DEVELOPMENT OF A FUNCTIONAL ELECTRICAL STIMULATOR WITH FEEDBACK CONTROL

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ABSTRACT

Functional Electrical Stimulation (FES) is a means of passing small electrical impulses through nervous tissue of paralyzed muscles that is no longer controlled by patient. Its function is not only to improve impaired function but also to slow down or stop bone and muscle deterioration, and to improve circulation in paralyzed limbs of spinal cord injury (SCI) and stroke patients. However, the major limitation of FES is muscle fatigue. Moreover, most works on FES system are focussed on open loop mode which do not automatically regulate the desired output. Thus, closed loop FES system need to be developed. This research paper presents the work on developing a closed loop FES system or FES system with feedback control. The work is divided into two parts namely the development part and the experiment part. In the development part, a FES stimulator is constructed. The FES stimulator includes the high voltage power and the current closed-loop control circuit. On the other hand, there are two sections in the experiment part. The first experiment uses a laboratory setting with beaker and oscilloscope to ensure the closed-loop control is successful. The second part utilizes FES with real human muscle to be stimulated with the voltage stepped up to overcome skin resistance. This project also addressed the issue of varying the skin temperatures used as a feedback parameter of FES system as this work has not been investigated before.

ABSTRAK

Rangsangan Elektrik Fungsian (FES) ialah satu cara mengalirkan denyutan kecil elektrik melalui tisu saraf pesakit yang tidak dapat mengawal ototnya yang lumpuh. Ianya berfungsi bukan sahaja untuk memperbetulkan bahagian yang tak berfungsi pada manusia tetapi juga memperlahan dan memberhentikan kerosakan otot dan memperbetulkan kitaran pada pesakit tulang belakang dan juga pesakit strok. Tetapi, halangan terbesar sistem FES ialah kelemahan otot. Selain itu, kebanyakan kajian mengenai sistem FES tertumpu kepada mod lelaran terbuka yang tidak menghasilkan output secara automatik. Oleh itu, lelaran tertutup FES perlu dicipta. Kertas kajian ini membina sebuah sistem FES bersama dengan kawalan maklumbalas. Ianya terbahagi kepada dua bahagian iaitu pembangunan FES dan secara eksperimen. Untuk pembangunan FES, sebuah perangsang FES telah dibina. Ianya mempunyai kuasa voltan yang tinggi dan litar tertutup arus elektrik. Bahagian eksperimen terbahagi kepada dua. Pertama, ianya berlangsung dilaksanakan di makmal untuk memastikan litar tertutup arus elektrik berjalan dengan jayanya menggunakan bikar dan osciloskop. Bahagian kedua menggunakan FES dengan otot manusia sebenar yang dirangsang dengan voltan yang tinggi bagi mengatasi rintangan kulit. Projek ini juga mengetengahkan isu mempelbagaikan suhu kulit sebagai parameter maklumbalas sistem FES oleh kerana ianya belum dikaji sebelum ini.

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In the name of Allah, The Most Gracious, The Most Merciful.

I would like to extend my gratitude to my supervisor, Dr Nur Azah Hamzaid who always gives her full attention and support throughout the semester.

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CHAPTER 1

1.0 INTRODUCTION

Functional electrical stimulation (FES) is a method used to electrify muscular contractions in subjects artificially impairing the volitional muscle activation, for example, due to a spinal cord injury (SCI) (Pennycott & Hunt, 2010). The rising of development in FES system in research studies as well as in clinical studies proved that FES system brings many benefits to the society. However, it is hard to control the movement of the stimulated neuro-musculoskeletal muscle because of its behavior are complex, non-linear, and varies in time (Riener & Quintern, 1997). A better FES system is developed if the parameters of the system are able to reduce the major limitation of FES which is muscle fatigue.

Until now, the real reason caused the muscle to fatigue is not known (Fornusek & Davis, 2008). Nevertheless, it may caused due to the external electrode activate the inverse size recruitment of axons, shift toward fast-fatiguing muscle fibers, activation of high rate of motor unit and rapid transition with synchronous activations of axons. (Karu, Durfee & Barzilai, 1995).

In addition, the open loop control mode of FES system is widely been applied by researches as well as clinicians to control the muscle movements. The clinicians tends to use the open loop control strategies rather than the closed loop mode because it is easy to use, safe and does not need to placed any sensors on subjects. However, this type of FES system does not concern much on reducing muscle fatigue. Thus, open loop control with a reliable controller should be used to solve the problem.

1.1 Problem Statements

Functional electrical stimulation (FES) is a method to stimulate and activate muscles of the patient who unable to control his own muscle such as spinal cord injury (SCI), stroke and neurological disorders by using electrical current. Besides that FES has also been used to restore muscle strength (Wu, 2002), assist in reducing foot drop and working with orthoses for central nervous system (CNS) lesions patients (Chen, et al., 2011).

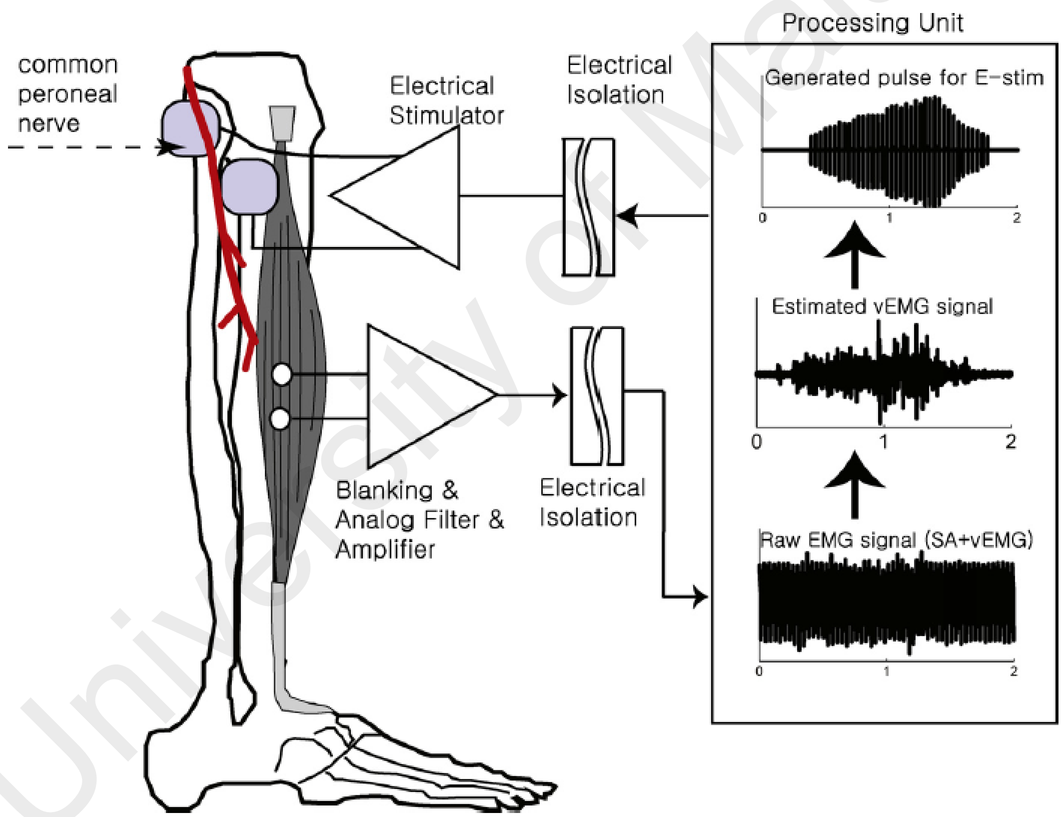

Figure 2.1 : FES device for ankle dorsiflexion control. The surface EMG electrodes at the belly of the tibialis anterior muscle. An example FES treating foot drop. Adapted from Hojun Yeoma &Young-Hui Chang (2010).

The research works on FES field started with the functional sensory-motor system produce the control signal for example a voluntarily controlled muscle. Later, the area of FES is introduced to the myoelectric application or electromyography (EMG) control of prosthetic devices. However, the EMG signal is not directly correlated and not reliable to the muscle force. Moreover, the length of the muscle, velocity of the shortening of the muscle, and the fatigue level are inversely proportional to the EMG signal (Sinkjaer, et. al, 2003). Besides, many FES applications operate in open loop mode including EMG signal but it is not automatically regulated the intended function. Thus, this problems need to be solved.

Today, the research on FES system with feedback control starts to rise. This feedback control solution or also known as the closed loop mode of FES system. This mode is possible to change the stimulation parameter dynamically in response to feedback from the limb, reduce muscle fatigue and regain the functional of the muscle.

1.2 Objectives Of The Study

The objective of this project is to control the FES with feedback system. The other objective is to study the skin temperature during the stimulator stimulates the muscle.

1.3 Hypothesis

This research will develop a FES system with feedback control. The FES system is able to stimulate the muscle with high voltage supply. User is allowed to enter a temperature value to command the controller to ensure that the skin temperature is equal to the entered value while the muscle is stimulated. Moreover, it is predicted that the skin temperature will be increasing when the muscle is stimulated. However, it should stop increasing and maintain its value equal to that user input value as the FES session progresses.

1.4 Scope Of The Study

The scope of the study is divided into two which are the development part and the experiment part. In the development part, a FES stimulator is constructed. The FES stimulator includes the high voltage power and the current closed-loop control circuit. On the other hand, there are two sections in the experiment part. The first experiment uses a laboratory setting with beaker and oscilloscope to ensure the closed-loop control is successful. The second part utilizes FES with real human muscle to be stimulated with the voltage stepped up to overcome skin resistance.

1.5 Significance Of Study

Previous works on FES system are mostly on open loop mode which according to Baumann (2011) does not automatically regulate the desired output. There are limited studies on feedback FES as many of them focused only on controlling the muscle activation by external command signals such as hand operated switches and external transducers (Sinkjaer, 2003). Furthermore, the FES system with electromyography (EMG) as the command signals of the system is widely covered by researchers over the years. However, the EMG signals has limitations in signal processing such as stimulation artefacts which leads to unreliable results. Thus, it is a hope that this FES project with feedback control by using a controller which receive and transmit data to regulate the skin temperature value according to the user desired value will benefit others for further research.

CHAPTER 2

2.0 LITERATURE REVIEW

FES is a means of passing small electrical impulses through nervous tissue of paralyzed muscles that is no longer controlled by patient (Mohammed, 2012). A suitable stimulation patterns are required to stimulate coordinated movements for example walking, grasping, standing, sitting up or sitting down (Zhijun Cai, Er-wei Bai & Shield, 2010). FES function is not only to improve impaired function but also to slow down or stop bone and muscle deterioration, and to improve circulation in paralyzed limbs of spinal cord injury (SCI) and stroke patients. However, the role of FES is limited because of the stimulated muscles tend to fatigue very rapidly (Graham, 2006).

In order to control the movement of the patients, the open loop control often been used by the clinicians because it is easy to implement. However, this strategy ignores the effect of fatigue and changes of load on the muscles. On the other hand, the clinicians are not using the closed loop control strategies because of sensors need to be placed on patient, safety, and embedded computational cost. Moreover, a closed loop controllers are difficult to produce accurate performances. Thus, a controller with a realistic model should be created (Mohammed, 2012). The difficulty is due to the nonlinearities in the musculoskeletal system. The stimulus frequency, intensity or pulse width of the modulation should be taken seriously in developing a FES system (Javoroski, 2011).

Several previous studies have conducted the muscle fatigue tests by dissecting the muscle fibers of animals. The activation failure, impairment of calcium kinetics, metabolite accumulation, substrate depletion and disruption of cross bridge dynamics can be studied by in vitro experiment. The ability of fibres to sustain a particular force or power production can be studied. However, the real human performance may not represent accordingly (Enoka, 1995).

2.1 Excitation, Contraction and Relaxation of Muscle Fiber

During excitation event in a motor axon, an action potential is initiated and propagated. The skeletal muscle fibers are innervated by the end branches of an axon of motor neuron which form a neuromuscular junction. At this junction, the acethylcholine is released. The membrane of muscle fiber or sarcolemma located under the axon branches has a special property named motor end plate. An end plate potential produced when the permeability of the motor end plate increased in sodium and potassium ions due to the released of acethylcholine. Sarcolemma is then depolarized by the potential end plate and a muscle action potential is generated and propagated over its surface. On the end plate membrane, acethylcholine is destroyed by acetylcholinesterase. Then, the transverse tubules are depolarized by the muscle action potential and calcium ions are released into sarcoplasm with troponin and tropomyosin from sarcoplasmic reticulum (SR) which surrounding the myofibrils. Tropomyosin molecule moved away from myosin receptor sites on the actin filament when troponin binded with calcium ions.

At this state, myosin-ATP (adenosine triphosphate) combines with actin. Actin activates ATP and caused it to hydrolyze into ADP (adenosine diphosphate) and phosphate (Pi). This releasing energy process produces a movement of the myosin cross bridge (myosin head). The movement of cross bridges produces sliding of the thick and thin filament past each other. A muscle contracts when all sacromeres shorten simultaneously which is called as twitch. The cross bridge dissociate with actin when fresh ATP binds with myosin cross bridge. The sarcomere is under relaxation when the myosin-ATP complex hydrolyzes to myosin-ATP complex by ATPase. The process continues as long as the calcium ions concentration is high enough to inhibit the action of troponin-tropomyosin system.

Lastly, the relaxation event takes place when the calcium ions concentration is reduced when it pumps into the SR by the energy that require to splits ATP. Calcium dissociates from troponin restoring the inhibitory action of troponin-tropomyosin. The muscle lengthens as the action filaments slide back to normal state. Actin and myosin remain in the dissociated relaxed state in the presence of ATP.

2.2 Muscle Fatigue

Muscle fatigue is defined as any exercise-induced reduction in the capacity to generate force or power output (Vollestad, 1997). Intense activation of skeletal muscle results in decreased contractile function that is reversed after a period of rest (Westerblad, 2010). Neuromuscular fatigue, therefore, represents any exercise induced reduction in force or power regardless of whether the task can be sustained or not.

