DEVELOPMENT OF HEAT FEEDBACK PARAMETER OF MUSCLE ACTIVATION DETECTION IN FUNCTIONAL ELECTRICAL STIMULATION

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ABSTRACT

Functional Electrical Stimulation (FES) was famously being applied in controlling stimulation of muscles for the restoration of movements in paralysed human. Thus, the development of sensory feedback is necessary to improve the performance of FES systems by detecting the level of the muscle force. This research project focuses on the development of a heat feedback parameter in FES. There are two components for this project. Firstly, the FES stimulator was constructed to produce a suitable stimulation by modulating the input parameter. A temperature sensor was used to detect the heat produced by the stimulated muscle. Secondly, two tests were conducted in several able-bodied subjects. First was voluntary training and second was using stimulation. During tests, the cycling resistance and amplitude of pulses current was increased. Then, the heat produced was compared to the muscle contraction level during the contraction of the vastus lateralis muscles and determine if either the heat produce is correlated to the level contraction of muscle.

ABSTRAK

Perfungsian Elektrik Stimulasi (FES) telah terkenal diaplikasikan di dalam pengawalan rangsangan otot untuk memulihkan pergerakan manusia yang lumpuh. Oleh itu, pembangunan tindak balas deria adalah diperlukan untuk memperbaiki prestasi sistem FES dengan mengesan tahap pengaktifan otot. Projek penyelidikan ini memberi fokus terhadap pembangunan parameter tindak balas haba di dalam FES. Terdapat dua komponen untuk projek ini. Pertama, sistem perangsang FES telah dibina untuk menghasilkan rangsangan yang sesuai dengan mengubah nilai parameter input. Alat pengesan suhu telah digunakan untuk mengesan haba yang dihasilkan oleh otot yang dirangsang. Kedua, dua eksperimen telah dijalankan terhadap beberapa orang yang sihat serta berupaya. Eksperimen pertama merupakan latihan secara sukarela dan eksperimen kedua akan menggunakan rangsangan. Semasa ujian dijalankan, rintangan kayuhan basikal dan amplitud arus rangsangan telah ditingkatkan. Kemudian, haba yang dihasilkan oleh otot terangsang akan dibandingkan dengan tahap pengaktifan otot ketika perangsangan otot ’vastus lateralis’ dan menentukan sama ada terdapat perhubungan di antara haba terhasil dengan tahap pengaktifan otot.

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LIST OF SYMBOLS

V	Voltage
Ω	Ohm resistance
mA	miliampere
ms	milisecond
Hz	Hertz for frequency
F	Farad for capacitance
^{o}C	Degree Celsius
min.	Minutes
R	Resistors
W	Watt

LIST OF ABBREVIATIONS

FES	Functional Electrical Stimulation
SCI	Spinal cord injury
EMG	Electromyography
IPI	Inter-pulse interval
MP	Motor Point
CNS	Central nervous system
ATP	Adenosine triphosphate
IC	Integrated Circuit
OP	Operational Amplifier
RMS	Root mean squared
MF	Median frequency
MAV	Mean absolute value
sEMG	Surface EMG
pEMG	Percutaneous EMG
INT	Intervals

PDS	Power Density Spectrum
FSRs	Force sensitive resistor sensor
LED	Light Emitted Diode
ADC	Analog-Digital Converter
Eq.	Equation
RPM	Round per minute

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CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT

Nowadays, Functional Electrical Stimulation (FES) was famously being applied in controlling stimulation of muscles for the restoration of movements in paralysed human. Spinal cord injury (SCI) is one of the troubling injuries that can cause paralyses to the other part of the human body. Although it has been mentioned that FES can gives significant medical and physiological benefits towards SCI patient, it may still cause muscle fatigue. Thus, the development of sensory feedback is necessary to improve the performance of FES systems by detecting the level of the muscle contraction and thus the forced produced. Many types of sensory feedback have been developed, but according to the findings, they are still in a stage of facing some limitations in order to detect the muscle fatigue.

In this Research Project, a new alternative of sensory feedback is developed to detect the muscle activation by using heat as the output parameter. The relationship between the muscle contraction and the heat produced by the muscle is examined.

1.2 OBJECTIVES OF THE STUDY

The purpose of this project is to develop a feedback parameter of FES to detect muscle activation using heat as the output parameter. The current sensory feedbacks of the FES systems still have their own limitations in detecting muscle fatigue.

Therefore, the main objectives of this project are:

i. To reconstruct a Functional Electrical Stimulation (FES) stimulator.
ii. To detect muscle contraction level using heat as the feedback parameter.
iii. To examine the relationship between muscle contraction level and heat production by the muscle by modulating the stimulation intensity i.e. current of the FES stimulator.

1.3 HYPOTHESIS

This research project focused on the development of a heat feedback parameter in FES. A stimulator and a set of temperature sensors were design to detect the heat produced by the stimulated muscle. This stimulator was tested on able-bodied subject to examine the relationship between the contraction level of stimulated muscle and the heat that produced. It was predicted that when the muscles level increased, the heat produced by the stimulated muscle would increased and the relationship between both parameter was linearly proportional to each other.

1.4 SCOPE OF THE STUDY

The scope of this project is to design and develop a heat feedback parameter of FES for detection of muscle activation. My project has two components. First, a FES stimulator was build to produce pulses current. In order to produce an effective stimulation, significant amount of input parameter for the stimulator such as pulse width, amplitude of pulse, and also the surface of the electrode. Temperature sensor was used to detect the heat produced by the stimulated muscle. Secondly, experiments were conducted in several able-bodied subjects where the heat produce will be compared to the muscle contraction level during the stimulation of the muscles. The objective is to determine if either the heat produce is correlated to the level contraction of muscle.

1.5 SIGNIFICANCE OF THE STUDY

Currently most FES systems used several types of feedback parameter such as EMG, force sensor and motor. However, from the previous studies, each of them still has their own limitation in detecting the muscle activation during stimulation. Their area of application are more to monitoring, thus did not provide a direct feedback of muscle activation. This project used a temperature sensor to detect the heat produced by the stimulated muscle. In the experiment, by modulating the stimulation intensity, the correlation between heat produced and the contraction of muscle will be examined.

CHAPTER 2: LITERATURE REVIEW

2.1 Functional Electrical Stimulation (FES)

Functional Electrical Stimulation (FES) is an approach of controlled stimulation of muscles for the restoration of movements in paralysed human (Grant, 1988; Tepavac et al., 1997). FES activates innervated but paralysed muscles by using an electronic stimulator to deliver trains of pulses to neuromuscular structures (Tepavac et al., 1997). FES also used to build and maintain the skeletal muscle strength as an addition to physical training for sports (Currier et al., 1983) (Valli et al., 2002).

Muscles composes of individual muscle fibers that will react to electrical pulses (Peckham, 1987). The muscles will undergo quick contraction and relaxation which is called muscle twitch as they react to electrical stimulation (Ew et al., 2005). Thus, the objective of FES is to elicit safely a controlled stimulation towards the muscle groups (Sabut et al., 2010).

The criteria of a FES stimulator is that it must be an independent device or portable with low power utilization, light in weight, small, and easily operated by user (Sabut et al., 2010) (Popovic, 2006). It is also be able to provide range of frequencies, pulse widths, and pulse current amplitude (intensities). Each of the parameter can be controlled separately and programmed to give repeatable treatment (Sabut et al., 2010).

Usually, most of the FES stimulator was used to assist the functional movement of a spinal injury patient (Cheng et al., 2004). Spinal-cord-injury (SCI) is one of the most disturbing injuries that have been occurred among humans. The spinal injury causes paralyses towards other part of human body. Paraplegic is a term for paralysed in the legs, occurred in people who have an injury to the lower part of their spine. As for tetraplegia or quadriplegia, it is a term for paralyses from the neck or arms level onwards (Grant, 1988).

2.2 Control parameters of electrical stimulation

For controlling the muscle stimulation, there are parameters that involved such as amplitude of pulse current, frequency and pulse width. During FES, the muscle force output was controlled by modulating the stimulation intensity and frequency (Kesar et al., 2008). The modulation of pulse amplitude or the pulse-width can increase or decrease the recruitment of muscle fibers while the modulation of pulse frequency can increase or decrease the firing rate of motor neurons (Graham et al., 2006).

For an efficacy of stimulation, the best stimulation for most people is 20 pulses per second. For achieving the efficacy, the pulse width of stimulators is determined at about 300μs and the amplitude of pulse is depending on individual circumstances. The pulses must be voltage-controlled and the current does not constant. Thus, the voltage pulses with the amplitudes of 80 to 150 V. As for the stimulation electrodes, currently surface electrodes are famously used. The electrodes are placed at the motor-end-point where motor nerve enters the muscle (Grant, 1988).

