.00

Table 3 shows the cost of each components and the total cost

In addition, other components have been listed in the table above. This cost is associated with all the other components such as resistors, LM741 op-amps and more that were taken from Murdoch University.

8.0 Conclusion

Overall the project was about 90% towards completion and the fact that this is a new project so no documentations were available compared to some other projects that are carried forward. The only disappointing part of it is that there was not enough time to replace the optocoupler. Also it should be appreciated with the level of boost of skill that has been achieved with this project. If there was a longer time limit, more could have been achieved.

The objectives that were achieved in this project are:

- understand more about op-amps and how they function,
- verify the working of an existing ECG design,
- develop an ECG circuit,
- confirm the ready-made ins-amp design as an ECG circuit,
- understanding the EKG sensor and experiment with it,
- modelling different aspect of how muscles work.

Throughout this project different skills were acquired and developed. Some of them are:

- being able to have a stronger understanding of how the heart functions,
- developing skills that involves the handling of electronics,
- having a better insight of how op-amps works,
- being able to develop a device that measures bio-signal,
- understand about filters and the different types with dissimilar responses,

- comparisons of results against a 'homemade ECG' and the EKG sensor from Vernier Technology,
- enhancing the skills in troubleshooting the optocoupler circuit
- Polishing the programming ability by modelling in Matlab/Simulink and LabView.

8.2 Problems encountered

Most parts of the project was fairly straight forward to deal with, however there were some difficulties to overcome. This is good as it enhances different skills such as problem solving. Different problems that cropped up during this task were:

- understanding electronics as this course is more inclined towards biomedical, but it was not impossible. In fact it should be appreciated with the level and depth of electronics acquired.
- the opto isolator was a mayhem during its construction phase, as each time a different output would be obtained which then creates the belief that the circuit does not work when it actually does. The issue might be in the breadboard as some connections might be loose.
- not much information was available on the EKG sensor such as what is inside the box. Minimum amount of material was available on how to set up this sensor.
- as usual, the time factor played a major role. The diagnostic process took a long time therefore stretching the project life.

8.3 Recommendations

Here are some recommendations of how this project can be enhanced:

- the optocoupler circuit is known to work, it would be good to solder connections in the circuit rather than placing it on a breadboard. This reduces the chance of loose connections.
- instead of using an optocoupler circuit, a wireless connection can be used such an Arduino with Bluetooth radio connection. This is becoming more popular as it is a safer way. Then other improvements can be put into action such as connecting the ECG directly to a printer which will print the result instantly.
- instead of displaying the result of the analogue circuits on an oscilloscope, a DAQ card can be used and the virtual filters can be used to experiment with instead of physically building them. This would be fabulous as it will enhance the skill of different types of filters and signal conditionings.

8.0 References

[1]B. Mackenzie, 'Muscle Types', *Brianmac.co.uk*, 2015. [Online]. Available: http://www.brianmac.co.uk/muscle.htm. [Accessed: 18- Oct- 2015].

[2] InnerBody, 'Muscle Cell Types', 2015. [Online]. Available: http://www.innerbody.com/image/musc01.html. [Accessed: 18- Oct- 2015].

[3]B. Mackenzie, 'Muscle Types', *Brianmac.co.uk*, 2015. [Online]. Available: http://www.brianmac.co.uk/muscle.htm. [Accessed: 18- Oct- 2015].

[4]A. Singh, 'Types of Muscles and Their Functions | Bone and Spine', *Bone and Spine*, 2008. [Online]. Available: http://boneandspine.com/types-of-muscles-and-there-functions/. [Accessed: 18- Oct- 2015].

[5] Bodybuilding.com, 'Muscle Fibers: How Do They Differ?', 2005. [Online]. Available: http://www.bodybuilding.com/fun/sclark20.htm. [Accessed: 18- Oct- 2015].

[6]R. Nall, 'The Three Types of Muscles in Human Body | LIVESTRONG.COM', *LIVESTRONG.COM*, 2015. [Online]. Available: http://www.livestrong.com/article/88742-three-types-muscles-human-body/. [Accessed: 18- Oct- 2015].

[7] Bodybuilding.com, 'Muscle Fibers: How Do They Differ?', 2005. [Online]. Available: http://www.bodybuilding.com/fun/sclark20.htm. [Accessed: 18- Oct- 2015].