There is several different physiological phenomena caused fatigue to occur during maximal or submaximal performance (Boyas & Guevel, 2011). There are central fatigue and peripheral fatigue. The former designates a decrease in voluntary activation of the muscle (i.e. a decrease in the number and discharge rates of the motor units (MUs) recruited at the start of muscle force generation). On the other hand, the latter indicates a decrease in the contractile strength of the muscle fibres and changes in the mechanisms underlying the transmission of muscle action potentials.

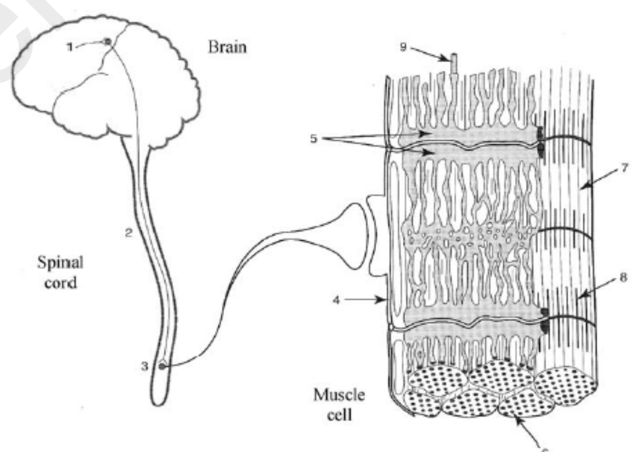

Figure 2.1 : Physiological sites which can contribute to fatigue (Adapted from Boyas & Guevel, 2011).

Based on the figure above, the central fatigue may caused by (1) activation of the primary motor cortex; (2) propagation of the command from the central nervous system to the motorneurons (the pyramidal pathways); (3) activation of the motor units and muscles. Meanwhile the peripheral fatigue caused by (4) neuromuscular propagation (including propagation at the neuromuscular junction); (5) excitation-contraction coupling; (6) availability of metabolic substrates; (7) state of the intracellular medium; (8) performance of the contractile apparatus; (9) blood flow.

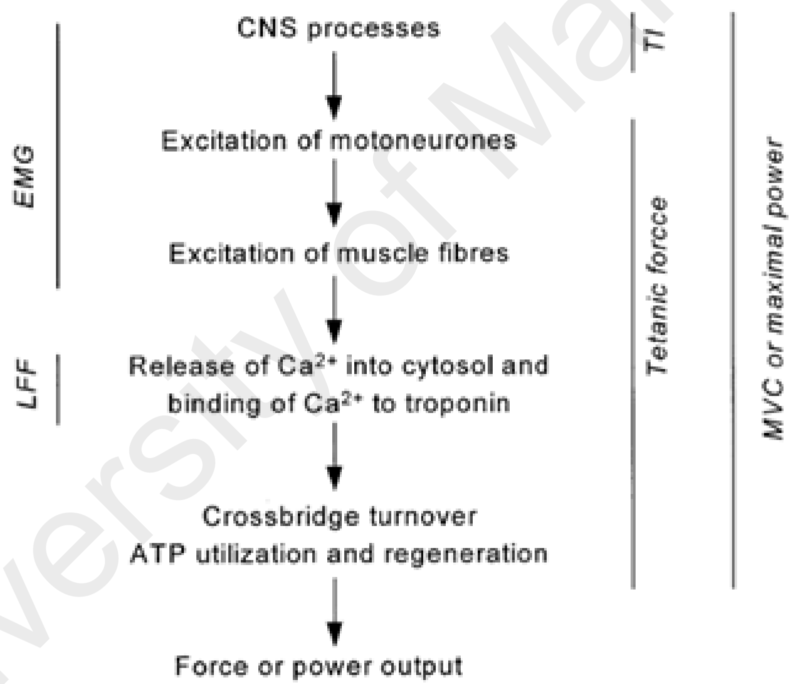

Figure 2.2 : Contraction events (Adapted from Vollestad, 2009)

The contraction muscles events at the end producing force or power output. Fatigue can arise because of impaired function in any step of the event. The activation chain starts with the process in central nervous system (CNS) which activates motorneurones. The activated motorneurones then activates several muscle fibers which later they together formed as motor unit. Motor unit is the smaller unit in the motor system. Central fatigue may occur at this stage when there is impaired motorneurones activation. Generally, central fatigue is controlled by the central nervous system to stop doing the activity before the muscle is totally damaged even though the muscle itself may works for more. The peripheral fatigue or local fatigue is caused by local factors in energy metabolism. There are many methods to measure muscle fatigue in any event which are electromyography (EMG), low frequency fatigue (LFF), TI, tetanic force and maximum voluntary contraction (MVC) as stated in the same figure.

2.3 Types of FES Modulation

Graham, Trasher & Popovic (2006) discusses several solution based on previous study on muscle fatigue. First solution is stochastic modulation which randomly modulating the pulse frequency. This varies modulation can extend the subject leg against gravity 37% more than the constant frequency stimulation. Nevertheless it is invalid because it is limited to a single subject only.

The second solution is muscle conditioning which it has its own limitations too. Due to increase in slow fatiguing muscle fibers, the muscular strength will be decrease. Besides, it is time consuming.

The third is the doublet stimulation which has its own advantages and disadvantages. However, the effect on the fatigue time is depending on the test conditions and protocol. If a doublet (two pulses separated by a very short interval) followed by a train of pulses is applied to a motoneuron, the result will be a much stronger contraction compared to that obtained by a train of pulses (Popovic & Malesevic, 2009).

Moreover, sequential stimulation of multiple motor points is quite harmful to humans as it needs to insert several electrodes for each muscle. For intermittent frequency stimulation in able-bodied and paraplegic subjects, it shows that the intermittent high frequency stimulation produces greater contractile forces with less fatigue than intermittent low frequency. However, it is not suitable for cyclic application like hybrid orthotics due to the extended periods of rest required between pulse trains.

2.4 Parameters of FES Stimulation Signal

There are three parameters of FES stimulation signal delivered by stimulator which are pulse width, the signal frequency and the current amplitude. Mohammed, et al (2012) keep constant the frequency of the stimulation signal but the pulse width and current amplitude are computed based on the use of a control strategy. The number of recruited motor units increases as a function of both pulse width and current of the stimulus and is represented by an activation model that expresses the ratio of recruited fibers. Thus, in this project the frequency will be kept constant too.

Graham, Trasher & Popovic (2006) aims to reduce muscle fatigue of SCI patients isometric contraction muscles by random modulation of frequency, amplitude, and pulsewidth. However, there is no effect on the fatigue rate. In order to imitate natural patterns of recruitment and rate coding, it was proposed to stochastically modulate stimulation frequency, current amplitude or pulse duration (Popovic &Malesevic, 2009).They concluded that it is not practical and fatigue reduction may still be possible using other parameters, such as a lower stimulation frequency. By lowering stimulation frequency we achieved a better resistance to muscle fatigue of paralyzed muscles (Popovic & Malesevic, 2009).

A minimum frequency that will result in a fused muscle contraction of skeletal muscles varies between different muscles in the body. True tetanic condition for stimulation frequency of tibialis anterior is in the range of 30-50Hz. A mean stimulation frequency of 40 Hz was used in Graham, Trasher & Popovic (2006) and the tibialis anterior muscles tend to vibrate noticeably at the stimulation frequency. The frequency in this study (40 Hz) is significantly higher than most FES applications. A smooth contraction of quadriceps can be generated at a minimum of 20 to 25 Hz. However, stronger contraction can be reached only at higher frequencies; therefore, in many applications 35 to 50 Hz is selected (Popovic & Malesevic, 2009). However, higher frequency tends to cause the muscle to fatigue rapidly during voluntary contractions.

In a study done by Mohammed (2012) its sampling period and stimulation frequency are set respectively to 0.01 s and 25 Hz. Besides, the overall number of received pulse, independent stimulation frequency may cause muscle fatigue (Karu, Durfee & Barzilai, 1995). In a study on the effect of surface vibration on muscle fatigue by using accelerometer, the frequency constant inter-pulse interval of 10 ms with 100 Hz frequency have been used (Ohta, Shima & Yabe, 2010).

The best method is to supply a small amount of current to the skin to avoid rapid fatigue of the muscle (Popovic & Malesevic, 2009). By lowering stimulation frequency they achieved a better resistance to muscle fatigue of paralyzed muscles. Based on the previous study, the stimulator circuit supplies a current range of 3.29mA to 79.1mA.

2.5 Skin Temperature

Energy expenditure in exercise can dramatically affect the skin temperature distribution. Muscular activity can produce an increase in the direct conduction of heat from the active muscles to the skin surface and this is often accompanied by a redistribution of skin blood. These combined effects greatly modified the skin temperature pattern from that observed at rest (Wang & Hock, 2001).

Temperature is an important parameter in affecting the FES system. During stimulating the muscle with constant current amplitude of modulation via the electrodes, the skin temperature increases as well as the muscle temperature. Previous studies are mostly doing research on the effects of skin temperature or core (body) temperature during exercise. Malkinson (2002) states that the activation of muscular produces a rate of metabolic heat which affecting the rate of body temperature. In another study done by Wang & Hock (2001) also mentions that the skin temperature distribution may be affect dramatically by the energy expenditure in exercise. First, the active muscle will conduct its heat to the skin surface which finally affecting the redistribution of skin blood. Thus, the skin temperature pattern great varies between at rest and during exercising. Beside, in their study suggests that the spurious noise of temperature values measured by the temperature sensors may be omitted if average temperature is measured. It also mentions that the range of frequency of skin modulation is between a few miliHertz (mHz) to Hertz (Hz) in the exercise which involved the activation of the muscular.

2.6 Previous Research on FES System with Feedback Control

Sinkjaer (2003) reviews related works on closed loop FES system which restore movements of subjects with in CNS. The command of the system is from Electronystagmography (ENG), Electroencephalogram (EEG) and EMG signals in humans. In the meantime, the electrical stimulation of motor nerves was used as the feedback signals in the systems. The EEG command signals for FES is 5 to 25 bit per minutes which is very low. Improvements in signal processing, translation algorithms and user training are important to obtain faster and more accurate signals. One of the challenges of the EMG signals is the stimulation artefacts. Sinkjaer (2003) suggests using blanking circuit to avoid that while recording the EMG amplitude.

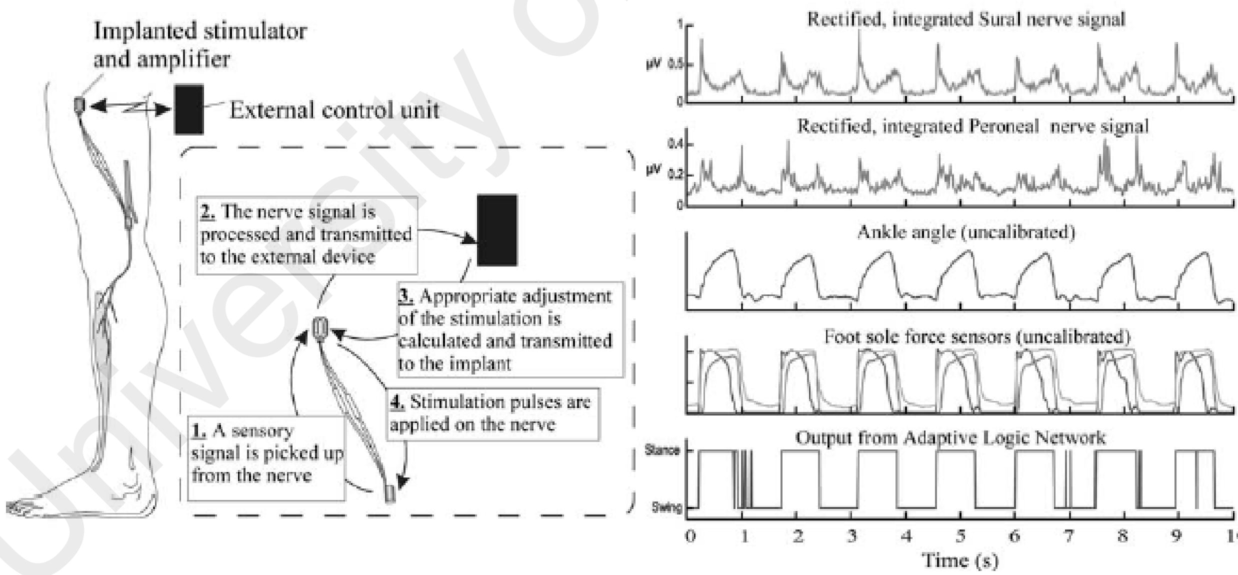

Figure 2.3 : Foot drop correction system. (Adapted from Sinkjaer, 2003)

Another study (Figure 2.3) reviewed by Sinkjaer (2003) is a foot drop correction system. The data obtain from sural nerve or peroneal nerve by using natural sensory to determine foot-to-floor contact. Adaptive logic network (ALN) processed the nerve signals. Then, the output was transferred through a set of restriction rules that decided when to stimulate the nerve. Through the same multipolar cuff electrode used for recorded the sensory signal on the peroneal nerve, the peroneal nerve being stimulated. However, as mentioned before the ENG signal is too low and difficult to analyze.

A clinical research done by Yu-Luen Chen (2004) develop a feedback controlled FES which is controlled by three tilt switches attached on the lateral sides of thigh, low leg, and fifth metatarsal of affected-side foot to detect the angular displacement of both knee and ankle. Meanwhile footswitches located on the unaffected-side plus affected-side and on the first metatarsal of the affected-side trigger the FES system to function with real time feedback. The muscles involved are tibialis anterior and quadriceps muscle. The hardware structure of the system is shown in Figure 2.4.