Another study used a portable, battery-operated, programmable and constant current stimulator. For the current output, they set the maximum value around 50mA. The pulse width is between10 to 500µs and the inter-pulse interval (IPI) is about 10 to 100ms which is the frequency is 10 to 100Hz. As for the electrode, they used the sel-adhesive electrode, larger electrode for cathode and smaller for the anode (Tepavac et al., 1997).

While, other study mentioned that in general, the amplitude of surface stimulation ranges from 10mA until 80mA, the stimulation frequency is between 20Hz to 4Hz, and the pulse width is between 50ms to 300ms, which appears continuously at the surface output (Sabut et al., 2010).

2.3 Factors that affect the stimulation

There have been mentioned by in previous study, the amount of current required during electrical stimulation was affected by several factors such as tissue impedance, pad placement, and shape and size of the electrode. Mostly, stimulation electrode was placed at a point where it is very sensitive towards stimulation which is called Motor Point (MP) (Forrester et al., 2004). Another study stated that the MP has a great density of sodium channels, thus has the lowest impedance. Therefore, the closer the electrode towards MP, the lesser the stimulation current though its nerve (Reichel et al., 2002).

Previous study investigated the relation between body fat and stimulation current. It seems that the fat thickness affects the impedance and also the current required for stimulation. Both quadriceps and gastrocnemius muscle have a thick fat layer compared to biceps muscle. Thus, the current required for stimulate the biceps muscle are lower than both quadriceps and gastrocnemius muscle (Petrofsky et al., 2008).

A study argued that larger electrode increases tolerance of electrical stimulation. However, larger electrode can cause the unwanted neighboring muscles to stimulate and deliver not enough current density to get the desired response (Alon et al., 1994). While other study discussed that for electrode size, there were no statistical differences for electrical stimulation as the size difference between the electrodes only about 50% (Forrester et al., 2004).

2.4 Physiological effects during electrical stimulation

During muscle stimulation, it increases the metabolic requirement with higher rates of inorganic phosphates and higher cell oxygen level, compared to the natural contraction. This phenomenon is directly interrelated to the intensity of the stimulation (Forrester et al., 2004; Vanderthommen et al., 2007).

Cardio-respiratory activity is also affected, with a higher oxygen consumption, ventilation and respiratory exchange ratio associated with concentric contraction of the quadriceps femoris induced electrically rather than voluntarily during resistance training (Theurel et al., 2007).

2.5 Muscle fatigue

During the restoration of movement function using FES, the force of the stimulated muscle eventually will reach its limit which is called muscle fatigue. The muscle fatigue will limit the effectiveness of FES (Graham et al., 2006). As patient of SCI lost their sensory pathways, they cannot recognize their muscle fatigue during the stimulation (Winslow et al., 2003). The muscle contraction via electrical stimulation will decline the muscle force far more rapidly than when voluntarily contraction. Thus, the occurrence of muscle fatigue is faster during stimulation of FES in SCI patient (Chesler et al., 1997).

Using FES system, pulses were delivered with a constant amplitude, pulse-width, and frequency that will stimulate contractions in the same motor units all the time, while natural contractions allow motor units to rest occasionally. These causes stimulated motor units to be worn out while the other non-stimulated motor units remain completely inactive. If the system continuously provides the stimulation, there will be no rest for the overworked motor units. Therefore, the stimulated muscle will fatigue more rapidly than if they were activated by the natural stimulation of central nervous system (CNS) (Graham et al., 2006).

During FES, a declination in force production was due to the fatigue of stimulated muscle. It could be related basically to changes in the factors below (Tepavac et al., 1997):

(a) Neuromuscular propagation;

M-wave consists of the synchronous sum of all muscle fibre action potentials that are elicited by the electrical stimulation. The changes in M-waves shows that there are changes in neuromuscular propagation between the site of initiation (axons) and the site of recording (muscle fibres) or a reduction in the excitability of the muscle fibre membrane. Low force – long duration voluntary contraction gives out a greater M-wave declination than the high-force contraction.

(b) Excitation- contraction coupling;

Different tasks activate various mechanisms that can cause force reduction. Usually the force loss cause by the excitation-contraction coupling can be found after long duration contractions with slow recovery (30-60 min). Recovery of force loss cause by neuromuscular propagation and metabolic changes are more rapidly with less than 6 minutes.

(c) Metabolic changes

Muscle force could also decline when the rate of supply ATP and metabolites generated by the contractile activity cannot support the energy supply. The energy cost of discontinuous stimulation seems to be higher than that of continuous stimulation.

2.6 Force-fatiguability Relationship

The greater the elicited force, the more rapidly the muscle fatigues. There is also more fatigue when the force-time integral is greater. The rate and amount of force decline both increases with the frequency of electrical stimulation (both for whole muscles and for single motor units) (Tepavac et al., 1997).

However, the degree in muscle force may be achieved in two ways which are varying the number of motor units recruitment and by modulating the firing rate. These were hypothesized by (Graham et al., 2006), that by randomly modulating the frequency, pulse amplitude, and pulse-width, would vary the resulting firing rate and level of recruitment of motor units over time.

2.7 Circuit of FES stimulator

Figure 2.1 shows the example of FES circuit from a previous study (Cheng et al., 2004). The circuit was divided into two parts. The first part consists of two integrated circuit (IC) timers 555 and some attached components such as resistors, capacitors, and diodes. The output of the IC2 is a series of pulses. An additional external trigger signal can be provided at the sensor input. The frequency and pulse width was controlled by adjusting the potentiometers (R1, RA and RB) and capacitors (C1 and C2). The second part of the circuit consists of four operational amplifiers (OP1–4), a transistor, and a transformer. OP1 as an error amplifier, OP2 will amplify the signal to drive the transformer; T1, OP3 and OP4 are the current-feedback network. The amplitude pulse current can be modulated by potentiometer, R2. For stepping up the output voltage, the transformer was used. By stepping up the voltage from 9V to 200V, it will also increase the amplitude pulse current up to 100mA. By including a current feedback loop, it ensured the current amplitude.

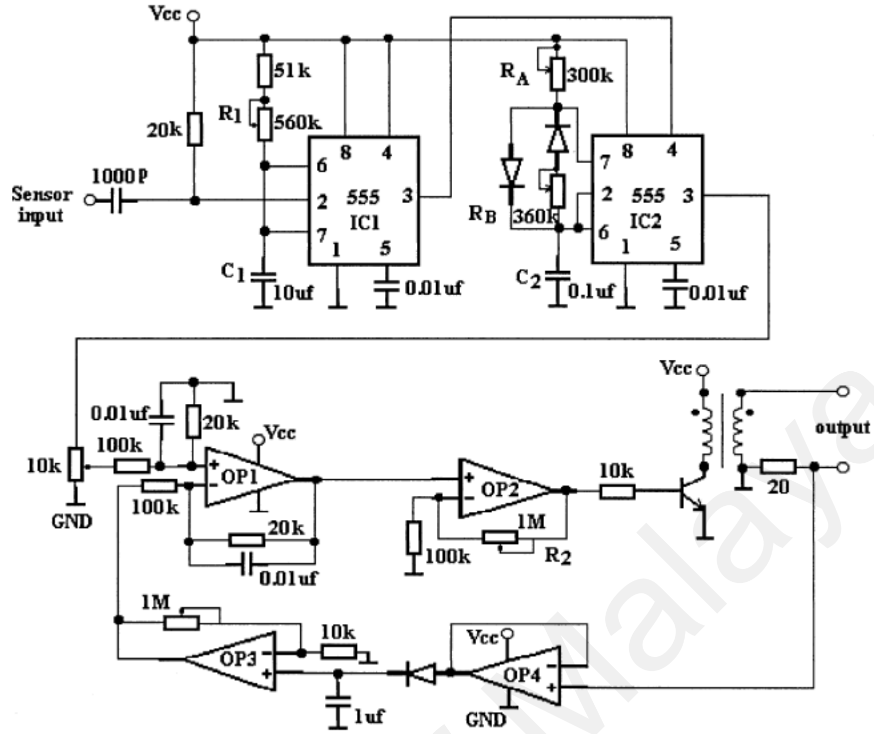


Figure 2.1: FES circuit. (Adapted from Cheng et al., 2004)

2.8 Feedback sensor of FES system

Sensory feedback is necessary for effective control of FES systems. The information about the level of muscle force can improve the performance of FES assistive systems (Tepavac et al., 1997). Without sensory feedback, the users cannot sense the fatigue state of their paralyzed muscle during stimulation, thus they may not be able to react before the contractile failure occurs (Chesler et al., 1997).

Most of current FES stimulator applied an open-loop control function. The advantage is that the feedback output of sensor did not provide the information about the effect of stimulations on the subject, plus the user need to control the input parameter manually. So, closed-loop system of the stimulator has been proposed. It would remove the need for time uncontrollable manual adjustment. However, for this application, it is important to calculate the expected accuracy of the detected sensor in order to integrate this information into the parameter's controller design (Sabut et al., 2010).