[8] Bodybuilding.com, 'Muscle Fibers: How Do They Differ?', 2005. [Online]. Available: http://www.bodybuilding.com/fun/sclark20.htm. [Accessed: 18- Oct- 2015].

[9]A. Singh, 'Types of Muscles and Their Functions | Bone and Spine', *Bone and Spine*, 2008. [Online]. Available: http://boneandspine.com/types-of-muscles-and-there-functions/. [Accessed: 18- Oct- 2015].

[10]'Study Guide', 2015. [Online]. Available: http://undertheepidermis.weebly.com/study-guide1.html. [Accessed: 18- Oct- 2015].

[11]'Study Guide', 2015. [Online]. Available: http://undertheepidermis.weebly.com/study-guide1.html. [Accessed: 18- Oct- 2015].

[12] Training.seer.cancer.gov, 'SEER Training: Muscle Types', 2015. [Online]. Available: http://training.seer.cancer.gov/anatomy/muscular/types.html. [Accessed: 18- Oct- 2015].

[13] Better Health Channel, 'Circulatory system - Better Health Channel', 2015. [Online]. Available: http://www.betterhealth.vic.gov.au/bhcv2/bhcarticles.nsf/pages/circulatory_system. [Accessed: 26- Oct- 2015].

[14] Better Health Channel, 'Circulatory system - Better Health Channel', 2015. [Online]. Available: http://www.betterhealth.vic.gov.au/bhcv2/bhcarticles.nsf/pages/circulatory_system. [Accessed: 26- Oct- 2015].

[15] Funsci.com, 'The Blood Cells', 2015. [Online]. Available: http://www.funsci.com/fun3_en/blood/blood.htm. [Accessed: 26- Oct- 2015].

[16] Qmul.ac.uk, 'New red blood cell simulator invented at Queen Mary', 2015. [Online]. Available: http://www.qmul.ac.uk/media/news/items/se/102687.html. [Accessed: 26- Oct- 2015].

[17] Funsci.com, 'The Blood Cells', 2015. [Online]. Available: http://www.funsci.com/fun3_en/blood/blood.htm. [Accessed: 26- Oct- 2015].

[18] WebMD, 'Human Anatomy: Blood - Red and White Cells, Plasma, Circulation, and More', 2015. [Online]. Available: http://www.webmd.com/heart/anatomy-picture-of-blood. [Accessed: 26- Oct- 2015].

[19] Kidshealth.org, 'Blood', 2015. [Online]. Available: http://kidshealth.org/parent/general/body_basics/blood.html#a_Nutrients_in_the_Blood. [Accessed: 26- Oct- 2015].

[20] Bodyandsoul.com.au, 'All about hormones', 2015. [Online]. Available: http://www.bodyandsoul.com.au/health/health+advice/all+about+hormones,13859. [Accessed: 26- Oct- 2015].

[21] MedicineNet, 'Albumin', 2015. [Online]. Available: http://www.medicinenet.com/script/main/art.asp?articlekey=2189. [Accessed: 26- Oct- 2015].

[22] Hes.ucfsd.org, 'Circulatory System', 2015. [Online]. Available: http://hes.ucfsd.org/gclaypo/circulatorysys.html. [Accessed: 26- Oct- 2015].

[23] CriticalCareDVM, 'Low Red Blood Cells - Understanding Anemia', 2015. [Online]. Available: http://criticalcaredvm.com/low-red-blood-cells-understanding-anemia/. [Accessed: 26- Oct- 2015].

[24] Better Health Channel, 'Circulatory system - Better Health Channel', 2015. [Online]. Available: http://www.betterhealth.vic.gov.au/bhcv2/bhcarticles.nsf/pages/circulatory_system. [Accessed: 26- Oct- 2015].

[25] Better Health Channel, 'Circulatory system - Better Health Channel', 2015. [Online]. Available: http://www.betterhealth.vic.gov.au/bhcv2/bhcarticles.nsf/pages/circulatory_system. [Accessed: 26- Oct- 2015].

[26]M. Farquhar, 'Fine Structure and Function in Capillaries of the Anterior Pituitary Gland', *Angiology*, vol. 12, no. 7, pp. 270-292, 1961.