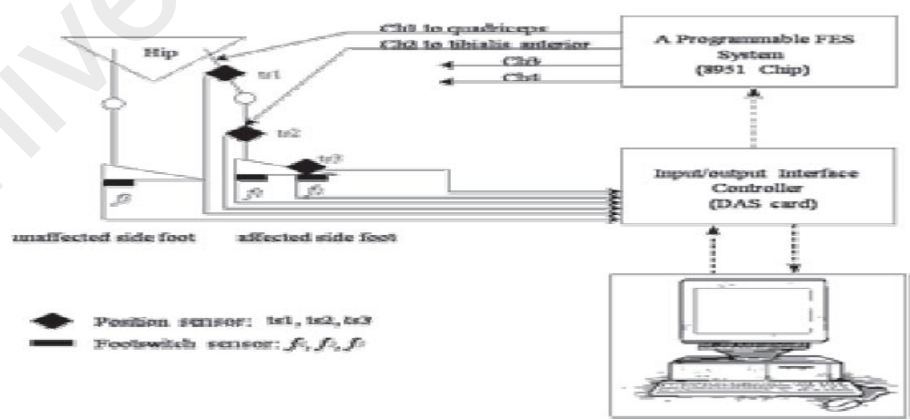

Figure 2.4 : The hardware structure of the proposed new feedback controlled FES system, which can work in two modes. (Adapted from Chen, 2004)

The feedback controlled FES system prevents these muscles from drop foot and instability in stance phase respectively. The output current intensity, the delayed time, the pulse duration and the frequency of FES were controlled and recorded by the main controller. Generally the system is comparing the data from tilt sensors θ (ts1, ts2, ts3) and the footswitches, T(f1,f2,f3) to stimulate patient muscles with the optimum parameters.

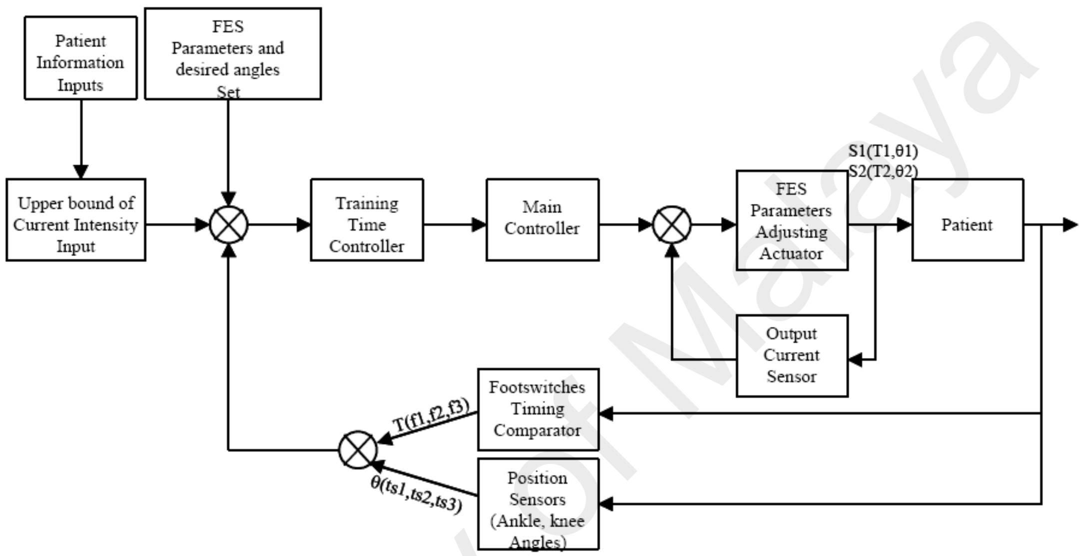

Figure 2.5 : Control architecture of the proposed sensors (footswitches and tilts) in feedback controlled FES modality. (Adapted from Chen, 2004)

As a result, the functional ambulation category (FAC) of the only hemiplegic subject improved from level 2 which need an assistance to walk to a better level 4 after tested within 15minutes per day for 12 weeks. After ninth week, there was no significance difference between the affected site feet with non affected foot based on the result by EMG.

Baumann (2011) work related to a closed loop FES system with neural feedback which controls a limb referred to the information recorded from a single nerve bundle. The nerve bundle is dorsal root ganglia (DRG). The action potentials from subject neurons recorded by the electrodes inserted into DRG. This is possible as the cell bodies for afferent fibers contained in DRG enter the spinal cord. The study recorded the signals from lumbar DRG in cats which decode the limb position and velocity.

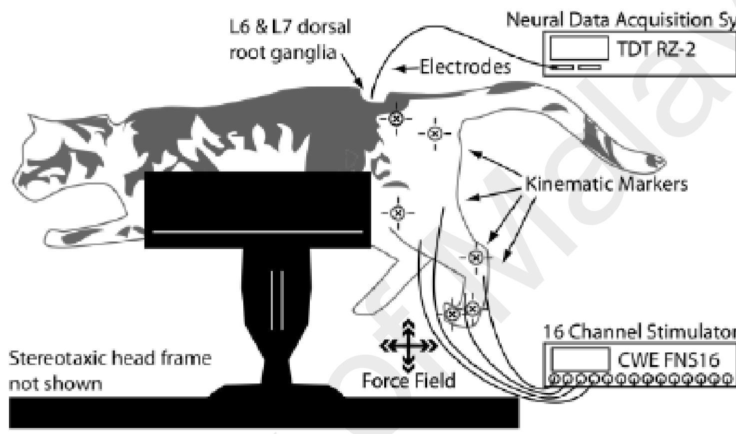

Figure 2.6 : Experimental setup. Adapted from Baumann (2011)

In order to record the neural activity, 40 and 50 channels of Blackrock MultiPort arrays were inserted in the L6 and L7 DRG. The hind limb kinematics was tracked by the active LED as shown in Figure 2.6. Besides, the hip, knee and joint ankle spanned as the electrodes were placed in muscles. Forces were generated by a haptic robot (not pictured) attached to the foot for simulating ground contact.

Finally, the objective of the study is achieved as the system can convey the position, velocity and force information for the limb by accessing the sensory neurons. However, the accuracy of the system is not accurate enough. Figure 2.7 shows the actual (solid line) and estimated (dotted line) position of the toe are not exactly the same.

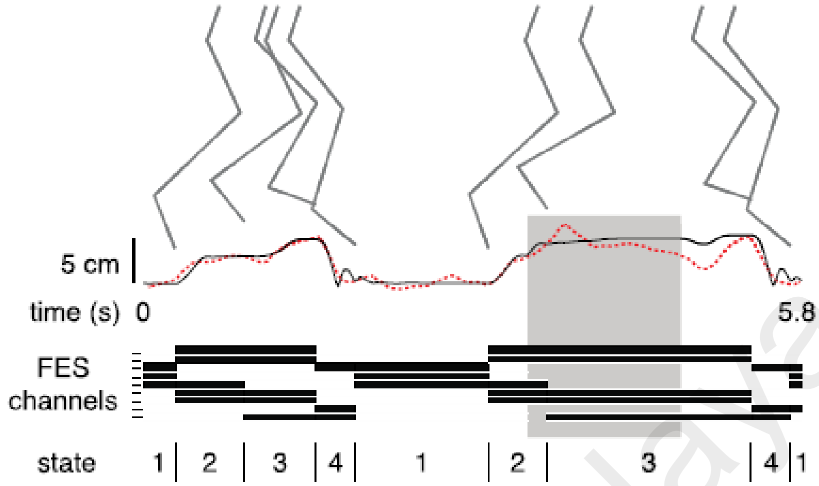

Figure 2.7 : Two step cycles of online feedback control of limb position. The stick figures at top represent the actual limb posture at each state transition. (Adapted from Baumann, 2011).

Based on these latest works FES system with feedback control, the results obtained are not accurate enough. There are some problems with signal processing as well as the feedback function. Moreover, the FES system with feedback test on animal is not encouraged as the result may not be the same as tested on human being. Thus, a more reliable FES system with feedback control is developed in this study to avoid all of these problems. Besides, there was no research has compared the temperature of the skin while muscle is being stimulated.

CHAPTER 3

3. 0 METHODOLOGY

In this chapter, we will discuss at length the explanation on the flowchart of the project, the schematic diagram of the circuits and the communication between the FES system with the feedback control. The discussion on the latter part starts with the overall system of FES, followed by the explanation on the control system part, muscle stimulator and the subject.

3.1 Project Flow Chart

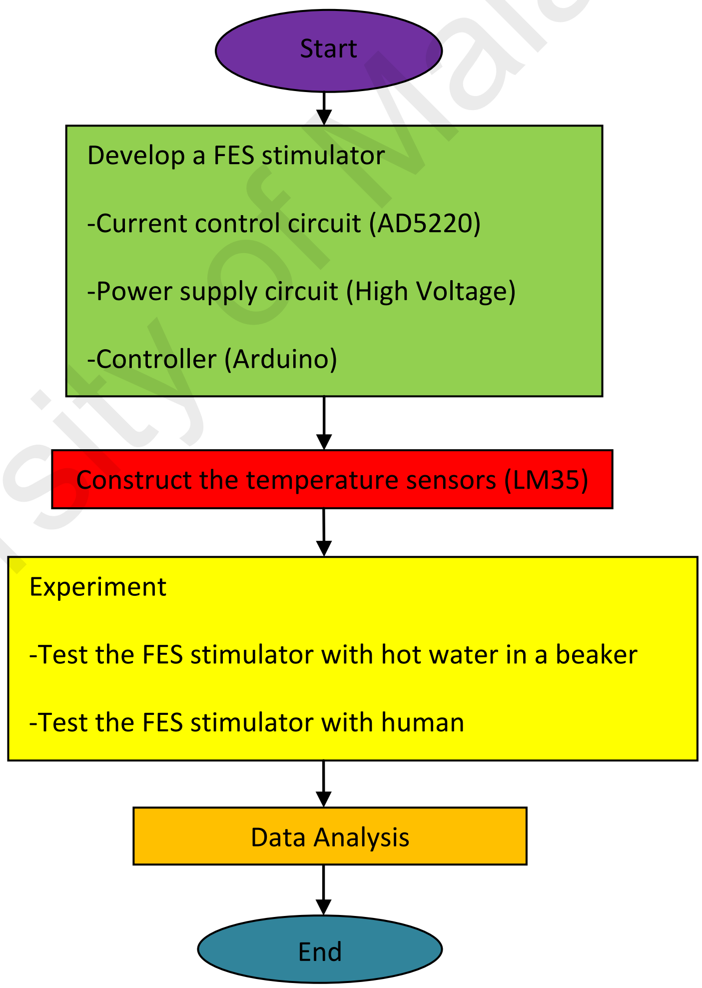

Figure 3.1 : Project flowchart

First, a FES stimulator was developed. The FES stimulator includes the current control circuit, the high power voltage, and the controller. The current control circuit output was connected to the gate pin of N-channel MOSFET (metal–oxide–semiconductor field-effect transistor) which switched the high voltage from the high power voltage. This high voltage stimulated the muscle according to the stimulation parameters provided by the current control circuit. The output of the current control circuit was controlled by a digital potentiometer connected to the controller, Arduino.

Second, the temperature sensors circuit was constructed. Four temperature sensors were considered in this study. Arduino Duemilanove was used to transmit and read data from the temperature sensors to the current control circuit.

Two parts were applied in this project. First, the FES system is tested to a beaker of water. Temperature sensors were attached on the surface of the beaker. The user was allowed to enter the desired temperature value. The Arduino compared the user input value with the average value of the temperature sensors and commands the digital potentiometer to adjust the output voltage of the current control circuit. Second experiment is the same as the first one but it was applied on human skin. The measured skin temperature was compared to the user input value and the digital potentiometer adjusted the required output current.

3.2 Block Diagrams of the Project

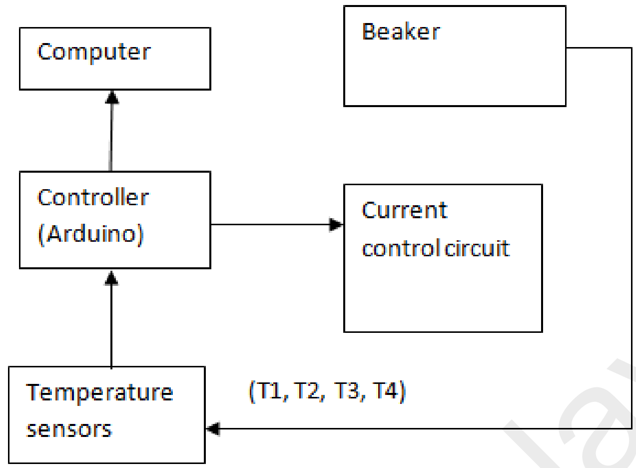

Figure 3.2 : Block diagram for the experiment with beaker of hot water

Figure 3.2 illustrates the interaction between the hardware for the experiment. The temperature sensors measured the temperature of the beaker and transmit the data to Arduino. Then, the controller increased or decreased the current value by adjusting the resistance value of the digital potentiometer. The computer displayed the data of the measured temperature as well as the resistance value after each second.

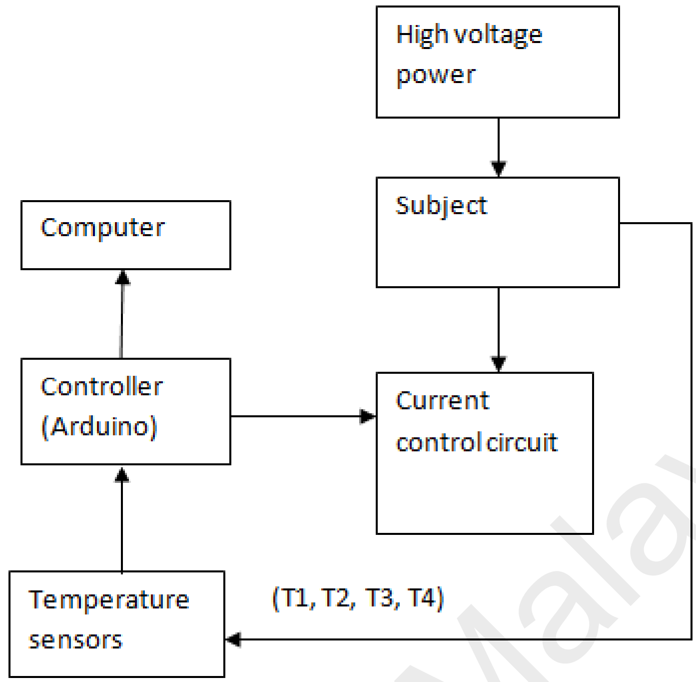

Figure 3.3 **:** Block diagram for the experiment with the subject

Generally the block diagram (Figure 3.3) of this experiment is the same as the first experiment (Figure 3.2). The obvious different is that there is high voltage power is employed to stimulate the muscle. However, the amplitude current of the high voltage kept changing as it was adjusted by the current control circuit. The resistance value of the current control circuit was controlled by Arduino. The Arduino received data of temperature values from the sensors attached to the subject's skin. Every second, the computer displayed the value of the skin temperature as well as the resistance value of digital potentiometer in the current control circuit.