Nowadays, there are a few common feedback parameters have been used to detect the activation of muscle. One of the most famous feedback parameter is by using the EMG. For analyze the muscle force output, the EMG signal was represented by root mean squared (RMS), median frequency (MF), and mean absolute value (MAV) (Chesler et al., 1997). Force sensor and motor sensor also is available to be use as feedback parameter, for example using f-scan at the patient's sole to examine the force of patient's leg during walking using FES stimulator. As for the common feedback parameter, it is the human perception. When the muscle stimulate, the patient can sense the movement of the arm or leg, thus it is consider success for applying the current to the muscle nerve.

2.8.1 EMG

Surface EMG (sEMG) or percutaneous EMG (pEMG) was famously used in the detection of muscle activation by deriving a voltage measured with electrodes (Tepavac et al., 1997) (Amft et al., 2006). The advantage of using EMG is because it can be obtained non-invasively and it reflects the contractile activity of the underlying muscle (Chesler et al., 1997).

However, the extracting of the muscle force from the sEMG is a difficult task because of the low signal-to-noise ratio, non-linear behaviour of the muscle force versus muscle length, velocity of shortening, activity of other agonist and antagonist muscles, and other mechanisms which are dependent on the central nervous system (CNS) (Tepavac et al., 1997).

Modified surface stimulation and EMG detection equipment were designed and built to minimize this artifact and to permit detection of the electrical signal generated by the muscle during contraction. Artifact reduction techniques included shorting stimulator output leads between stimulus pulses and limiting and blanking slew rate in the EMG processing stage (Chesler et al., 1997).

Study done by Tepavac et al (1997) was to determine which parameter and processing technique of the sEMG is best suited to generate the warning signal about muscle fatigue. After preamplifier and filtering the Semg signal, This signal was used to derive seven different parameters of the sEMG - four in the time and three in the frequency domain. In the time domain we calculated RMS, MAV value and fully rectified, integrated sEMG over 10 ms intervals (INT). In the, frequency domain we calculated power density spectrum (PDS), MNF and MDF. While the force recorded using strain gauge transducer (Tepavac et al., 1997).

2.8.2. Detection of gait phase & monitoring joint angle sensor

Previous reports have shown there are two common sensors that were applied in FES system. The first system was use to detect the gait phase such as swing and stance phase while the other system was use to monitoring the joint angle, commonly in knee flexion angle. For controlling motion in SCI patient, it is necessary to use both sensors for detecting gait phase and the position of the joint angle.

Thus, a study had proposed a single sensor system and signal processing system that could provide real time data, such as gait phases and events, and joint kinematics. They designed sensor system comprising of Analog Devices accelerometer, rate gyroscopes, piezoelectric strain gauge and magnetic sensors. At the end, the modified sensor system did surpass the previous systems that only addressed to one aspect in lower limb control of FES. These tests suggest that a small, clustered, sensor system worn in conjunction with other components of a FES system can be designed to provide the variables typically used for feedback (Williamson et al., 2000).

However, these sensors only manage to detect and control the motion of the patient but not in term of detecting the muscle fatigue. It is still useless to maintain the controlling motion in SCI patient as muscle fatigue will limit the effectiveness of FES (Winslow et al., 2003).

2.8.3 Pressure sensor

Pressure sensor can be also called as force sensitive resistor sensor (FSRs). FSRs is a polymer thick film device that given out a different values of resistance as the force applied to its active surface. The resistance is inversely propotional to the applied load. The resistance value is high up to 1MΩ if the sensor is unloaded, whereas will decreases to several kΩ if the load is applied to the sensor (Amft et al., 2006).

Previous study shows that FSRs is capable to be used to monitor individual muscles. Figure 2.2 shows the placement of FSRs at the lower arm to detect the muscle activation (Amft et al., 2006).

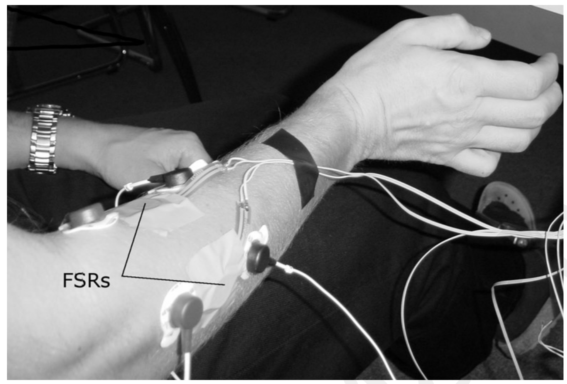


Figure 2.2: Placement of FSRs on the surface of subject's arm.
(Adapted from Amft et al., 2006).

An automatic system controlling the correction of foot drop in hemiplegics was proposed by another study (Sabut et al., 2010). They used a real-time detection of the foot pressure using piezo-resistive sensors at insole as a close loop controlled FES system for the correction of foot drop in hemiplegics. The foot pressure signals from patients were utilized for signal modulation and hence controlling the stimulation amplitude of the FES system. As in Figure 2.3, the system includes foot insole sensors, amplifier, microcontrollers, stimulation unit and stimulating electrodes.

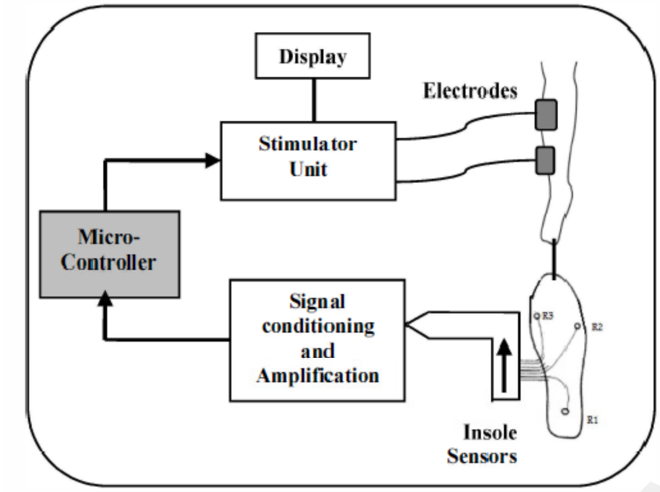


Figure 2.3: Block diagram of pressure sensor FES system.
(Adapted from Amft et al., 2006).

Their result showed that the direct feedback from the foot pressure sensitive signals in a feedback FES system provides a real time control of stimulus current amplitude to correct foot drop during the swing phase of gait. Since, the stimulation being controlled automatically which leaves the hands and the mind free could be used to perform other activities (Sabut et al., 2010).

2.8.4 Fabric stretch sensor

Fabric stretch sensor can be used as a strain sensor. When the fabric was stretched, will resulting changes of the electrical resistance. The resistance increases when the fabric elongated. However, the sensor can become a problem to some applications due to highly non-linear of the resistance in its response to strain and cause a hysteresis. Despite the disadvantages, the sensor still be attempted to be used to detect body postures and arm gestures (Lorussi et al., 2005).

In previous study, the fabric stretch sensor attached to the lower arm in Figure 2.4 was used to capture muscle activations during specific hand and arm activities. For measuring the changing resistance of the fabric stretch sensor, they use a Wheatstone bridge depicted in Figure 2.5. However by the end of the study, it shows that fabric stretch sensor cannot be used to monitor the individual muscles as it is limited due to strong hysteresis (Amft et al., 2006).

Figure 2.4: Placement of Fabric Stretch Sensor. (Adapted from Amft et al., 2006).

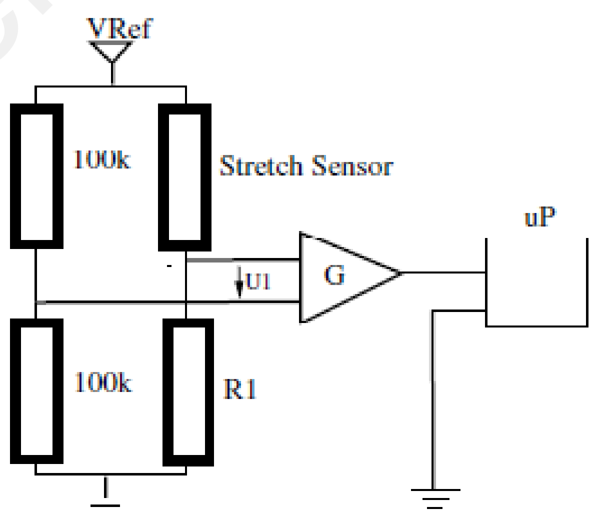


Figure 2.5: Fabric stretch sensor interface. (Adapted from Amft et al., 2006).

2.9 Relationship between skin temperature and stimulation current

A study had included the investigation of relationship between skin temperature and stimulation current. Skin temperature was measured with a BioPac skin temperature thermistor probe. The three conditions which are; normal room exposure, five minute exposure of cold pack and five minute exposure of hot pack on the surface of the muscles. Figure 2.6 shows that the skin temperature was different between the three conditions and it was almost linear. Based on the equation in the figure, the stimulation current was increased by 0.54 mA for every degree increase in skin temperature (Petrofsky et al., 2008).