[27]V. profile, 'AS biology Ms Timms: Pictures from blood vessels lesson', *Mstimm-asbiology.blogspot.com.au*, 2013. [Online]. Available: http://mstimm-asbiology.blogspot.com.au/2013/01/pictures-from-blood-vessels-lesson.html. [Accessed: 26- Oct- 2015].

[28] LiveScience.com, 'Human Heart: Anatomy, Function & Facts', 2015. [Online]. Available: http://www.livescience.com/34655-human-heart.html. [Accessed: 27- Oct- 2015].

[29] a. Palmer, a. Palmer and V. Profile, 'Human Cardiac and Respiratory Systems: The Heart Structure and the Cardiac Cycle', *Anitacardioresp.blogspot.com.au*, 2010. [Online]. Available: http://anitacardioresp.blogspot.com.au/2010/05/heart-structure-and-cardiac-cycle.html. [Accessed: 27- Oct- 2015].

[30] Tackk, 'Cells - Tackk', 2015. [Online]. Available: https://tackk.com/tsgdfn. [Accessed: 27- Oct- 2015].

[31] Training.seer.cancer.gov, 'SEER Training: Structure of the Heart', 2015. [Online]. Available: http://training.seer.cancer.gov/anatomy/cardiovascular/heart/structure.html. [Accessed: 27- Oct- 2015].

[32] Nhlbi.nih.gov, 'Your Heart's Electrical System - NHLBI, NIH', 2015. [Online]. Available: https://www.nhlbi.nih.gov/health/health-topics/topics/hhw/electrical. [Accessed: 27- Oct- 2015].

[33] Nhlbi.nih.gov, 'Your Heart's Electrical System - NHLBI, NIH', 2015. [Online]. Available: https://www.nhlbi.nih.gov/health/health-topics/topics/hhw/electrical. [Accessed: 27- Oct- 2015].

[34] Imgarcade.com, 'Gallery For > Depolarization of Heart', 2015. [Online]. Available: http://imgarcade.com/1/depolarization-of-heart/. [Accessed: 28- Oct- 2015].

[35] Clinical Cardiology, 'Willem Einthoven-The Father of Electrocardiography', 2015. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1002/clc.4960151020/pdf. [Accessed: 28- Oct- 2015].

[36] Nobelprize.org, 'Willem Einthoven - Biographical', 2015. [Online]. Available: http://www.nobelprize.org/nobel_prizes/medicine/laureates/1924/einthoven-bio.html. [Accessed: 28-Oct- 2015].

[37] Jems.com, 'Einthoven's Triangle Unlocks 12-Lead ECG Interpretation', 2015. [Online]. Available: http://www.jems.com/articles/2012/03/einthoven-s-triangle-unlocks-12-lead-ecg.html. [Accessed: 31-Oct- 2015].

[38] Webs.wofford.edu, 'HUMAN CARDIOVASCULAR LAB', 2015. [Online]. Available: http://webs.wofford.edu/davisgr/bio342/cardio.htm. [Accessed: 31- Oct- 2015].

[39] WebMD, 'Electromyogram (EMG) and Nerve Conduction Studies', 2015. [Online]. Available: http://www.webmd.com/brain/electromyogram-emg-and-nerve-conduction-studies. [Accessed: 01- Nov-2015].

[40]R. Merletti and D. Farina, 'Analysis of intramuscular electromyogram signals', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 367, no. 1887, pp. 357-368, 2009.

[41]A. Hambley, *Electrical engineering*, 5th ed. Upper Saddle River, N.J.: Prentice Hall, 2011, p. 711.

[42]W. Storr, 'Differential Amplifier - The Voltage Subtractor', *Basic Electronics Tutorials*, 2013. [Online]. Available: http://www.electronics-tutorials.ws/opamp/opamp_5.html. [Accessed: 03- Nov-2015].

[43]P. Horowitz and W. Hill, *The art of electronics*. Cambridge [England]: Cambridge University Press, 1989.

[44]W. Storr, 'Differential Amplifier - The Voltage Subtractor', *Basic Electronics Tutorials*, 2013. [Online]. Available: http://www.electronics-tutorials.ws/opamp/opamp_5.html. [Accessed: 03- Nov-2015].