3.3 Schematic Diagrams

The schematic diagrams of the development FES circuit were drawn by using the National Instrument Multisim version 12.0. It assists in circuit design flow including the schematic capture and simulation.

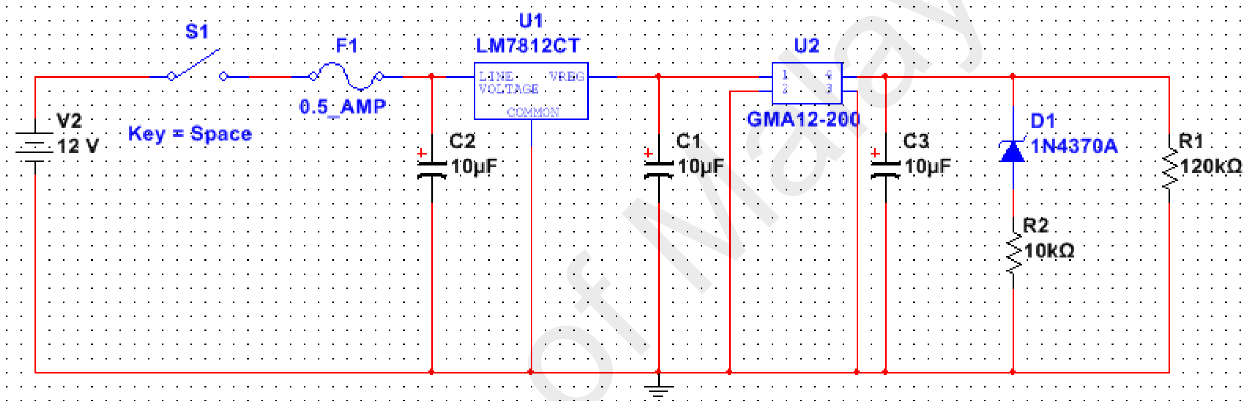

Figure 3.4 **:** Schematic diagram of power supply

Figure 3.4 presents the schematic diagram of power supply circuit. The function of the fuse is to protect the circuit from short circuit. The voltage regulator (LM7812) together with capacitors, C1 and C2 ensured that the voltage supply to the circuit maintain with 12 V to protect the circuit from overload if the supply voltage is high. The DC-DC converter (GMA12-200) converts the 12V to 200V. Zener diode and resistors ensured the voltage not increasing beyond 200V in order to protect the circuit.

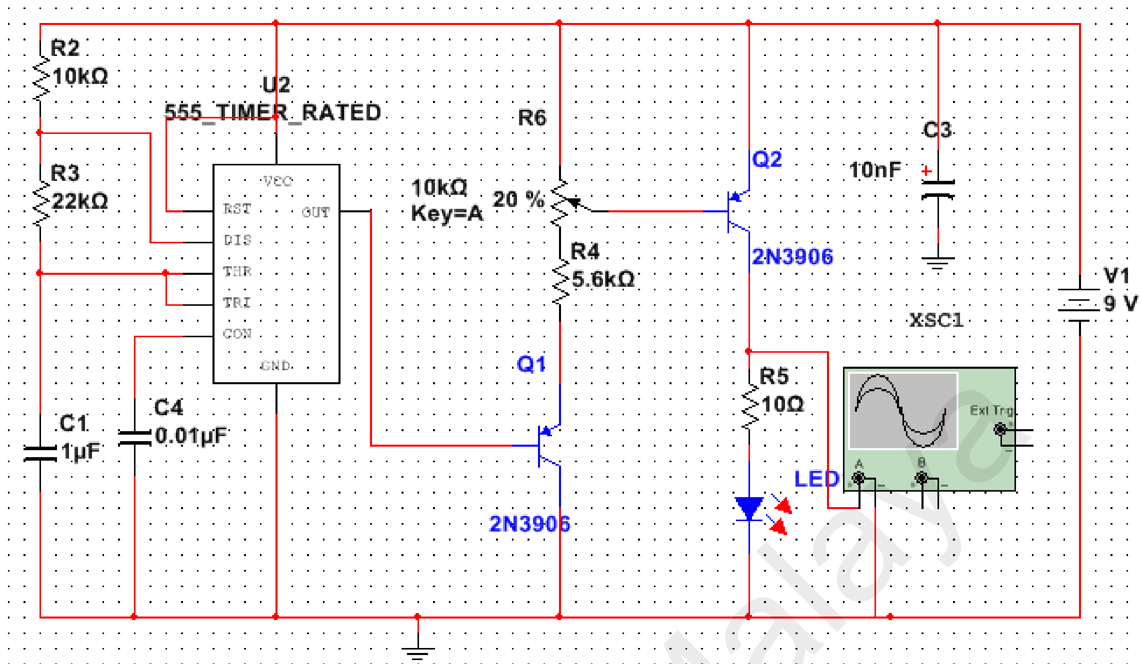

Figure 3.5 : Schematic diagram for current controlled circuit

The current controlled circuit has a basic 555 timer astable circuit which produce square waveform. The value for resistors and capacitors were chosen such that the circuit will produce a frequency approximately closer to 30Hz. The potentiometer controls the amplitude value. If the wiper is tapered closer to state A of the potentiometer, the output will become almost zero. Meanwhile if the wiper is tapered towards the state B, the output will be in its maximum state. The voltage supply is 9V DC and the capacitor ensured the current is flowing towards the ground and not the other directions as shown in Figure 3.5.

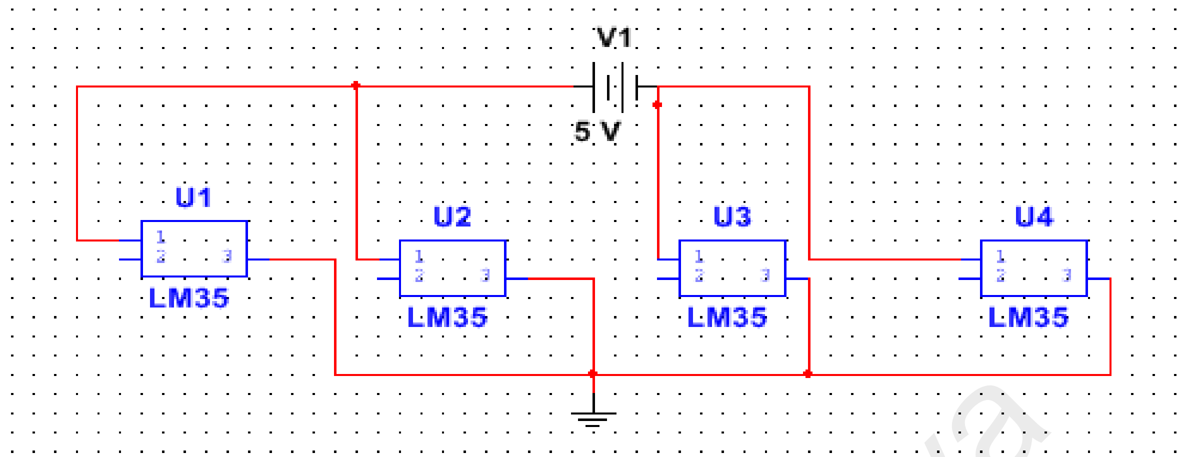

Figure 3.6 **:** Schematic diagram for temperature sensors (LM35)

The schematic diagram for temperature sensors (LM35) is shown in Figure 3.6. Four temperature sensors were used to measure the temperature of the beaker and the skin temperatures. The first pin (+Vs) is connected to 5V and the third pin (GND) is connected to the ground. The second pin (Vout) is placed on the outside surface of the beaker and later on the subject skin.

3.4 Details on FES System and Feedback Control

The design involved the portable computer, muscle stimulator and temperature sensors as shown below in Figure 3.7.

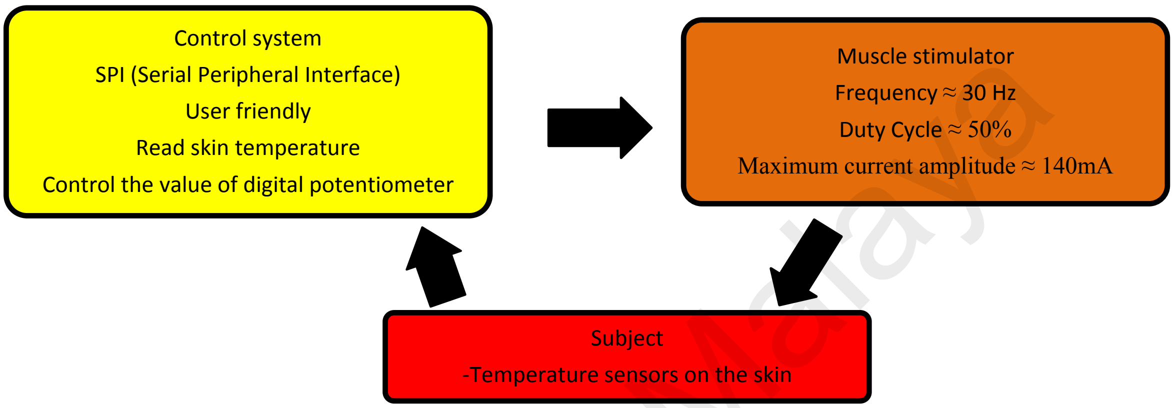

Figure 3.7 **:** Overall system of FES with feedback control

The control system has a microcontroller embedded in Arduino Duemilanove to read the skin temperature and control the value of digital potentiometer while subject's muscle is being stimulated by the muscle stimulator. The stimulator circuit produces the square waveform with approximately 30Hz of frequency, 50% of duty cycle and 140mA maximum constant current. There are four temperature sensors will be attached to the subject muscle. The controller in stimulator circuit will compare the value of temperature entered by the user with the current average value of the four sensors. If there are differences between them, the controller will command the digital potentiometer to increase or decrease its value in order to change the current supply to stimulate the muscle. Each of the components will be described in further details.

3.4.1 Control System

In the control system part, Arduino Duemilanove (Figure 3.8), an easy-to-use open source physical computing platform which has a 28 legs chip called ATmega328. It has two major parts which are the Arduino board and the Arduino IDE (Integrated Development Environment) represents the hardware and software elements respectively. The computer program used is simple C programming. The code can be easily uploaded to the hardware by the IDE via a USB cable.

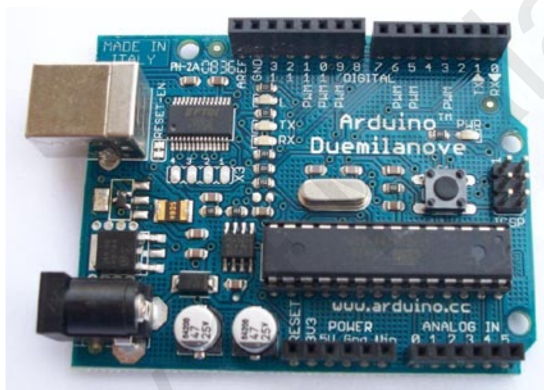

Figure 3.8 : Arduino Duemilanove

In this project, the programming code is receiving and sending data from the computer to the hardware and vice versa by using a serial object. Besides, by pressing the “Serial Monitor” icon on the Arduino IDE, the data received will be appeared as shown in Figure 3.9. Besides it has a simple command to ask the user to input data. In this case, the user input is the desired skin temperature during the stimulation process.

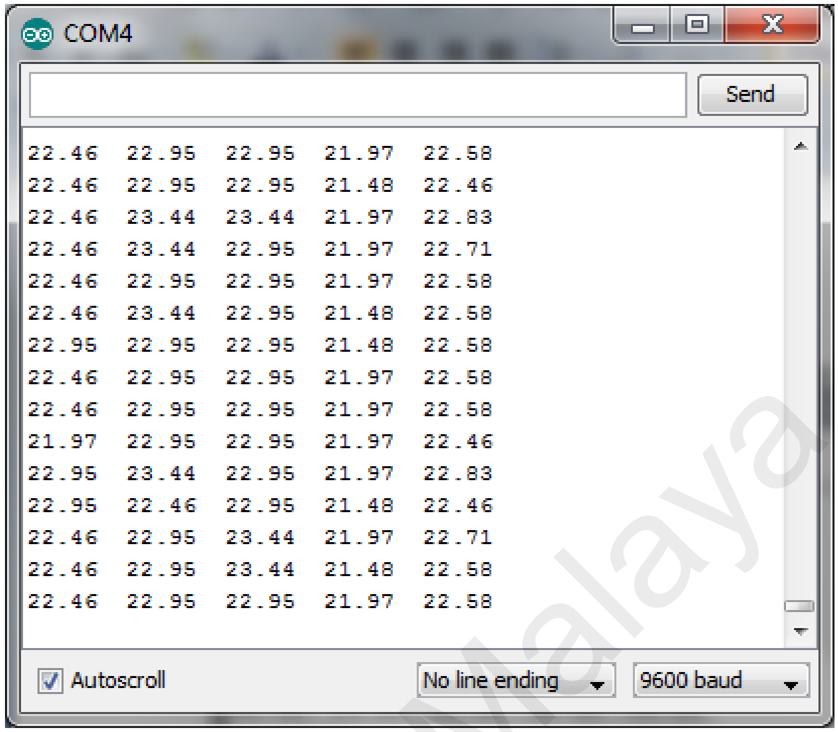

Figure 3.9 : Serial Monitor displays the temperature data from Arduino pins

After the user key in the input into Arduino IDE, the microcontroller; ATmega328 will compare the value with the average value of the 4 temperature sensors (LM35) (Figure 3.10). LM35 produces an output value in degree Celsius.