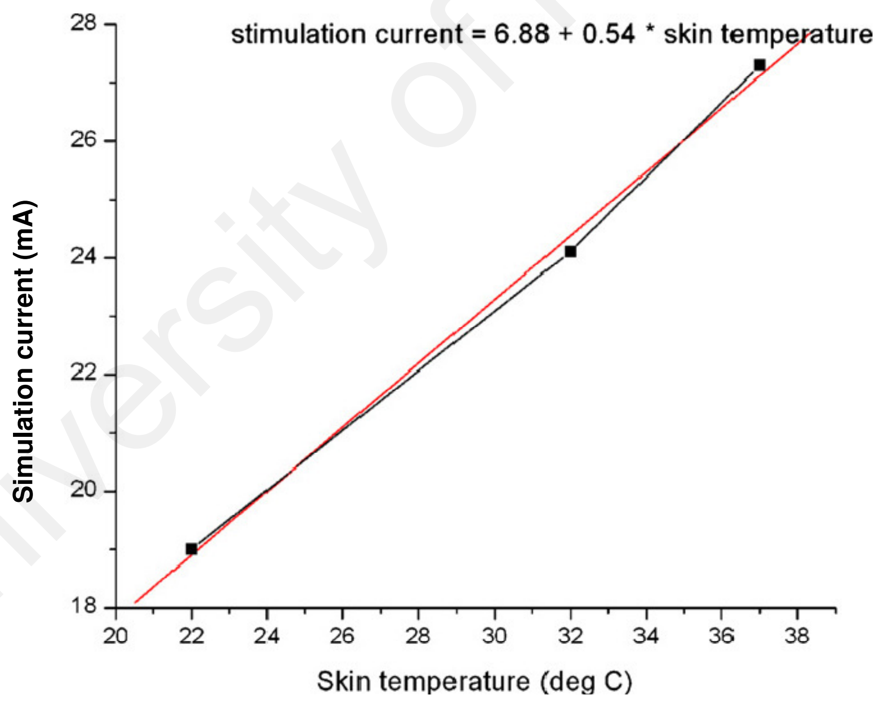


Figure 2.6: Relationship between stimulation current and skin temperature. (Adapted from Petrofsky et al., 2008).

Previous study have shown that by applying a heating towards the skin surface will shifts the currents in the skin during electrical stimulation. Blood has a lower electrical resistance. By increasing the blood flow in the skin, the currents were shifted to that area. When the skin were heated by a hot pack, it increased the blood circulation, thus increased the current required to stimulate the muscle (Petrofsky et al., 2007).

Previous studies mentioned above, they investigated and recorded the value of stimulation current as the skin temperature changes through different conditions. As for this research, a new investigation was take place to study whether the change of stimulation current will also affect the skin temperature and produce a linear relationship.

CHAPTER 3: METHODOLOGY

3.1 Project Flow Chart

This section describes the procedure of constructing; experimenting and analyzing in order to achieve the main objectives. Flow chart in Figure 3.1 shows the procedures throughout this study. The whole procedure was divided into three stages. The first stage involved with the construction of FES stimulator and temperature sensors. For building the FES stimulator, an integrated circuit (IC) timer 555 was used to produce a pulse wave. Then, circuit timer was connected to other analog components to produce required current amplitude for muscle stimulation. Skin surface stimulation electrode was used to transfer the stimulation current to the specific muscles. For detecting the muscle activation, this study used a temperature sensor as a feedback sensor to detect changes of skin temperature during stimulation. An Arduino microcontroller board was used to read the voltage output of temperature sensor, thus display it in form of degree temperature. After successfully construct the FES stimulator, at the second stage, two tests were conducted towards the subjects. Test 1 involved the study of relationship between cycling resistance and skin temperature. This test was carried out as a voluntary training by subjects. Test 2 involved the study of relationship between current amplitude and skin temperature. At the third stage, data analysis was taken place. For both tests, the correlation between the muscle activation and the muscle heat production was examined.

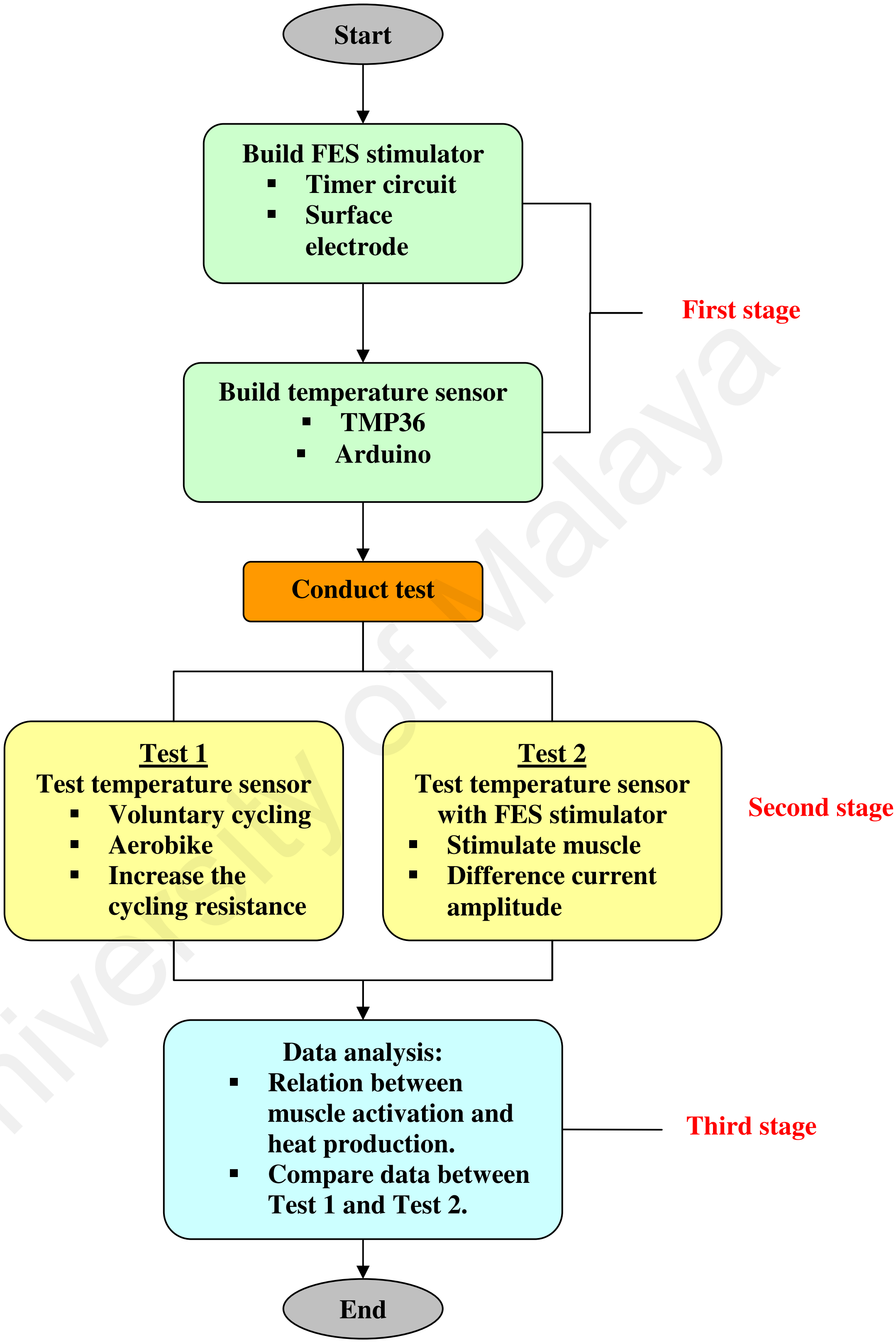


Figure 3.1: Project's flow chart.

3.2 First stage: FES stimulator and temperature sensor

3.2.1 FES stimulator

Before constructing the actual circuit of FES stimulator, Multisim software was used to construct a non-real circuit and the simulation was done in order to study the connection of the circuit and produce the required outcome. By going through this step, it helped by reducing the complication during constructing the actual circuit.

The FES stimulator was comprises of three parts, as shown in Figure 3.2. The first part consists of IC LM555 timer and a group of resistors and capacitors. The second part consists of resistors, two PNP transistors and a step-up transformer. Lastly, the third part was the stimulation electrodes that will deliver the stimulation current to the muscle.