[45]W. Storr, 'Differential Amplifier - The Voltage Subtractor: Instrumentation amplifier', *Basic Electronics Tutorials*, 2013. [Online]. Available: http://www.electronics-tutorials.ws/opamp/opamp_5.html. [Accessed: 03- Nov- 2015].

[46]A. Hambley, *Electrical engineering*, 5th ed. Upper Saddle River, N.J.: Prentice Hall, 2011, p. 712.

[47] Texas Instrument, 'LMx58-N Low-Power, Dual-Operational Amplifiers', 2015. [Online]. Available: http://www.ti.com/lit/ds/symlink/lm158-n.pdf. [Accessed: 04- Nov- 2015].

[48] My Circuits 9, 'My Circuits 9: SIMPLE ECG (ELECTROCARDIOGRAPH) CIRCUIT', 2015. [Online]. Available: http://www.mycircuits9.com/2012/08/simple-ecg-electrocardiograph-circuit.html. [Accessed: 04- Nov- 2015].

[49]R. Khandpur, *Handbook of biomedical instrumentation*. New York: McGraw Hill Education, 2014.

[50]J. Webster and J. Clark, *Medical instrumentation*, 4th ed. Boston: Houghton Mifflin, 2010, p. 275.

[51]J. Webster and J. Clark, *Medical instrumentation*, 4th ed. Boston: Houghton Mifflin, 2010, p. 274.

[52] Radio-electronics.com, 'Slew Rate | Op Amp Tutorial Calculator | Radio-Electronics.com', 2015. [Online]. Available: http://www.radio-electronics.com/info/circuits/opamp_basics/operational-amplifier-slew-rate.php. [Accessed: 06- Nov- 2015].

[53] Ti.com, 'INA128 | Dual Supply | Instrumentation Amplifier | Description & parametrics', 2015. [Online]. Available: http://www.ti.com/product/ina128. [Accessed: 06- Nov- 2015].

[54] Ti.com, 'LM741 | General Purpose Amplifier | Operational Amplifier (Op Amp) | Description & parametrics', 2015. [Online]. Available: http://www.ti.com/product/lm741. [Accessed: 06- Nov- 2015].

[55] E2e.ti.com, 'INA128, Adding -9V offset with reference pin - Precision Amplifiers Forum - Precision Amplifiers - TI E2E Community', 2015. [Online]. Available: https://e2e.ti.com/support/amplifiers/precision_amplifiers/f/14/t/146851. [Accessed: 06- Nov- 2015].

[56] Terpconnect.umd.edu, 'Intro. To Signal Processing: Signals and noise', 2015. [Online]. Available: https://terpconnect.umd.edu/~toh/spectrum/SignalsAndNoise.html. [Accessed: 08- Nov- 2015].

[57]J. Rowe and N. Vinen, 'Isolating High-Voltage Probe For Oscilloscopes - January 2015 - Silicon Chip Online', *Siliconchip.com.au*, 2015. [Online]. Available: http://www.siliconchip.com.au/Issue/2015/January/Isolating+High-Voltage+Probe+For+Oscilloscopes. [Accessed: 09- Nov- 2015].

[58]'Michaelmas term', *Choice Reviews Online*, vol. 39, no. 01, pp. 39-0163-39-0163, 2001.

[59] Pdf1.alldatasheet.com, 'TLV2372 pdf, TLV2372 description, TLV2372 datasheets, TLV2372 view ::: ALLDATASHEET :::', 2015. [Online]. Available: http: //pdf1.alldatasheet.com/datasheet-pdf/view/82996/TI/TLV2372.html. [Accessed: 10- Nov- 2015].

[60] Ti.com, 'LM6132 | Precision Amplifier | Operational Amplifier (Op Amp) | Description & parametrics', 2015. [Online]. Available: http://www.ti.com/product/lm6132/description. [Accessed: 10- Nov- 2015].

[61]J. Rowe and N. Vinen, 'Isolating High-Voltage Probe For Oscilloscopes: The Full probe circuit - January 2015 - Silicon Chip Online', *Siliconchip.com.au*, 2015. [Online]. Available: http://www.siliconchip.com.au/Issue/2015/January/Isolating+High-Voltage+Probe+For+Oscilloscopes. [Accessed: 10- Nov- 2015].