Figure 3.10 **:** Temperature sensor, LM35

It is easy to use LM35 because it does not require any external calibration to provide typical accuracies of ±1°C at +25°C and ±2°C over the –40°C to +125°C temperature range. In the program code, the inputs received from the analog pins of the Arduino board (A1-A4). The measured value added up together and the average of that value is evaluated by the controller and then the data is displayed on the computer screen.

After the microcontroller compared the user input value with the average value of the temperature sensors, the 8 pins 10kΩ digital potentiometer (AD5220) was functioned. There are only three pins of AD5220 connected to digital pins of the Arduino board namely clock, clk (pin1 to pin D6), up/down, U/D (pin 2 to pin D7) and CS (pin 7 to pin D5).

If the user input value is greater than the average value, microcontroller will ask it to lower its resistance by changing its wiper position and vice versa until both values are equal to each other. It can be easily done by changing the output of the U/D pin either high (1) or (0). The part of this coding is simply referring to the truth table and the timing diagram stated in its datasheet.

3.4.2 Muscle Stimulator

The muscle stimulator stimulates square waveform with 30Hz frequency, 60% duty cycle and 100mA maximum current amplitude. By constructing a simple 555 timer circuit based on the formula for its resistors and capacitor values, the output of 555 timer is easily been obtain. The values of components used in 555 timer circuit are shown in Figure 3.11 by using software named fritzing.

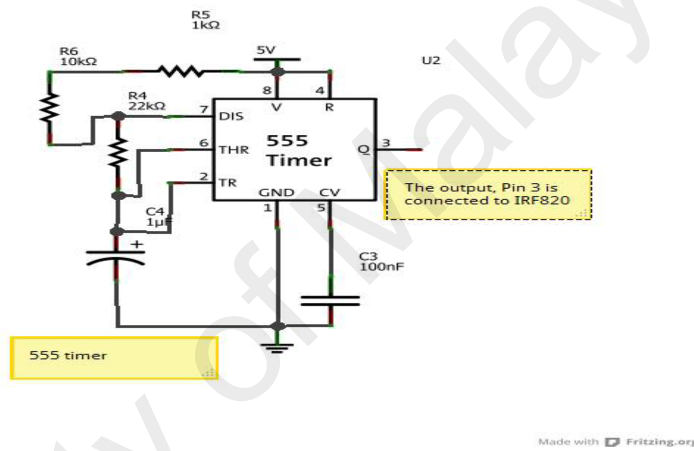

Figure 3.11 : The 555 timer circuit

The frequency of the 555 timer circuit is approximate to 30Hz, its duty cycle (D) is 60% (1) and the pulse width is 20ms (2). First the value for capacitor, C1 is chose which is 1µF. Then, the formula below (3) was used to obtain the value for R2.

$$D = \frac{R1+R2}{R1+2R2} = \frac{11k+22k}{11k+2(22k)} = 0.60 = 60\% \qquad (1)$$

$$t = \frac{1}{f} xD = \frac{1}{30} x\ 0.60 = 0.02s = 20ms \qquad (2)$$

$$R2 = \frac{0.7}{(30Hz\ x\ 1\mu F)} \qquad (3)$$

$$= 23k\Omega\ (R2\ chosen\ is\ 22k\Omega)$$

The value of resistor R1 is 10 times lesser than R2. Thus,

$$R1 = \frac{R2}{10} = \frac{22k\Omega}{10} = 11k\Omega \tag{4}$$

The output of the 555 timer is connected to the gate (G) of N-channel 500V - 2.5Ω - 4A TO-220 MOSFET. The function of this N-channel MOSFET is for switching. The high voltage (200V) produced from the power supply circuit will be connected to the drain (D) of IRF820 (Figure 3.12) while the source (S) of the MOSFET will be connected to the ground. Two pins (B1, terminal B1 and W1, wiper) from the 10k Ω digital potentiometer, AD5220 were connected in between pin 3 of 555 timer and the gate pin of IRF820. This allows the flowing current through the electrodes changing during stimulating the current.

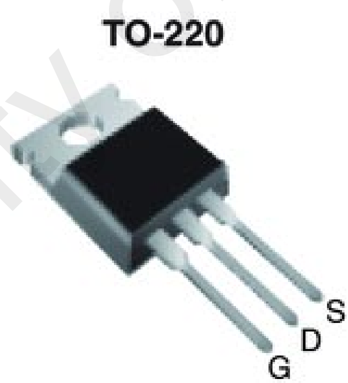

Figure 3.12 : N-channel MOSFET IRF820

The main component in the power supply circuit is GMA12-200PE which converts the 12V to 200V which is high enough to stimulate the human muscle. The safety instruction for using this component is attached in the Appendix C.

3.4.3 Subject

Electrodes were attached to the subject at the proximal and distal of Vastus Lateralis muscle of the lower body. The electrodes will be powered by the HV power supply (200V) and the current will keep on changing which is controlled by the microcontroller as there is a difference between the temperature sensors and user input. A gel is applied to the surface of the subject's skin before the electrode is placed on the skin to reduce skin resistance.

CHAPTER 4

4.0 RESULTS

4.1 Development of FES System with Feedback Control

In this section, a complete description of the FES system with feedback control is explained. Each part in the system as shown in Figure 4.1 was tested to ensure that it is functioning. Subsequently, the parts will be assembled together.

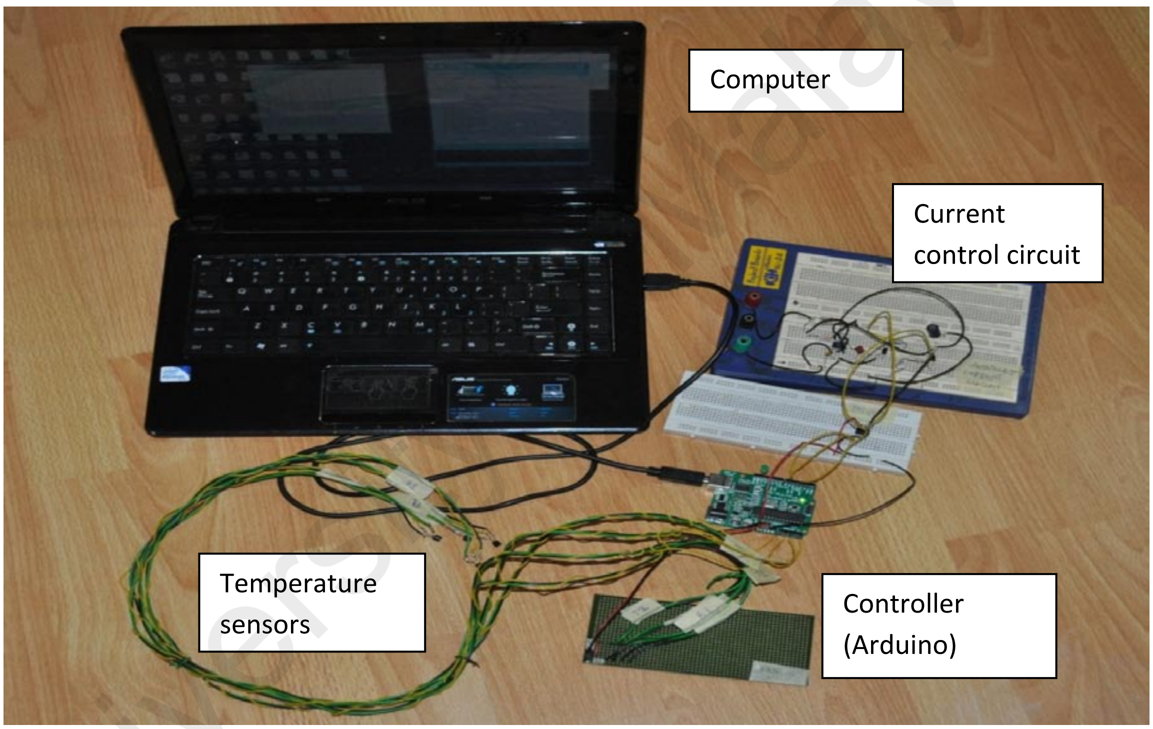

Figure 4.1 : The core hardware of the system

4.1.1 Computer

The computer received and displayed the data transmitted by Arduino. Arduino and the computer were connected by Universal Serial Bus (USB) connection. The data received was displayed on the Arduino 'Serial Monitor' window. The serial port sends data to computer at 9600 bits per second.

4.1.2 Arduino Duemilanove with Atmega328 Chip

Arduino Duemilanove received the data from the temperature sensors and commands the digital potentiometer. The data from both temperature sensor and digital potentiometer were displayed by the computer. The computer communicates with Arduino through universal serial bus (USB).

4.1.3 Current Control Circuit

The figures illustrate the output waveforms for the current controlled circuit using software named National Instrument Multisim Edition 12.0. The amplitude of voltage changed when the potentiometer is adjusted to its maximum and minimum value. Based on Figure 4.2 and Figure 4.3 the output voltage is zero when the potentiometer at its maximum state. In contrast the output voltage is 1.061V when the potentiometer at its minimum state.

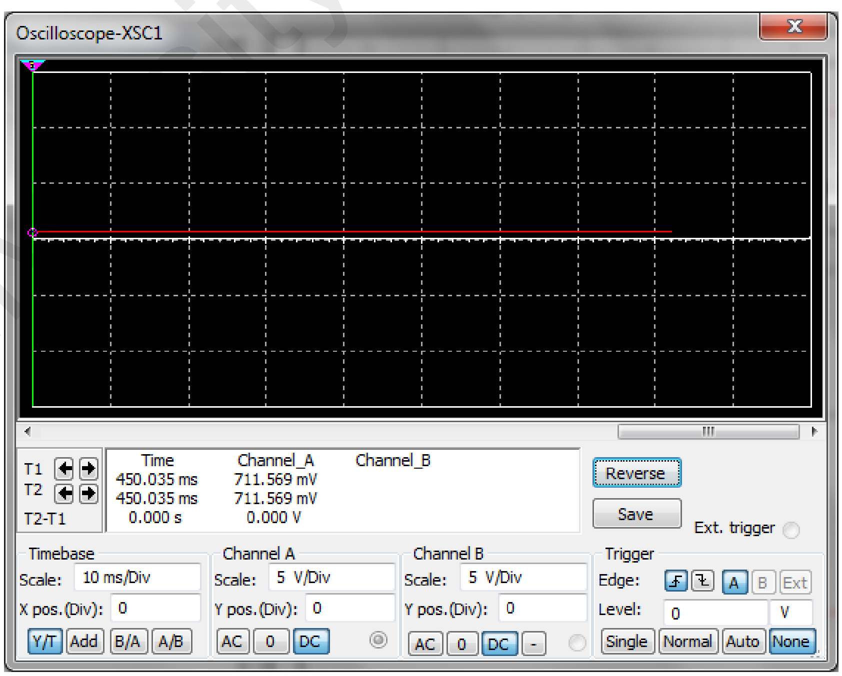

Figure 4.2 : Output voltage when potentiometer at its maximum value (0%)

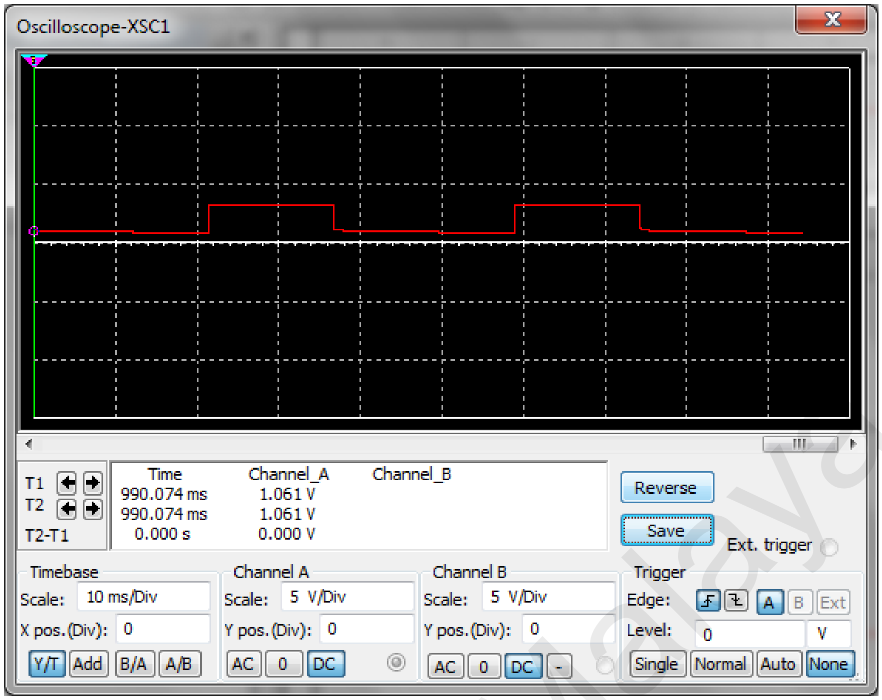

Figure 4.3 : Output voltage when potentiometer at its minimum value (100%)

The real result of the output waveforms of current control circuit using oscilloscope is shown in Figure 4.4. The frequency of the square waveform is 32.59Hz. The peak to peak voltage is 4.8V and the period is 30.68ms.