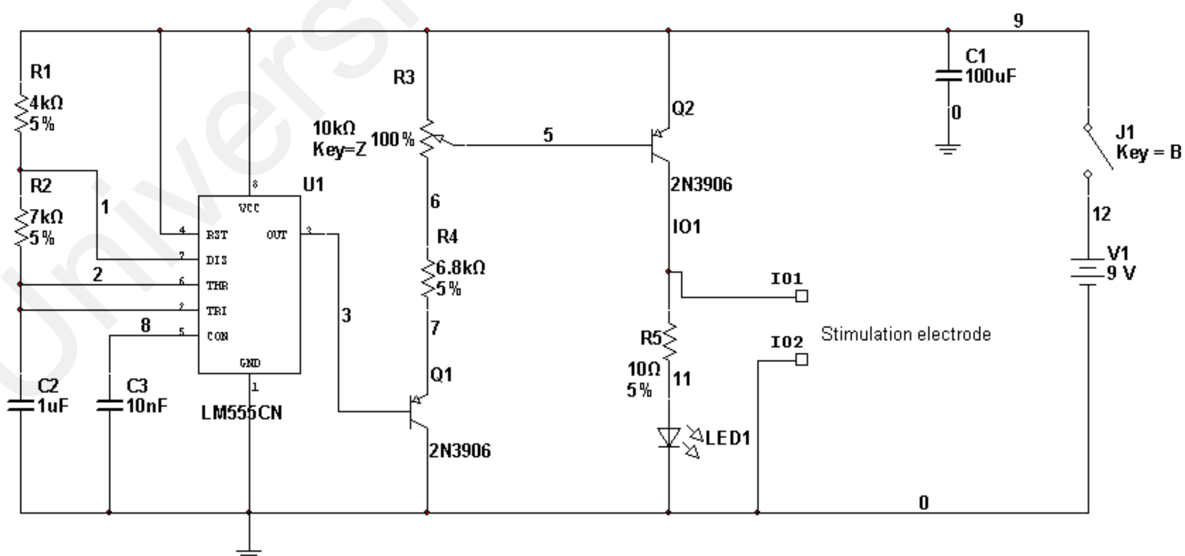


Figure 3.2: FES stimulator circuit.
(Adapted from http://www.diy-electronic-projects.com/p231-Muscular-Bio-Stimulator)

(a) Part 1: Timer circuit

The IC LM555 timer circuit in Figure 3.3 was suitable to be used as it is a highly stable device for generating accurate time delays or oscillation. For astable operation as an oscillator, the included external components are resistors, capacitors and diodes will accurately control the free running frequency and duty cycle.

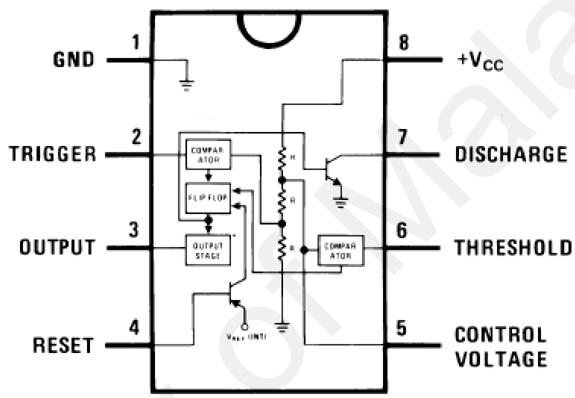


Figure 3.3: Top view of IC LM555 timer.
(Adapted from National Semiconductor Datasheet, LM555 timer)

For setting up the value of frequency pulses and duty cycle, the value of R1, R2 and C2 was controlled. According to the datasheet for LM555 timer, the formula in Eq. 1 was used to obtain the frequency pulses. In this project, it had been decided to set the value of frequency pulses to 80Hz. As in previous studies, most of them set up the range of frequency pulses between 10 – 100Hz. The calculation below shows how to obtain f = 80Hz and the value for R1 = 4kΩ, R2 = 7kΩ while C2 = 1µF.

f = 1.44 / (R1 + 2R2) C2 ------------- (Eq. 1)

f = 1.44 / [4kΩ +2 (7kΩ)] 1µF ------------- (Eq. 2)

f = 80Hz ---------------- (Eq. 3)

For duty cycle, this formula in Eq. 4 was used to obtain approximate 38%. For the calculation;

$$D = R2 / (R1 + 2R2) \quad \text{------------- (Eq. 4)}$$

$$D = 7k\Omega / 4k\Omega + 2\ (7k\Omega)] \quad \text{------------- (Eq. 5)}$$

$$D = 0.3888 \times 100 \quad \text{------------- (Eq. 6)}$$

$$D \approx 38\% \quad \text{------------- (Eq. 7)}$$

Aside the calculation theory, the oscilloscope was connected to the output of LM555 timer to display the output pulse wave. Figure 3.4 shows the display of the oscilloscope. It also shows the frequency pulse is 80Hz and the maximum output voltage is 9V.

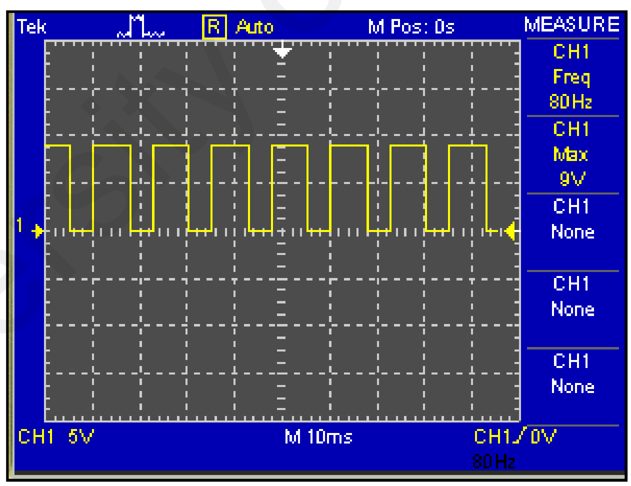


Figure 3.4: Output Pulse Wave of LM555 timer.

(b) Part 2: Transistors and other electronic devices.

According to the previous Figure 3.2, second part of the stimulator circuit consists of two PNP Transistor, Q1 and Q2 (2N3906), some resistors, a 10kΩ digital potentiometer

(AD5220), and LED1 (green). The output of LM555 timer was connected to Q1. Q1 acts as a buffer to control the flow of current. While Q2 inverts the pulses polarity.

For the 10kΩ potentiometer, it controls the amplitude of pulse current and approximately displayed by LED1 brightness. Originally, the circuit uses an analog potentiometer, but it was replaced with a digital potentiometer (AD5220) as in Figure 3.5, that provides a push-button application.

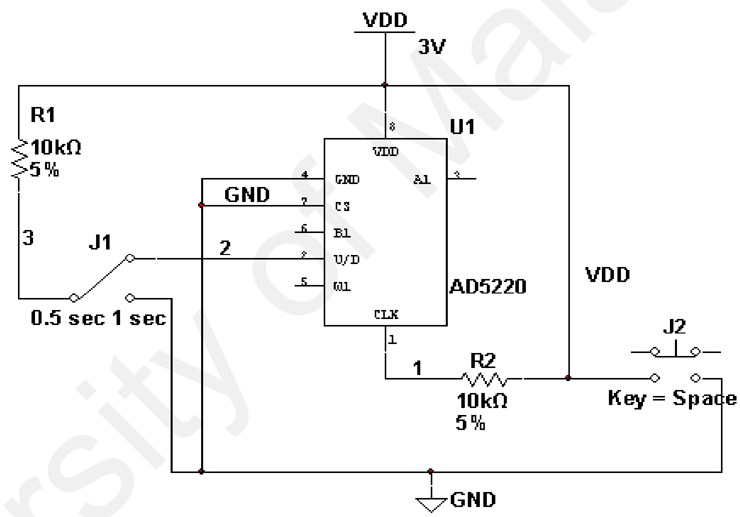


Figure 3.5: Push-button application of AD5220.

Potentiometer has three pins which are A1, B1 and W1, the wiper. For this connection in Figure 3.5, the pin A1 was connected to V_{CC} which is 3V. While pin B1 was connected to 6.8kΩ as in Figure 3.2. Pin W1 was connected to the transistor PNP, Q2.

The push button application of AD5220 is only a simple application to increment or decrement the value of resistance. The switch button, J1 in Figure 3.5 determined either to increment or decrement. As the switch connected to pin U/D of AD5220, the resistance of the potentiometer would increment when the push button was applied repeatedly. It reduced the brightness of LED1. When the switch connected to the ground, the resistance would decrement when applied push button. Thus, it increased the brightness of LED1.

The outcome that produced by the stimulator were displayed using an oscilloscope and a multi-meter. Figure 3.6 show the oscilloscope displayed the pulse wave with the maximum amplitude voltage 2.77V and the pulse frequency 80Hz.

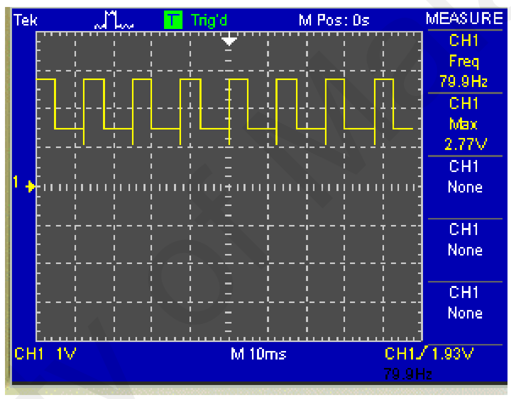


Figure 3.6: Output pulse wave.