[62] Vernier.com, 'EKG Sensor > Vernier Software & Technology', 2015. [Online]. Available: http://www.vernier.com/products/sensors/ekg-bta/. [Accessed: 10- Nov- 2015].

[63] Texas Instrument, 'LM157 Datasheet', 2015. [Online]. Available: http://www.ti.com/lit/ds/symlink/lm158-n.pdf. [Accessed: 11- Nov- 2015].

[64] Texas Instrument, 'LM386 Datasheet', 2015. [Online]. Available: http://www.ti.com/lit/ds/symlink/lm386.pdf. [Accessed: 11- Nov- 2015].

[65]'Muscle Fatigue', *Boundless*, 2015.

[66] Bbc.co.uk, 'BBC - KS3 Bitesize Science - Life processes: Revision, Page 8', 2015. [Online]. Available:
http://www.bbc.co.uk/bitesize/ks3/science/organisms_behaviour_health/life_processes/revision/8/.
[Accessed: 12- Nov- 2015].

[67] Google.com.au, 'response of an antagonistic muscle - Google Search', 2015. [Online]. Available: https://www.google.com.au/search?q=response+of+an+antagonistic+muscle&newwindow=1&source=l nms&tbm=isch&sa=X&ei [Accessed: 12- Nov- 2015].

[68] Shadier Lab, 'Muscle Models', 2015. [Online]. Available: http://www.shadmehrlab.org/book/musclemodel.pdf. [Accessed: 12- Nov- 2015].

[69] Physiome.Cz, 'CAUSAL OR CAUSAL MODELLING: LABOR FOR HUMANS OR LABOR FOR MACHINES', 2008. [Online]. Available: http://www.physiome.cz/references/tcp2008.pdf. [Accessed: 12- Nov- 2015].

[70] [12] Australian Health Survey, 'Heart Disease', 2015. [Online]. Available: http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/4338.0~2011-13~Main%20Features~Heart%20disease~10005. [Accessed: 12- Nov- 2015].

[71] Mayoclinic.org, "Symptoms and causes - Sudden cardiac arrest - Mayo Clinic", 2015. [Online]. Available: http://www.mayoclinic.org/diseases-conditions/sudden-cardiac-arrest/symptoms-causes/dxc-20164872. [Accessed: 23- Dec- 2015].

[72] Michigan State University, Team 3 Design, "Electrocardiogram Circuit Design", 2015. [Online]. Available: http://www.egr.msu.edu/classes/ece480/capstone/spring13/group03/documents/ElectrocardiographyCircuitDesign.pdf. [Accessed: 23- Dec- 2015].

[73] Centre of Educational Media, "Standard PID Tuning Methods", 2015. [Online]. Available: http://www.chem.mtu.edu/~tbco/cm416/tuning_methods.pdf. [Accessed: 28- Dec- 2015].

9.0 Appendix

9A Differential Amplifier
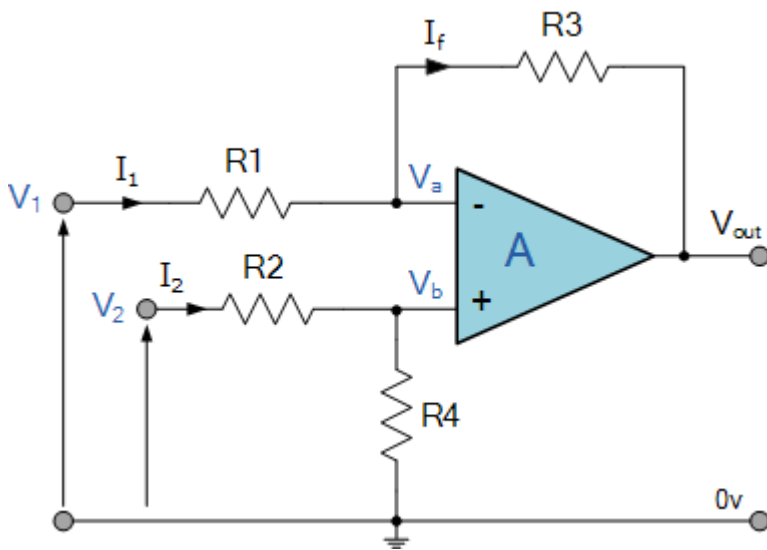
$$I1 = \frac{V1 - Va}{R1}, \qquad I2 = \frac{V2 - Vb}{R2}, \qquad If = \frac{Va - Vout}{R3}$$