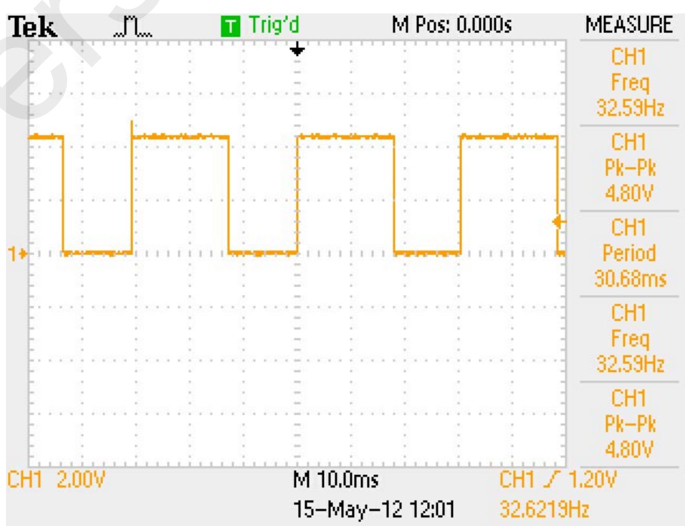

Figure 4.4 : The output waveform of 555 timer

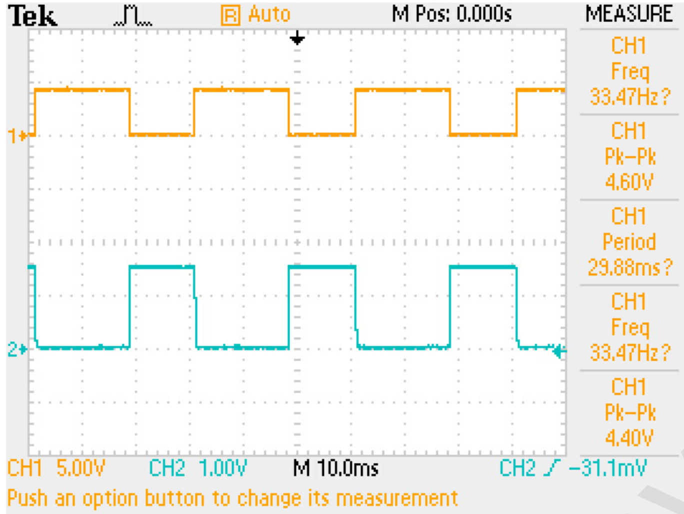

Figure 4.5 : Output waveforms of 555 timer and the current control circuit

Figure 4.5 illustrates both the 555 timer output (orange) and the current control circuit output (green). The maximum value of the 555 timer output is 5V. Meanwhile, the overall current control output is approximately 1.6V. Both are different because of the resistance value is more towards the overall output of the circuit.

In addition, there is a huge different between the simulated output waveform (Figure 4.3) and the experiment output waveform (Figure 4.5). The simulated value is 1.061V meanwhile the experiment value is 1.6V.

The amplitude of the output waveform is different as digital potentiometer adjusted the wiper either towards its minimum state (A) or towards its maximum state. The maximum voltage peak to peak is 1.76V. On the other hand the minimum voltage peak to peak is 0V. The results are shown in figures below:

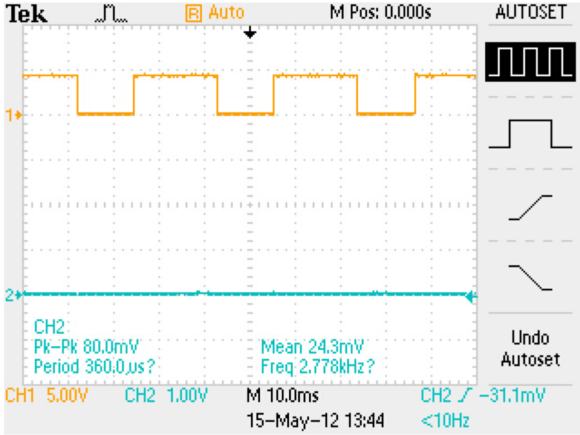

Figure 4.6 : Peak to peak voltage is 0V(minimum)

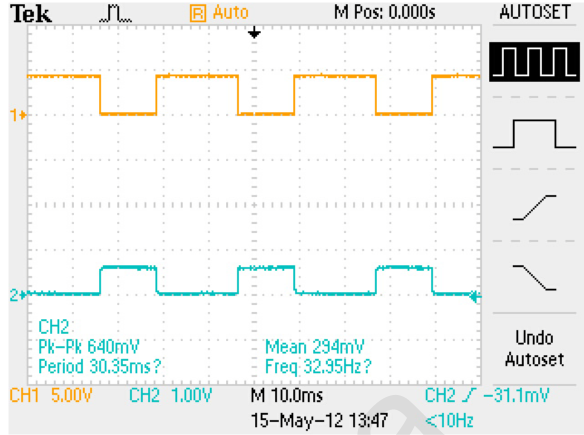

Figure 4.7 : The minimum output value 0.64V

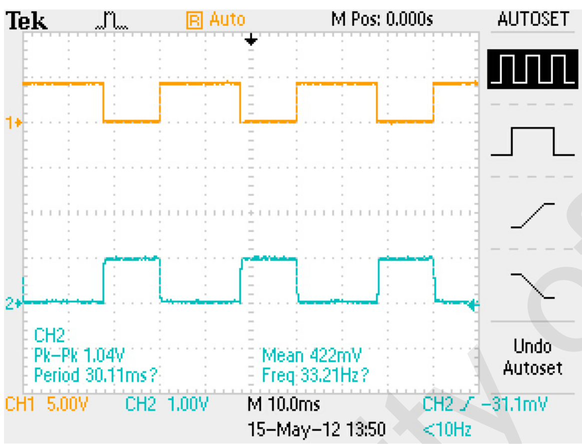

Figure 4.8 : Peak to peak voltage is 1.04V

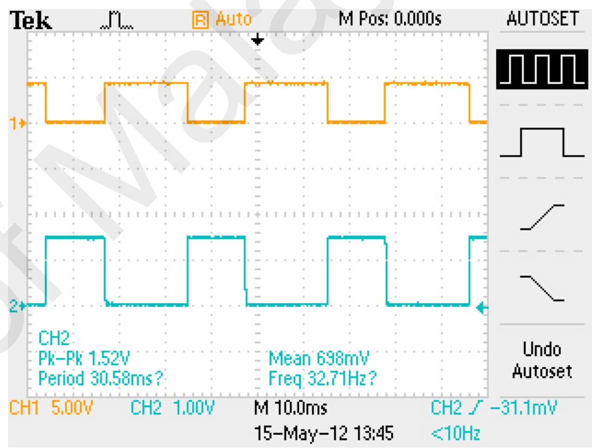

Figure 4.9 : Peak to peak value is 1.52V

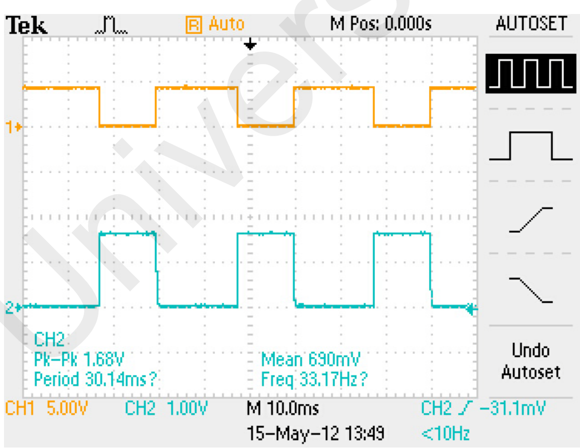

Figure 4.10 : Peak to peak value is 1.68V

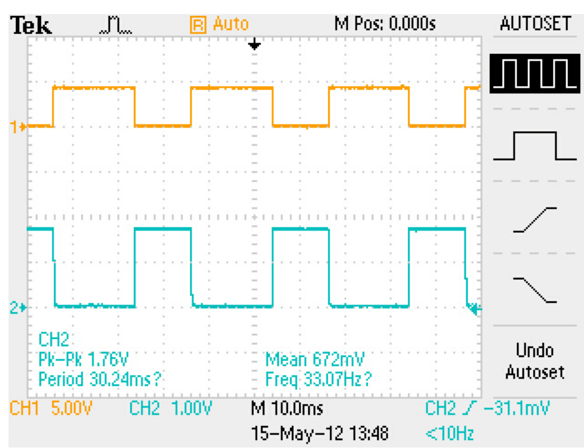

Figure 4.11 : Peak to peak value is 1.76V (maximum)

The digital potentiometer (AD5220) was tested and the value obtained from the Serial Monitor of the Arduino. Based on the AD5220 timer operation, the digital potentiometer will increased its wiper position if the up/down pin is in the low state. The result in Figure 4.12 proved that. Meanwhile, the wiper position will be decreased towards the ground if the up/down pin is in the high state. The data is shown in Table 4.1.

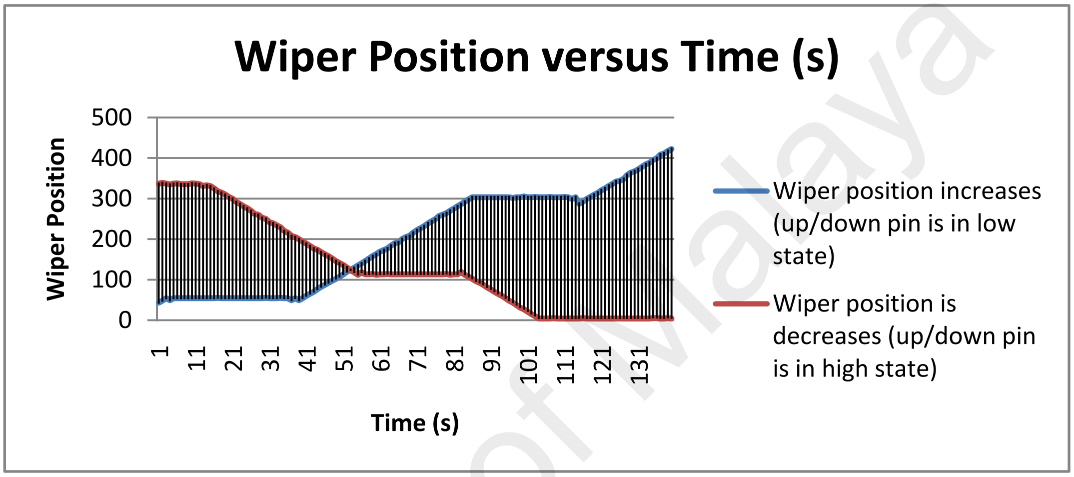

Figure 4.12 : The digital potentiometer test

Table 4.1 : Wiper position value when the up/down pin is high and low condition

Time (s)	Wiper position (up/down pin is in low state)	Wiper position (up/down pin is in high state)
1	43	337
10	54	338
20	54	304
30	55	250
40	54	194
50	107	141
60	163	112
70	216	113
80	270	112
90	303	81
100	305	27
110	303	4
120	314	4
130	367	4
140	422	4

4.1.4 Temperature Sensor

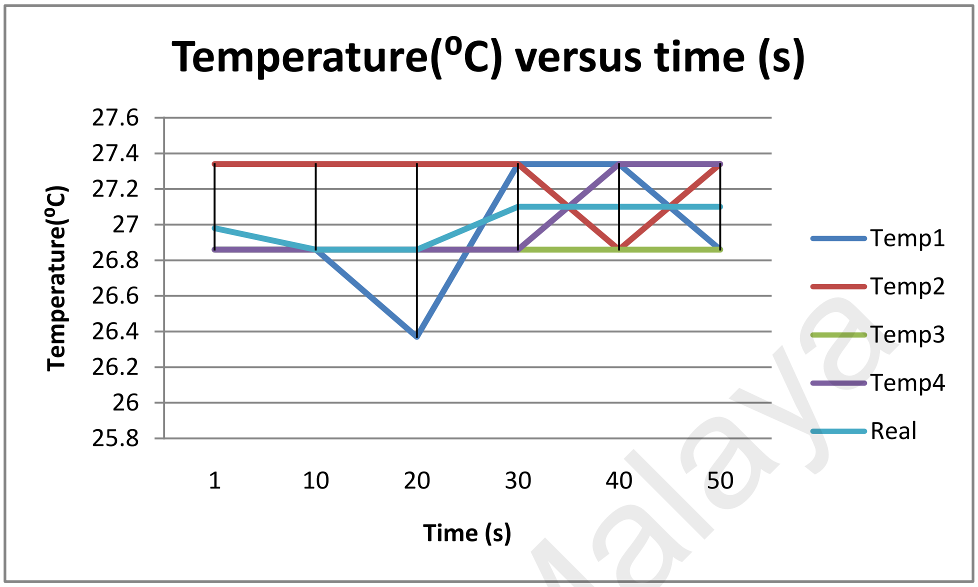

Figure 4.13 : Temperature sensor test

Before the temperature sensors circuit is connected to the Arduino analog pins (A1, A2, A3 and A4), the sensors were tested first. The value obtain from the four sensors (Temp1, Temp2, Temp3 and Temp4) were compared to the real environment temperature sensor (Real). The values were taken for every ten second for fifty seconds. The results in Figure 4.13 indicate that the measured values are getting close to the real temperature starting at 30 seconds after the test was started. Thus, the sensors are reliable to be used. The data of the graph is shown in the Table 4.2.