For displaying the value of current amplitude, multi-meter was used. The maximum amplitude of pulse current produced by the circuit simulation is 48.3mA as shown in Figure 3.7.

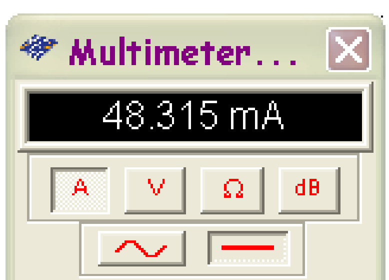


Figure 3.7: Maximum output of pulse current.

After completing the circuit simulation, the construction of actual circuit was take place. The construction was done on a breadboard as a temporary circuit as it is easy to connect parts of the circuit without soldering. The outcome result of the circuit was tested and recorded first before transferring the circuit permanently onto a circuit board with soldering.

A 9V battery was used as the power supply for the whole circuit except the digital potentiometer (AD5220); instead it used two batteries of 1.5V which total of 3V. Figure 3.8 shows the entire stimulator circuit. The red switch, J1 connected between 9V battery and the whole circuit. It works as an ON/OFF switch for the circuit. The blue switch is a switch to determine the increment or decrement value of resistance of AD5220. Figure 3.9 show the circuit was connected to the oscilloscope to display the voltage pulse wave.

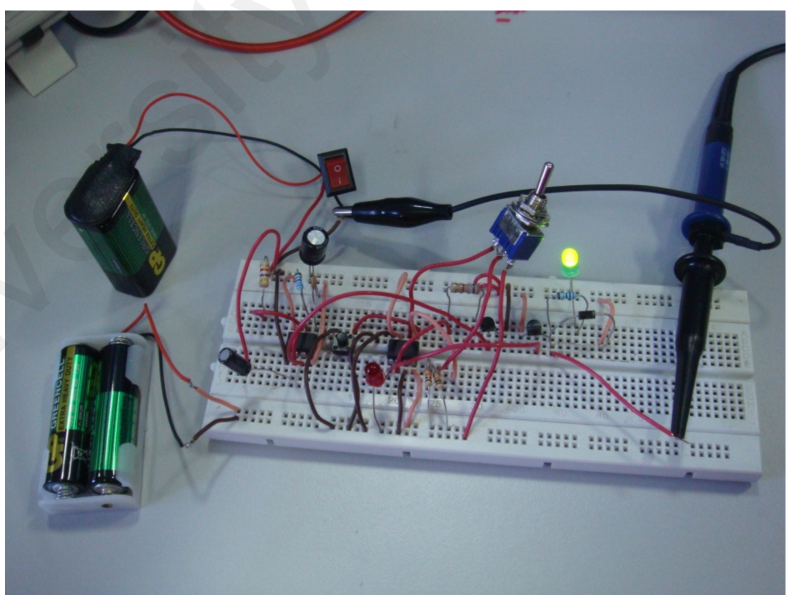


Figure 3.8: FES stimulator circuit on a breadboard.

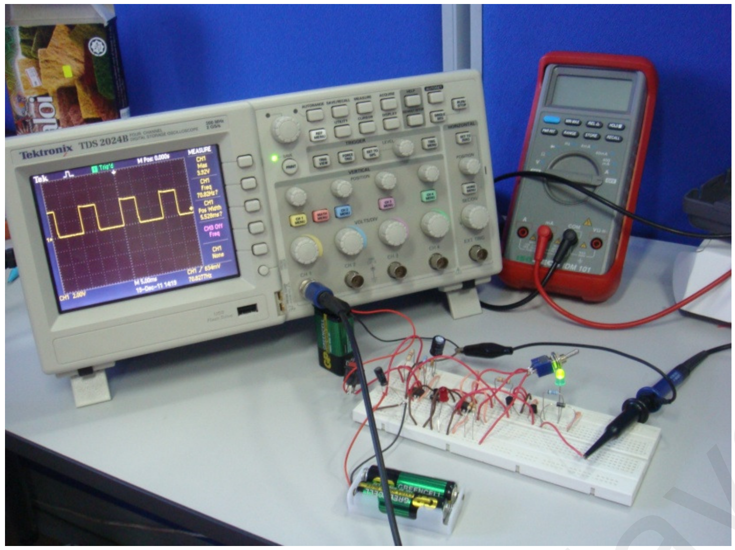


Figure 3.9: Stimulator circuit connected to oscilloscope.

(c) Part 3: Stimulation electrode

For the stimulator's electrode, two self-adhesive 4.5cm x 9cm surface electrodes (EMPI, STIMCARE) were used as in Figure 3.10. The electrodes were used for a single patient, non-sterile, reusable and self-adhering. Hydro-gel was applied between the surface of electrode and surface of the skin as the gel helped to conduct the pulse current during stimulation.

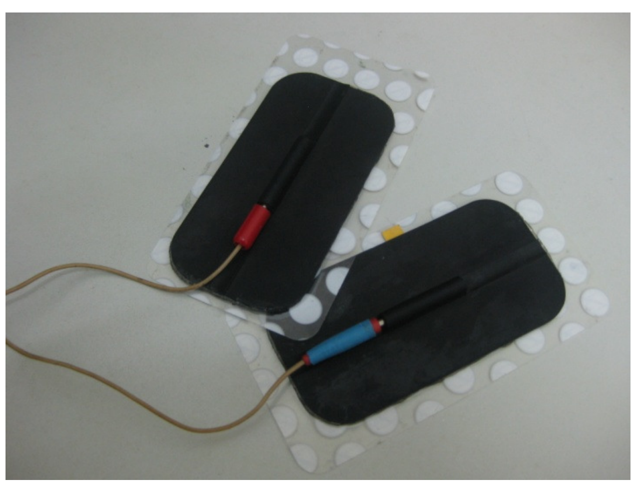


Figure 3.10: Stimulation electrodes.

3.2.2 Temperature Sensor

For the detection of muscle activation, this study proposed to use simple, low cost sensors to meet the following requirements: unobtrusive integration into garments, small power consumption for extended lifetime and simple interfacing. The investigation of temperature sensor to detect the muscle activation was done by sensing the heat changes of skin surfaces.

(a) TMP36 temperature sensor

For this project, a temperature sensor (TMP36) was used to detect the heat temperature of the skin surface above the stimulated muscle. In order to get more accurate data, five temperature sensors were used and placed along the skin surface of the stimulated muscle. TMP36 is a low voltage, precision centi-grade temperature sensor. It has three pins which indicate 2.7 – 5.5V_{in}, analog voltage out and ground as shown in Figure 3.11.

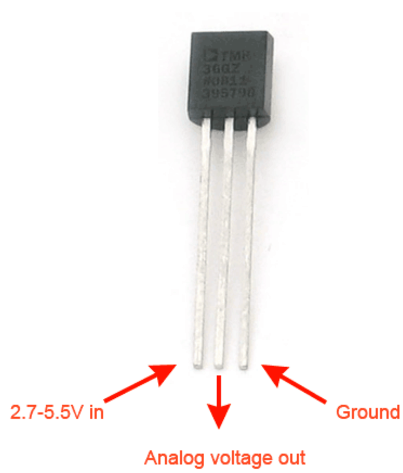


Figure 3.11: TMP36 temperature sensor.
(Adapted from http://www.ladyada.net/learn/sensors/tmp36.html)

According to the ‘b’ line in Figure 3.12, TMP36 provides a voltage output which linearly proportional to the Celsius temperature and it is specified from −40°C to +125°C, provides a 750 mV output at 25°C.

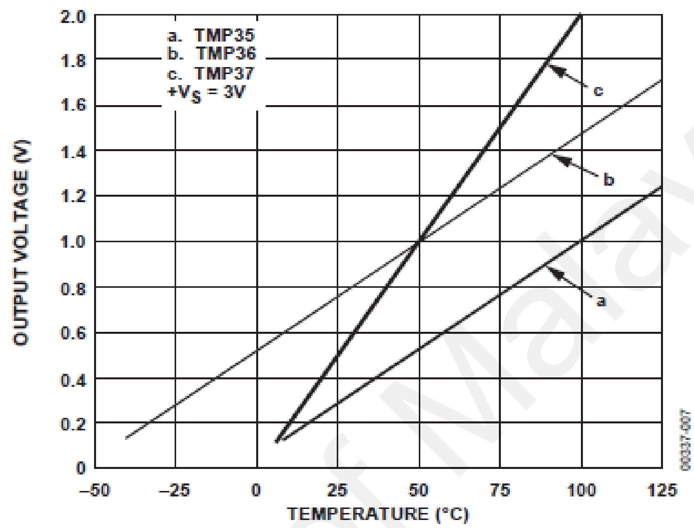


Figure 3.12: Output voltage vs. temperature.