Assuming ideal op-amp: $Va = Vb$

Then $Vb = V2\left(\frac{R4}{R2+R4}\right)$

Let $V2 = 0$, then $Vout(a) = -V1\left(\frac{R3}{R1}\right)$

Let $V1 = 0$, then $Vout(b) = V2\left(\frac{R4}{R2+R4} * \left(\frac{R1+R3}{R1}\right)\right)$

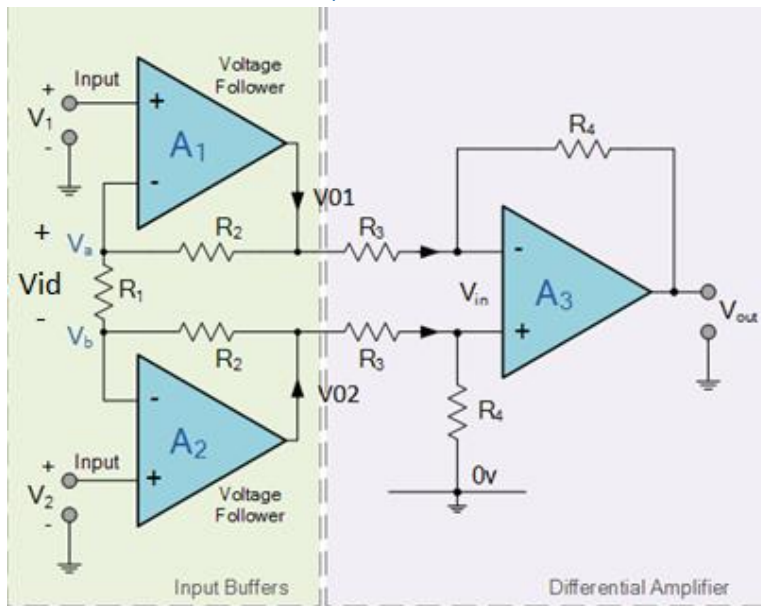In other words: $Vout = Vout(a) + Vout(b)$

Hence: $Vout(total) = V2\left(\frac{R4}{R2+R4} * \left(\frac{R1+R3}{R1}\right)\right) - V1\left(\frac{R3}{R1}\right)$

Now let R1=R2 and R3=R4;

$$Vout = \left(\frac{R3}{R1}\right)(V2 - V1) \qquad\qquad [42]$$

9B Instrumentation amplifier

Using Kirchhoff's Voltage Law (KVL) at V01:

$$V01 = \left(1 + \frac{R2}{R1}\right) * V1$$

Using KVL at V02:

$$V02 = \left(1 + \frac{R2}{R1}\right) * V2$$

Assuming ideal op-amp so no voltage goes to the op-amp:

Voltage at V_a = V1 and V_b = V2;

So $d = V2 - V1$; then current at feedback loop, $Iin = \frac{Vid}{R1}$

$$Vin = Vid\left(1 + \frac{2R2}{R1}\right)$$

$$Vout = \frac{R4}{R3} * Vin$$

Hence $Vout = \left(\frac{R4}{R3}\right)\left(1 + \frac{2R2}{R1}\right) * Vid$

So overall gain of system:

$$Av = \left(\frac{R4}{R3}\right)\left(1 + \frac{R2}{R1}\right)$$

9C Circuit 2

As the signal from the body is in mV, let V1=10mV and V2=30mV;

Then: $Vout2 = \left(\frac{47K}{10K}\right)\left(1 + \frac{2*22K}{10K}\right) * (20mV)$

So: $Av2 = \left(\frac{47K}{10K}\right)\left(1 + \frac{2*22K}{10K}\right)$

Therefore $Av2 = 25$

9D Circuit 3

Since R_G is variable, the gain is subjected to the same gain as Circuit 2

Thus: $Av3 = \left(\frac{40K}{40K}\right)\left(1 + \frac{2*RG\ K}{25K}\right)$

$$25 = \left(\frac{40K}{40K}\right)\left(1 + \frac{2*RG\ K}{25K}\right)$$

So $RG = 325K\Omega$

If 325KΩ is not available, any value near it would be used.