Table 4.2 : The measured temperature values and their average values

Time (s)	Temp1 (ºC)	Temp2 (ºC)	Temp3 (ºC)	Temp4 (ºC)	Real Temperature (ºC)
1	26.86	27.34	26.86	26.86	26.98
10	26.86	27.34	26.86	26.86	26.86
20	26.37	27.34	26.86	26.86	26.86
30	27.34	27.34	26.86	26.86	27.1
40	27.34	26.86	26.86	27.34	27.1
50	26.86	27.34	26.86	27.34	27.1

4.2 Experiment

4.2.1 Experiment on Beaker with Hot Water

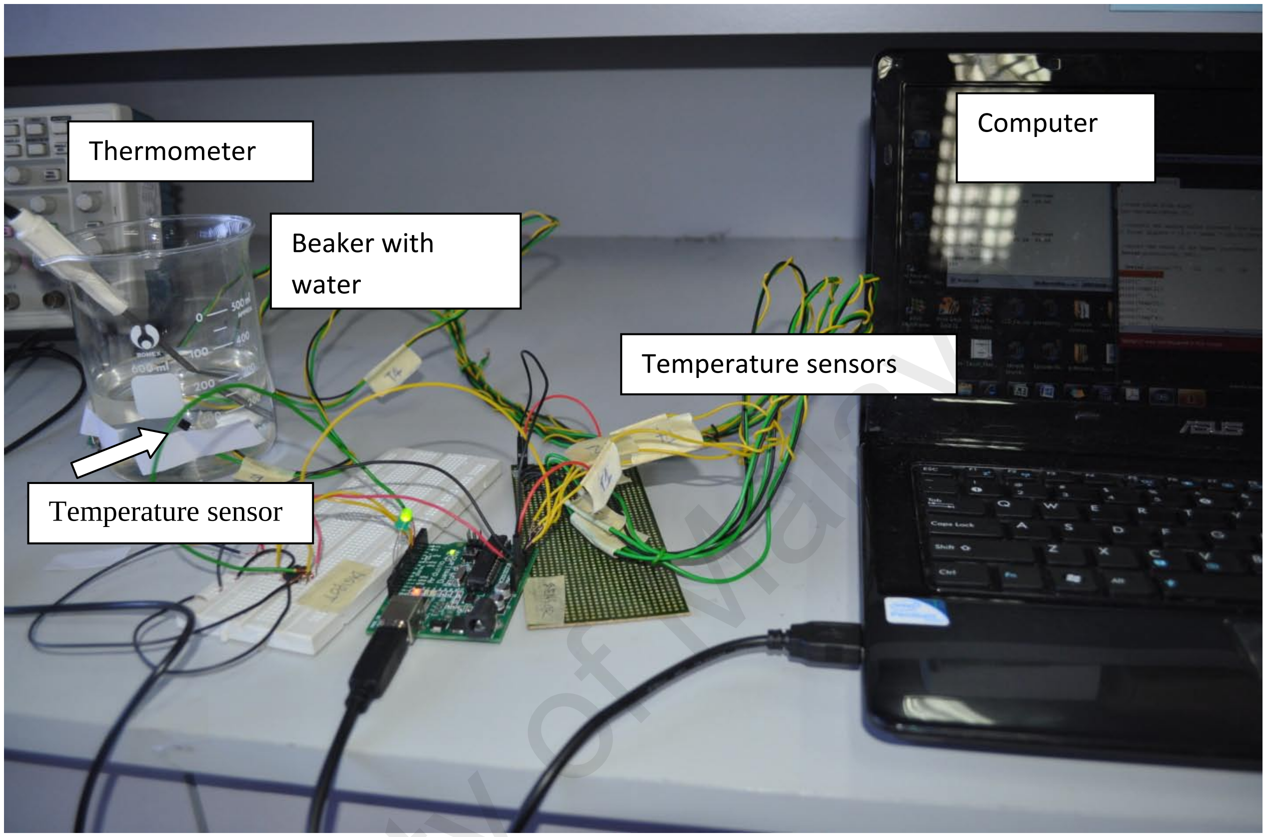

Figure 4.14 : Experiment setup (beaker with water)

The temperature sensors were attached to the surface of the beaker. A thermometer was used to measure the water temperature too. The data from temperature sensors were read for every second and displayed on the computer screen. The experiment setup is shown in Figure 4.14. User is allowed to enter an input which later its value will be compared to the average reading of the temperature sensors. The relationship between the average readings from temperature sensors with the user input values are shown in Figure 4.15. That data in Table 4.3 are used to plot the graph in Figure 4.15.

Table 4.3 : The average temperature and the user input value

User input (^oC)	Time (s)	Average temperature (^oC)
30	1	24
30	5	25
30	10	26
30	15	27
30	20	26
30	25	25
30	30	25
30	35	26
30	40	26
30	45	30
30	50	28
30	55	26
30	60	26
30	65	24
30	70	27
30	75	25
30	80	23
30	85	28
30	90	24

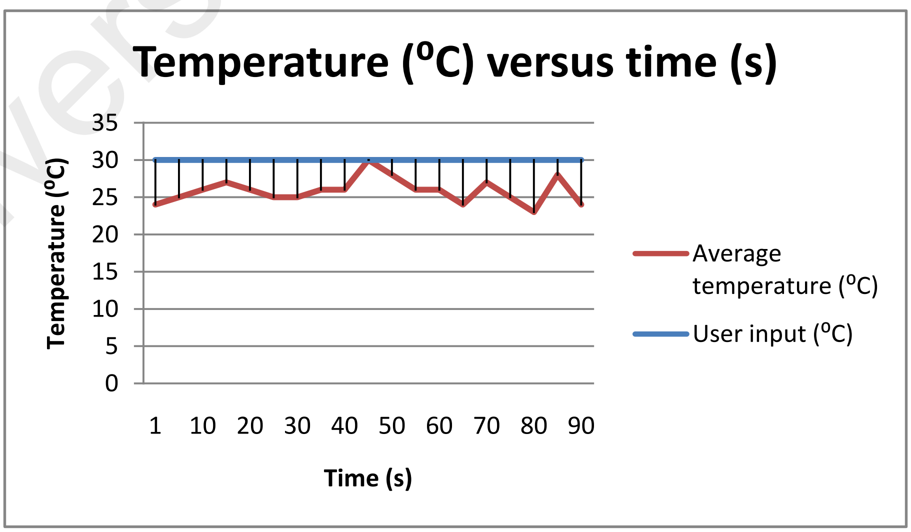

Figure 4.15 : Comparing user input with average value of temperature sensors

The user input (red) is 30^{o}C and the average of measured temperature (blue) is fluctuates nearer the user input. Another experiment on this method is shown in the Figure 4.16. The pattern of the graph is approximately the same as Figure 4.15.

Table 4.4 : The average temperature and the wiper position values when the input user is 23^{o}C

Time (s)	Average temperature (^{o}C)	User input (^{o}C)	Wiper position
1	26	23	355
10	28	23	399
15	28	23	411
20	28	23	426
25	28	23	436
30	27	23	453
35	29	23	269
40	29	23	487
45	27	23	498
50	27	23	508
55	28	23	436
60	27	23	453
65	29	23	269
70	29	23	487
75	27	23	498
80	27	23	508

The relationship between the resistance of the digital potentiometer, the user input and the average of the temperature sensors were plotted too. The user input is 23^{o}C. The resistance is keep changing according to the average temperature. On the other hand the average temperature is fluctuating near to the input user value.

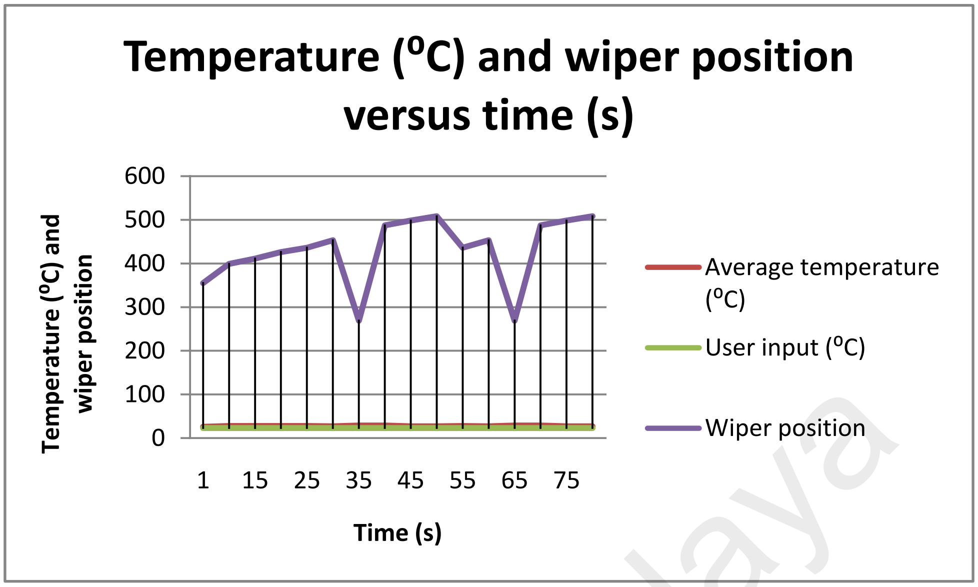

Figure 4.16 : Graph on the average temperature, user input temperature value and the resistance

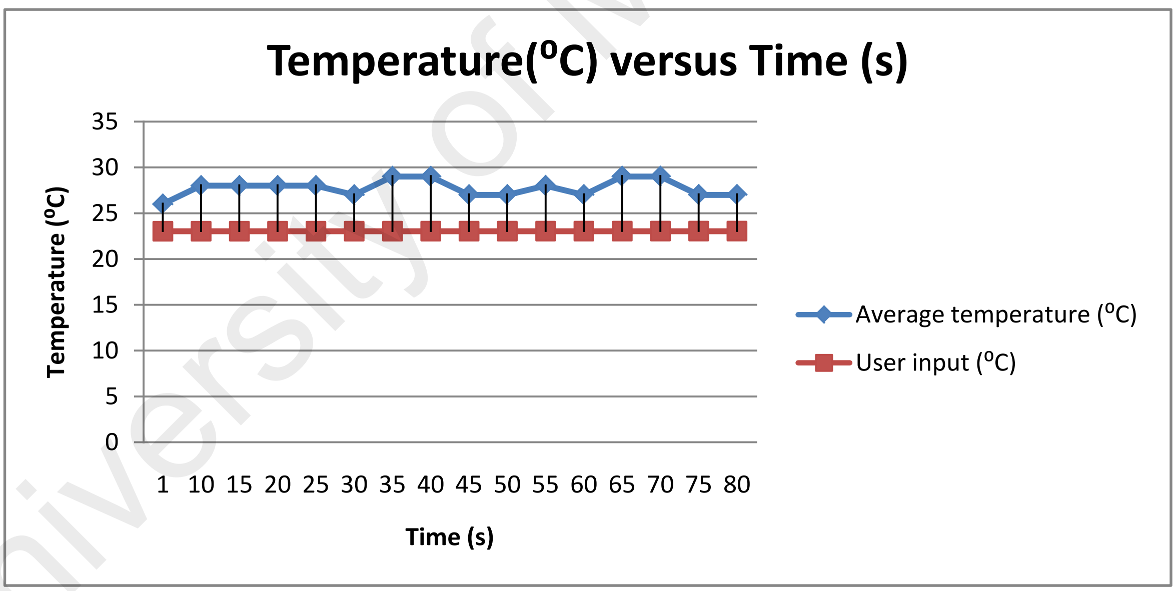

Figure 4.17 : Comparing the average temperature from sensors with user input

The graph in Figure 4.17 shows a clear figure comparing the average temperature values from the temperature sensors with the user input. The average temperature tends to varies closer to the input user value.

4.2.2 Experiment on the Human Skin

There are two trials in this experiment. The user input temperature value for both trials are 30^{o}C. The variations of the data for both trials are plotted in the graphs shown in Figure 4.19 and 4.21.

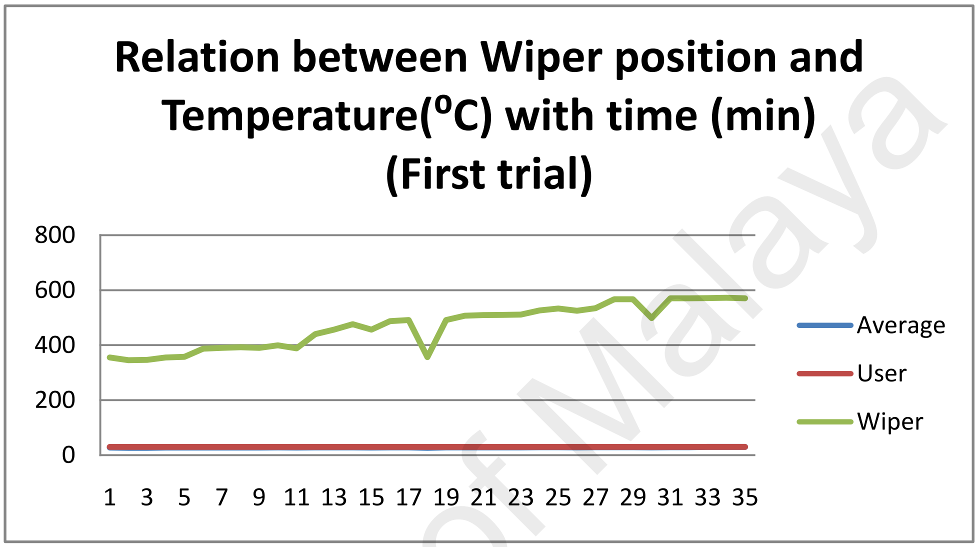

Figure 4.18 : Relation between skin temperature and resistance value (first trial)

In can be seen from Figure 4.19 that in the first trial, the user input is 30^{o}C and the skin temperature at the beginning is 27^{o}C. The resistance increases as the time passes. The skin temperature increases as well but sometimes it drops and after sometimes it increases back.