(Adapted from Analog Devices Datasheet, Low Voltage Temperature Sensors, TMP35/TMP36/TMP37)

(b) Arduino Duemilanove

The output of the TMP36 is in analog voltage, thus to read the temperature value from the sensor; need to plug in the output pin directly into an Analog Digital Converter (ADC) input. In this project, a microcontroller board, Arduino Duemilanove was used to change the output of voltage and display it in form of temperature value.

As in Figure 3.13, Arduino Duemilanove has six analog inputs, a USB connection, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

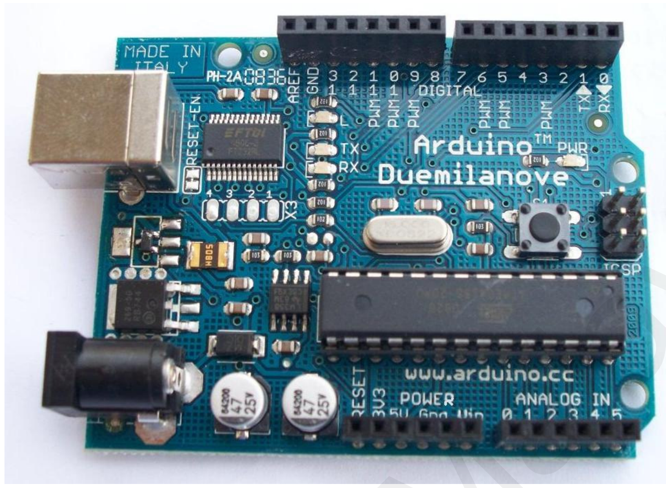


Figure 3.13: Arduino Board Duemilanove.
(Adapted from www.arduino.cc)

(c) Connection between TMP36 and Arduino Duemilanove

The connection between TMP36 and the Arduino board was simple. Figure 3.14 shows the connection between the sensor and the board. The V_{in} pin of sensor will connected to either pin 3.3V or 5V on the Arduino board. As for this project, pin 3.3V was used, which mean 3.3V was supplied to the temperature sensor. The leg of analog voltage output was connected to the pin analog IN ‘0’ on the board. As for the ground leg of sensor, it was connected to the ground pin on the board.

However, this project was using five temperature sensors which are S1, S2, S3, S4 and S5, thus each of analog voltage output of each temperature sensor were connected to different analog IN pin; A0, A1, A2, A3, and A4 on the Arduino board. According to

Figure 3.15, the output of S1 connected to A0, these connections goes on until S5 that connected to A4. The V_{in} and ground of each sensors were arranged in series on a circuit board, then were connected to pin 3.3V and ground pin on the board.

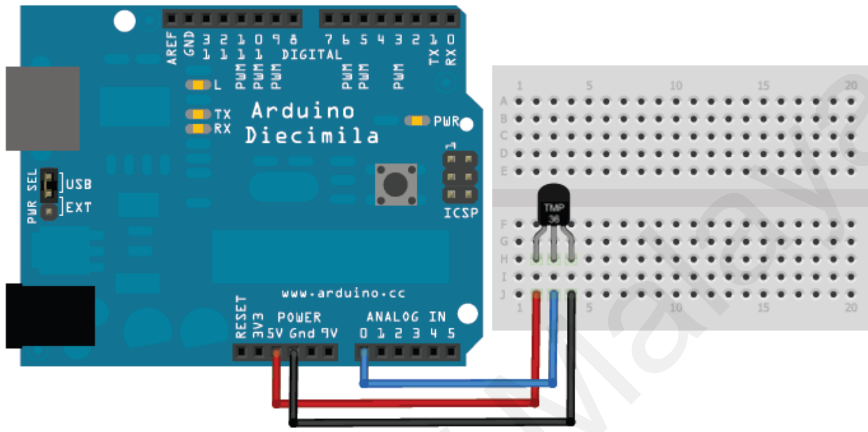


Figure 3.14: Connection between TMP36 and Arduino board.
(Adapted from http://www.ladyada.net/learn/sensors/tmp36.html)

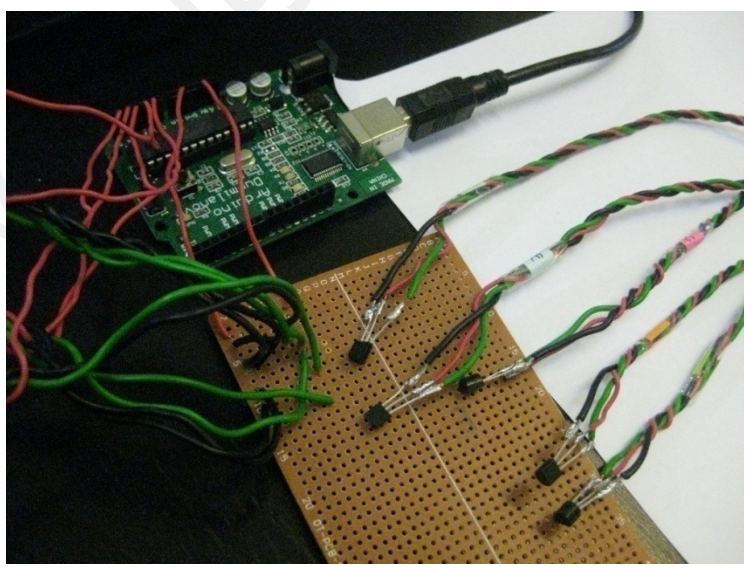


Figure 3.15: Five temperature sensors and Arduino board.

For the temperature reading, the listing command to read all five TMP36 sensors showed in Appendix A was programmed into the arduino board. Figure 3.16 shows the display of temperature reading in the computer. C0 until C4 indicate the sensors S1 until S5. The reading was programmed to update every two seconds.

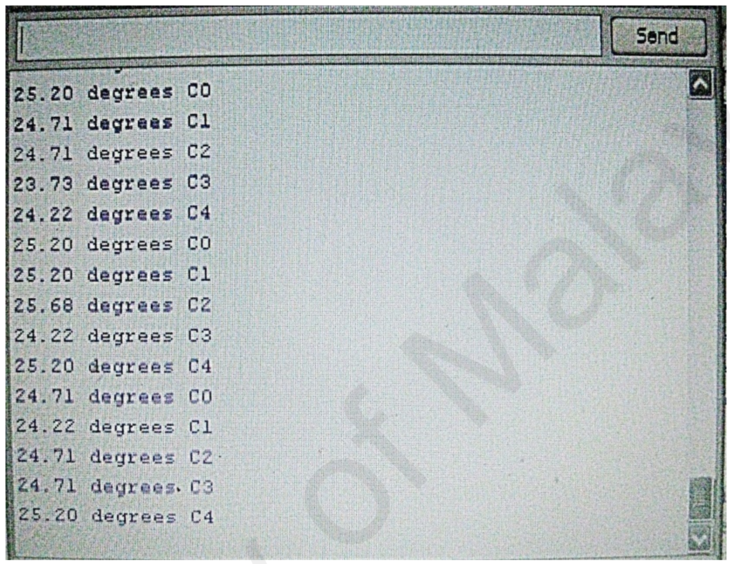


Figure 3.16: Display of temperature reading.

3.3 Second part: Conducting Test

Second part of this project was divided into two tests. Test 1 involved with voluntary training to test the accuracy of the temperature sensor and to study the relationship between the cycling resistance and the skin temperature. Test 2 used the FES stimulator to stimulate specific muscles. During stimulation, the temperature sensor was used to detect the changes of skin temperature.

3.3.1 Subjects

In this project's experiment, four individuals were recruited as test subjects. Four of them are 16 to 24 years old males and are able-bodied individuals. The inclusion criteria for the study include having a healthy body and normal weight individual. Two subjects were arranged to do Test 1 and the remaining two subjects were arranged to do Test 2. Table 3.1 shows the personal data of participated subject.

For subject's preparation before conducting both tests, they were advised not to have any heavy exercise within five to six hours, have a meal within one to two hours and wear a pair of short pants for easily placed the stimulation electrode and temperature sensors on the thigh surface.

Table 3.1: Subject's personal data.

	Age	**Height (cm)**	**Weight (kg)**
Test 1			
Subject 1	17	166	66
Subject 2	20	176	74
Test 2			
Subject 3	24	167	69
Subject 4	21	170	70

3.3.2 Test 1: Voluntary training

(a) Instrument

For Test 1, an Aerobike 75XL II in Figure 3.17 was used by the subjects for voluntary cycling. The aerobike can be used for sport training. The parameters that can be controlled by the bike system are the resistance in Watt and the speed of the cycling in round per minute (rpm). But to control the parameters is up to the capability of the user to maintain the cycling performance.

Figure 3.17: Aerobike 75XL II.

Figure 3.18 shows the screen display of the aerobike. For maintaining the good performances, the user must maintain the speed of cycling in range of 46 rpm to 52 rpm. As the needle on the screen remains in good condition, the resistance of cycling would be increased by 1 Watt for each 5 seconds. Thus, the longer the time of cycling, the resistance will increase bit by bit.