As the signal from the body is in mV, let V1=10mV and V2=30mV;

Then: $Vout3 = \left(\frac{40K}{40K}\right)\left(1 + \frac{2*325K}{10K}\right) * (20mV)$

9E Muscle modelling- Antagonist pair

The aim of this is to get an approximation hence putting random waves and experimenting with response suits the normal answer.

```
%%%ADEESH %%%
% Antagonistic model using harmonics
t=1:0.1:20;
y1=sin(t)+ sin(3*t)/3+ sin(5*t)/5+sin(7*t)/7+sin(9*t)/9+sin(11*t)/11;
plot(t,y1,'b')
hold on
y2=-(sin(t)+ sin(3*t)/3+ sin(5*t)/5+sin(7*t)/7+sin(9*t)/9+sin(11*t)/11)
plot (t,y2,'r')
title (' Antagonistic Muscle action' )
ylabel('Force(N)'); xlabel('Time(s)');
legend ('biceps','triceps')
```

9F Muscle Fatigue

Using a transfer function, some noise is added to give the graph a realistic look as it will look like in a normal ECG.
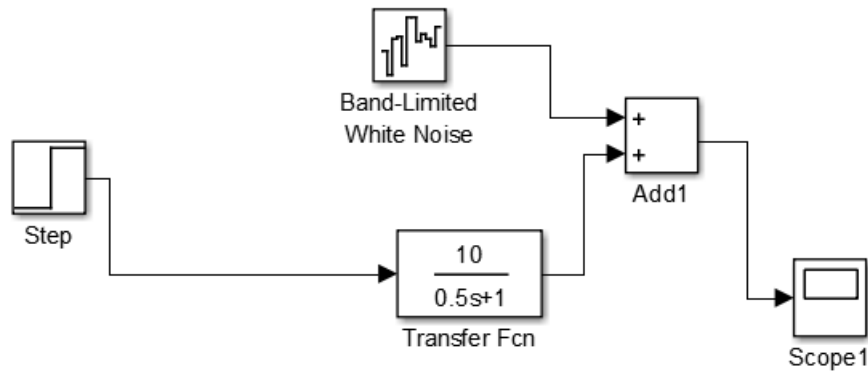
9G Smooth Muscle
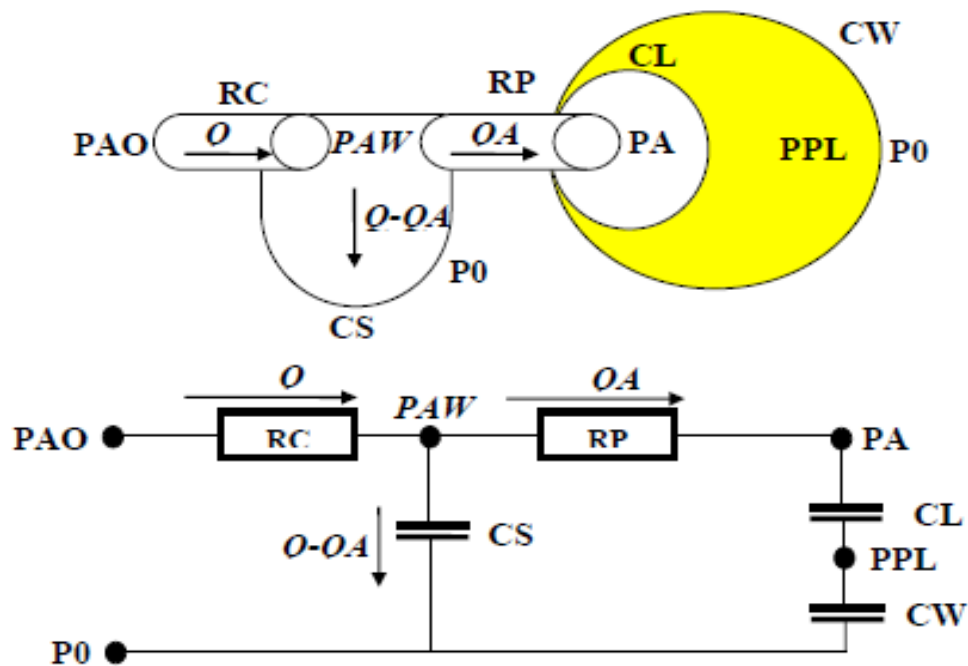
As the electrical version of the lungs operations is available, an analysis can be done to analyse this circuit and is given below:

Using Ohm's Law:

$$PAW - PA = RP * QA$$

$$PAO - PAW = RC * Q \qquad (1)$$

Relationship between elasticity, pressure gradient and volume (denoted as flow integral):

$$PA - PPL = \left(\frac{1}{CL}\right) * \int QA\,dt$$

$$PPL - PO = \left(\frac{1}{CW}\right) * \int QA\,dt$$

$$PAW - PO = \left(\frac{1}{CS}\right) * \int Q - QA\,dt \qquad (2)$$

According to KVL, sum of voltages = 0. So along PAO node:

$$(PAW - PA) + (PA - PPL) + (PPL - PO) + (PO - PAW) = 0$$

$$(PAO - PAW) + (PAW - PO) + (PA - PAO) = 0 \qquad (3A)$$

Replace (1) and (2) in 3A:

$$RP * QA + \left(\frac{1}{CL} + \frac{1}{CW}\right) * \int QA\,dt - (1/CS * \int (Q - QA)dt = 0$$

$$QRC + (1/CS \int (Q - QA)dt + (PO - PAO)) = 0 \qquad (3B)$$

3A and 3B are the complete solution, however in order to plot it in Matlab/Simulink, it should be solved and simplified. The aim here is to calculate the air flow to and from the lungs. To implement in Simulink, a differential equation needs to be implemented which would be solved to relate the input (PAO) to the output (Q).

The equations involved are too complex and not all derivations are given below, only the main ones are:

$$\frac{d^2(PAO)}{dt^2} + \frac{1}{RP.CT} * \frac{d(PAO)}{dt} = RC * \frac{d^2 Q}{dt} + \frac{\left(\frac{1}{CS} + \frac{RS}{RP.CT}\right)dq}{dt} + \frac{1}{RP * CS}\left(\frac{1}{CL} + \frac{1}{CW}\right)Q$$

The constants (some of them are assumed): RC= 1, RP=0.5, CL=0.2, CW=0.2, CS=0.005
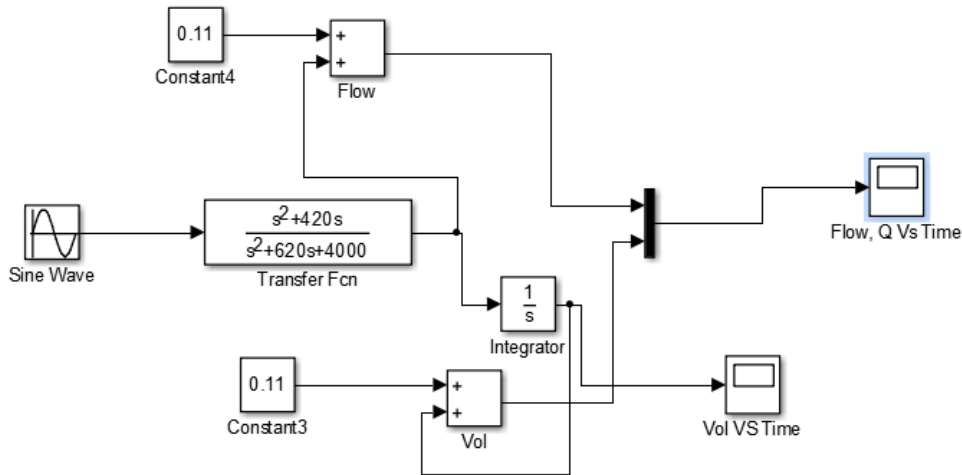
Replacing the constants yield the following:

$$\frac{d^2 PAO}{dt^2} + 420\left(\frac{dPAO}{dt}\right) = \frac{dQ^2}{dt} + \frac{620dq}{dt} + 4000Q$$

Using Laplace transform and simplify the equation, the following is obtained [69]:

$$\frac{Q(S)}{PAO} = s^2 + \frac{420s}{s^2 + 620s + 4000}$$

The equation above can be used in Simulink to experiment with.

This transfer function is implemented in Simulink:

9H Cardiac muscle modelling
This equation is developed by knowing how the heart functions such as when does the atrium contract.

61