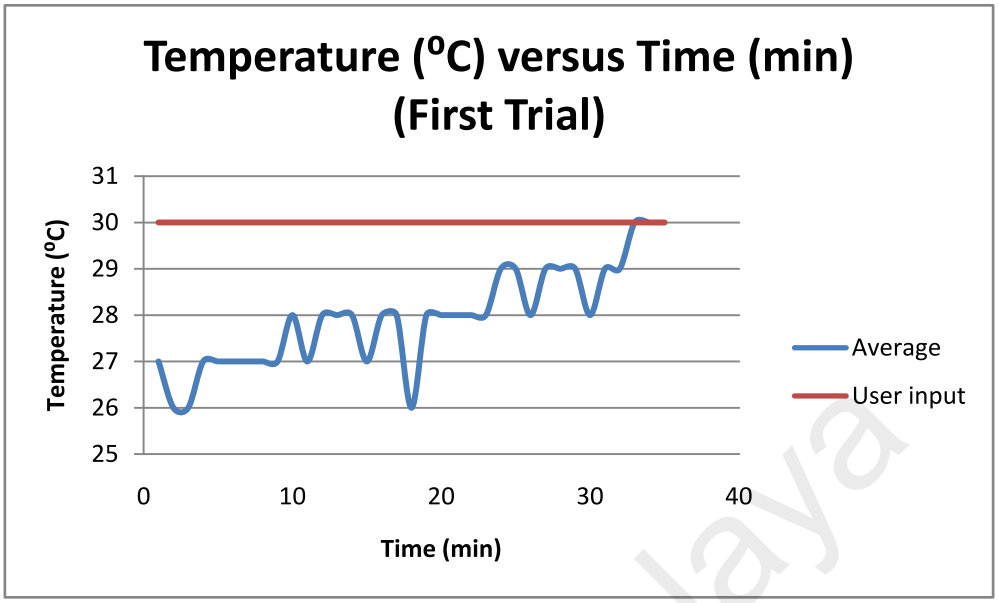

Figure 4.19 : Temperature (^{o}C) versus Time (min) (First Trial)

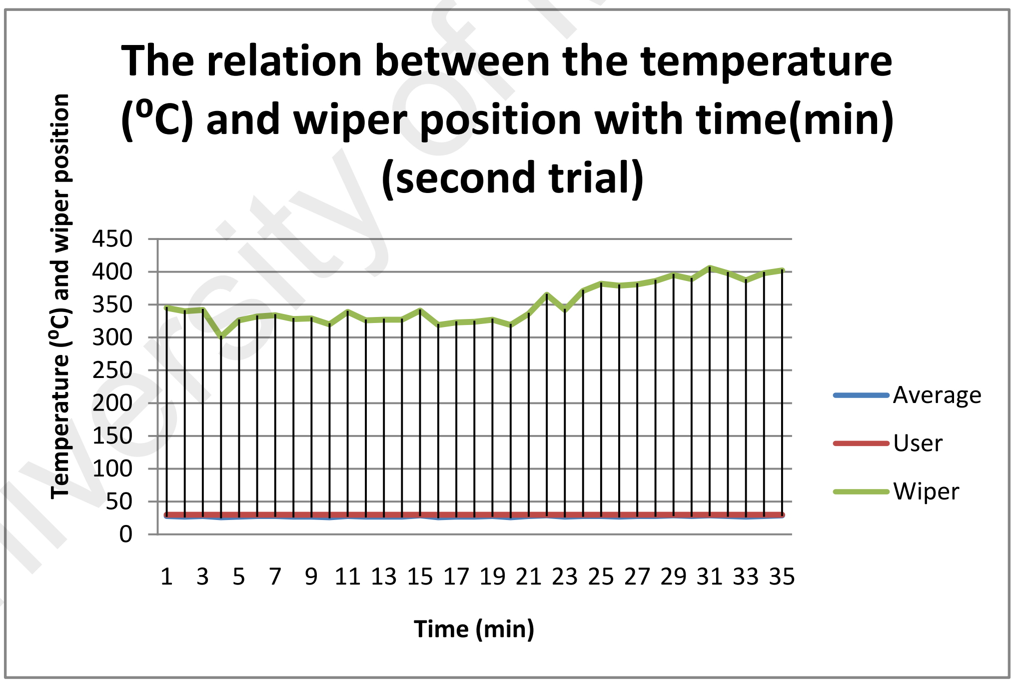

Figure 4.20 : Relation between the skin temperature and resistance value (second trial)

On the other hand, for second trial, the user input is 30°C and the skin temperature at the beginning is 28°C. The resistance increases throughout the time. However, the variation is not obvious compared to the first experiment. The average temperature is closed to the input temperature key in by the user.

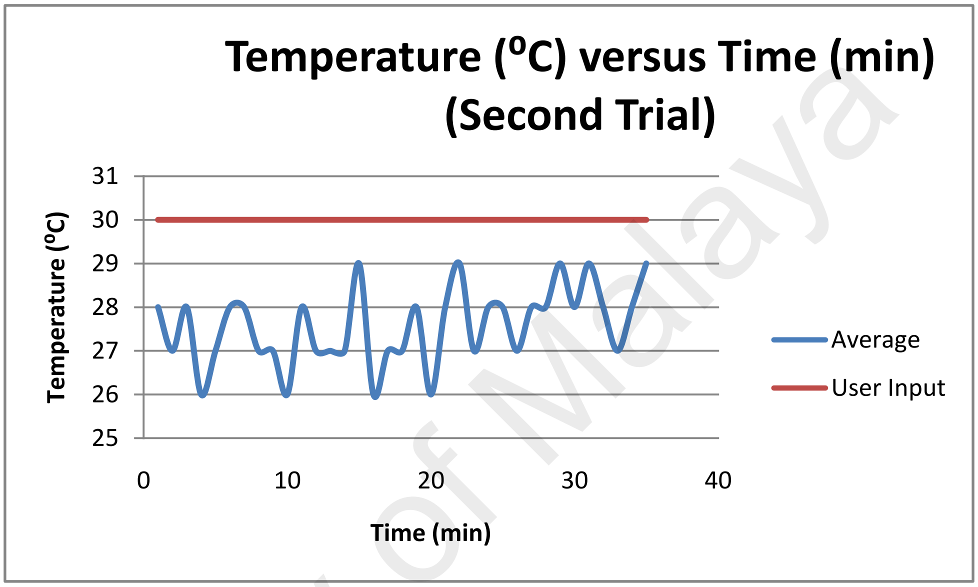

Figure 4.21 : Temperature (°C) versus Time (min) for second trial

Table 4.5 : First and second trials on human skin

Time (min)	First trial		Second trial	
	Average	Wiper	Average	Wiper
1	27	355	28	345
2	26	345	27	340
3	26	346	28	342
4	27	355	26	301
5	27	357	27	326
6	27	387	28	332
7	27	390	28	334
8	27	392	27	328
9	27	390	27	329
10	28	399	26	320
11	27	388	28	339
12	28	440	27	326
13	28	456	27	327
14	28	476	27	327
15	27	456	29	341
16	28	487	26	319
17	28	491	27	323
18	26	356	27	324
19	28	491	28	327
20	28	507	26	319
21	28	509	28	336
22	28	510	29	365
23	28	511	27	342
24	29	526	28	371
25	29	533	28	382
26	28	525	27	379
27	29	534	28	381
28	29	567	28	386
29	29	567	29	395
30	28	498	28	389
31	29	570	29	406
32	29	570	28	398
33	30	571	27	387
34	30	572	28	398
35	30	570	29	402

CHAPTER 5

5.0 DISCUSSION

The project on FES system with feedback control is divided into two parts; the development of FES system with feedback control and the experiments done in the laboratory using the FES system. Two experiments were conducted the laboratory. The first experiment was conducted to compare the user input temperature value with the average value of the readings obtained from the temperature sensors. The second experiment is done on human skin. The average values of the skin temperatures read by the sensors were compared to the user input values. The differences in both values allow the controller to command the digital potentiometer to be adjusted accordingly. The adjusted digital potentiometer affects the output current of the current control circuit. This situation causes the stimulated current on the human skin to be regulated over time.

In the first part of the project, the developed FES system parameters developed are the frequency of the square waveform, 32.59Hz, the peak to peak voltage, 4.8V and the period is 30.68ms. FES with 40 Hz is higher than other most FES application. The frequencies between 20 to 25Hz are considered too small but it can generate a smooth contraction of quadriceps. In many applications, frequency of 35 to 50Hz was selected because contraction can be generated at higher frequencies. Thus, this project with 32.59Hz is considered reliable to stimulate the muscle. But, higher frequency tends to cause the muscle to fatigue rapidly during voluntary contractions. The stimulation frequency for both experiments is 32.59Hz which in the range that is usually adopted for neuromuscular stimulation frequency. According to Frigo (2000), 40% of MVC was obtained with a current of about 60 mA at 16.67 Hz stimulation frequency meanwhile at 25 Hz only 50 mA were required. Thus, a stimulator with 32.59Hz should obtain 40% of MVC with a smaller amount of current.

It is important to point out that the simulation and experiment results of the output from the current control circuit are not similar. The maximum peak to peak voltage for the simulation result (Figure 4.3) is 1.061V. Meanwhile, the maximum peak to peak voltage from the oscilloscope (Figure 4.5) is 1.6V. This is due to the sensitivity of the digital potentiometer itself as it has 128 positions with each resistance value of 78Ω. Other component which is more stable should be used to obtain an accurate result.

Based on the result in Chapter 4.1.4, Figure 4.13 shows that the reading values of the temperature sensors are quite different from each other. But, the reading temperature values do not greatly varied from the temperature value measured by the thermometer. Moreover, the thermometer was placed inside the beaker and the temperature sensor is attached outside of the beaker which is on the surface of the beaker. The temperature measured by both sensors is thus different to each other. LM35 seems not suitable for this project as there was only a small proportion of the sensor in contact with the skin. Meanwhile the remainder will act as an absorber or radiator to the surroundings. In order to avoid this, LM35 need to be insulated then the skin is the only source of heat. Moreover, the heat lost or heat gain from the surrounding is reduced. Another issue is the sensitivity of LM35 is 0.5°C. A sensor with 0.1 degree sensitivity should be used to measure skin temperature accurately. A skin temperature sensor which is suggested to replace LM35 is NeXus-10 Temperature Sensor which is very sensitive, can read skin temperature changes of 0.0001 degree.

Additionally, in Chapter 4.2.1, the graph (Figure 4.15) clarifies that the temperature sensors average value is being adjusted as their values are keep on changing and closer to the user input value. At the beginning, the value from the sensors is a small ripple. Throughout the time, the value is fluctuates higher and higher. However, it does not getting closer enough to the value. There is a small gap between the values. This may be due to the temperature sensor itself. It is not suitable enough to be used in this application as the area of the surface is big and environment temperature may affects their values and later affects the average value as well.

Besides that, the relation between the temperature value and the resistance of digital potentiometer, AD5220 was studied. The overall measured value plotted on the graph in Figure 4.16 indicates that the resistance is generally increasing towards time. There are certain points of time on that graph where the resistance drops drastically. This may be due to the average temperature measured is higher than the threshold and affects the value of AD5220. Other reason is due to the environment temperature or the poor soldering technique applied on the component to the PCB.

On the other hand, the result for the second experiment which is done on human skin is much smoother than the first experiment (Figure 4.17 and 4.19). The reason is that the temperature value measured on the skin temperature does not changed much during stimulation. Other possible reason is the frequency of the stimulator is not high enough to stimulate the muscle and thus the skin temperature does not changed much.

Based on a book writtern by Dorf & Bishop (2008), a closed loop control system compares the feedback of the measurement of the output with the desired output. In this project the output measured was the temperature readings from beaker and human skin. The desired output is the user input value. For the first experiment (Figure 4.15) shows that the readings are increasing gradually at the beginning and after 40 seconds it is equals to the desired output. However, it decreases gradually after that. Another experiment (Figure 4.16) shows that the readings are closed enough with the desired output but do not equal to the desired output. Both result for the first experiment is gradually approaching the desired output. On the other hand, the first trial of the second experiment (Figure 4.19) is very appealing as it shows that the output is stable after reaching the desired output. From the graph, the response time is approximately 33 minutes. However, the overshoot and settling time cannot be obtained from the result. The experiment need more time to obtain that desired results. However, it is dangerous to let the subject being stimulated for a longer time. Same goes to the second trial. The output tends to rise towards the desired output after 30 minutes of the experiments. But, prolonged the stimulation time may affect muscle fatigue and affect the safety of the user.

Finally, the result of the FES system with feedback control is not accurately produce due to reasons already discussed. More reliable and stable components should be used to replace the digital potentiometer as well as the temperature sensors. In addition, more trials with longer time should be done in both experiments so that the result can be analyzed extensively and more accurate. Riener & Quintern (1997) stated that the simultaneous application of recruitment and frequency modulation is a promising FES control strategy because it contributes to better fatigue resistance. However, due to time constraints, only two trials were done for each experiment.

CHAPTER 6

6.0 CONCLUSION

In conclusion, the FES system with feedback control is successfully constructed and well functioned. There is a good communication between the temperature sensors and the digital potentiometer with Arduino as the medium. However, the temperature sensors are slightly unstable and can be considered less suitable to be used as a component to measure the temperature value of the water in the beaker as well as the skin temperature. This situation affects the resistance value of the current control circuit as well as the stimulation current to human skin. The objectives of the study are achieved. However, the temperature readings are affected by room temperature and less sensitive sensors employed in this study. In this project, long experimental times are not considered due to muscle fatigue and the safety of the subjects.

6.1 Recommended For Future Work

The temperature sensor used in this experiment is less suitable. A more stable and reliable sensor should be used in future work to obtain a more accurate data from the subject.

Higher frequency stimulation causes muscle fatigue whereas lower frequency causes the stimulation frequency contains ripple. Thus, it is suggested to apply the interleaved stimulation for the next project. The electrodes will be asynchronously activated. The composite frequency of pulses over all electrodes is equivalent to the desired frequency as the frequency of stimulation pulses delivered at any given individual electrode is a fraction of the desired overall frequency (Hughes, Liang Guo & DeWeerth, S.P, 2010).

In order to easily analyze the huge data obtained from the experiments, a suitable open source programming languages is needed to automatically plot the data from the Arduino serial communication into a graph or into Graphical User Interface (GUI) which can be used easily by user. The Processing software which has the similar languages and IDE as Arduino is recommended for future studies.

Besides, the output data obtained from the developed FES system should be compared to the output data which is obtained from a stimulator which used the function generator in its system. Then, the accuracy of the developed FES project can be analyzed and improved.

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