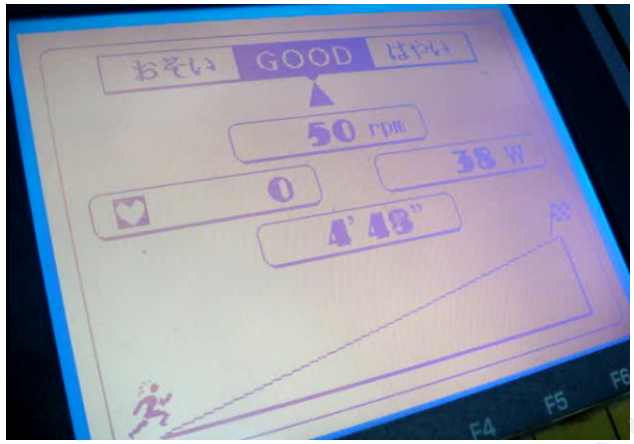


Figure 3.18: Screen display of Aerobike 75XL II.

(b) Placement of temperature sensors

Cycling activity was involved by a certain group of muscles; one of the group muscles is the quadriceps muscles. Vastus lateralis of quadriceps muscles was chosen to be tested for this voluntary training. Five temperature sensors were aligned along the skin surface of vastus lateralis muscle from distal to proximal as in Figure 3.19. S1 was placed at the very distal of the muscle and S5 was placed at the very proximal of the muscle.

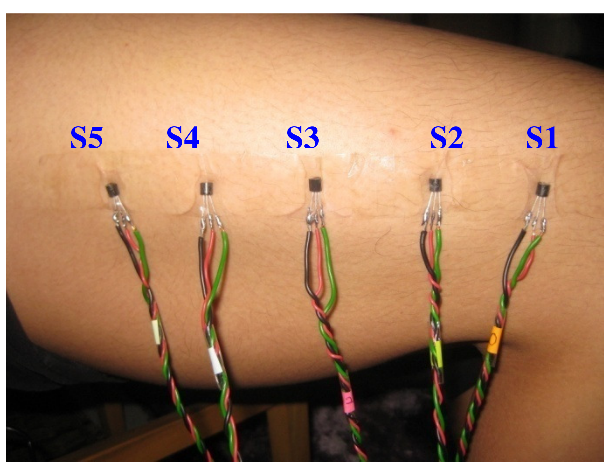


Figure 3.19: Placement of temperature sensor on the surface of Vastus Lateralis muscle.

(c) Protocols for Test 1

The first subject was asked to roll-up only one side of the short pants so that it would be easy to place the sensors. Then, the subject was ordered to sit on the Aerobike 75XL II to get ready for cycling. The temperature sensors were placed as mentioned previously and leave them for a few seconds before the initial skin temperature recorded. Subject's personal data was taken such as height, weight and age. After done entering the data into the aerobike's memory, need to wait for one minute before start the cycling. The subject was asked to cycle for 20 minutes straight without stop and maintained the good performance of cycling. During the cycling duration, the resistance of cycling was increased, thus each 5 minutes; the temperature of each sensor was recorded. All the above procedures were repeated for the second subject.

3.3.3 Test 2: FES stimulation

(a) FES Stimulator

For Test 2, the constructed stimulator was replaced with a previous stimulator that was done by an undergraduate student (How, 2011). The problem faced by the constructed stimulator will be discussed in Chapter 5. Figure 3.20 shows the FES stimulator that was used for Test 2. For setting up the stimulator, firstly the controlled parameter was set up. In this study, the amplitude of the pulse was modulated, while the other parameters were set as constant. The maximum voltage amplitude was ≈7V and the frequency pulse was 17Hz. By modulating the resistance value of potentiometer, the current output was modulated. The range of current output that modulated was between 0.85mA to 1.55mA which will be increment for every five minutes. The total time to stimulate the muscle was 20 minutes.

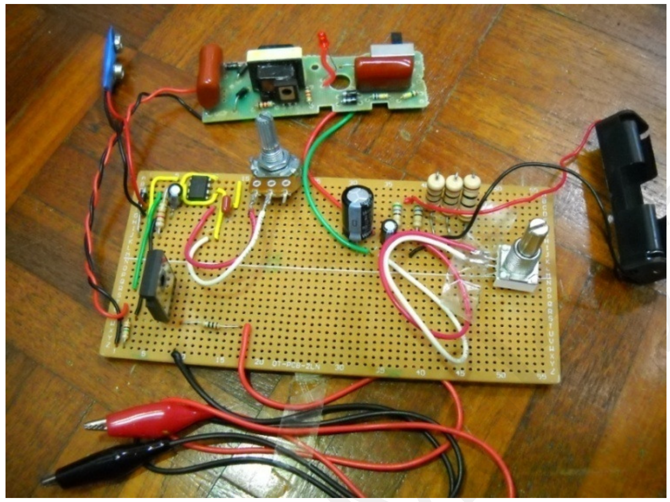


Figure 3.20: FES stimulator used for Test 2.
Adapted from (How, 2011).

(b) Placement of electrode and temperature sensor

The two surface electrodes were placed on the skin surface of the same muscle. For this project, the electrodes were at the proximal and distal of Vastus Lateralis muscle as in Figure 3.21. Vastus Lateralis is one of the four quadriceps muscles as shown in Figure 3.22. Before placing the electrodes on the subject's surface thigh, the skin was washed and dried in order to ensure good conductivity and electrodes were placed only on healthy skin. A light finger pressure was applied to the entire electrode surface. The electrodes were stayed on the skin better when they reached the skin temperature.

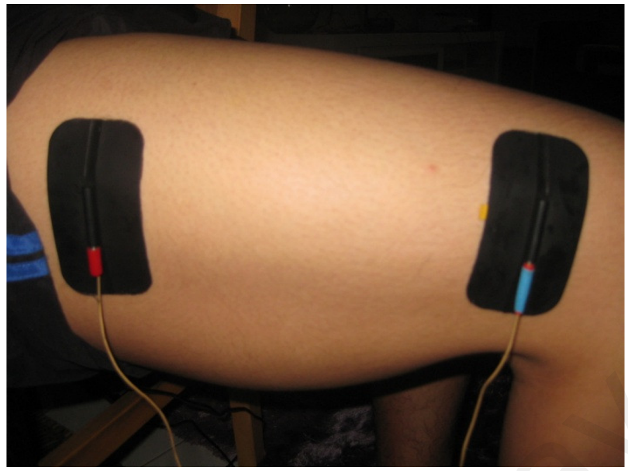


Figure 3.21: Placement of stimulation electrode.

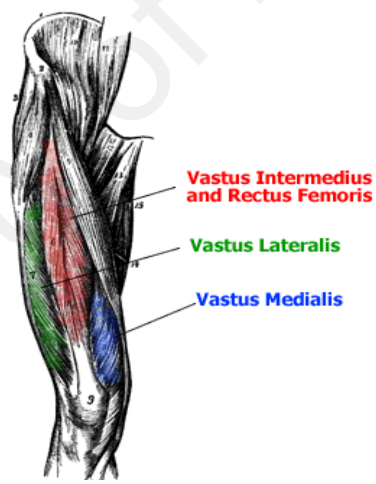


Figure 3.22: Quadriceps muscles.
(Adapted from http://www.fitstep.com/Advanced/Anatomy/Quadriceps.htm)

As for the temperature sensors, five of them were placed in series along the skin surface from proximal to distal as shown in Figure 3.23.

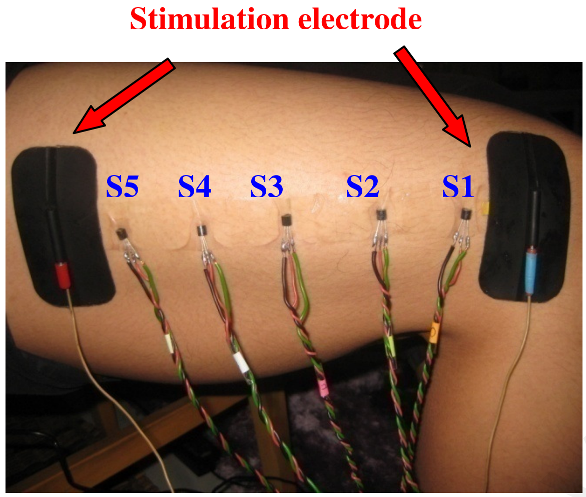


Figure 3.23: Placement of electrode and temperature sensors.

(c) Protocols for Test 2

For Test 2, two subjects were participated. The first subject was asked to sit on a chair with a 90^o posture as in Figure 3.24. The stimulation electrode and temperature sensors were placed as mentioned previously. The personal data of patient; height, weight and age were taken. Before starting the stimulation, the initial temperature of muscle surface was read by the arduino. For starting, the output current was modulated until the subject can feel the presence of current and feel comfortable. The first five minutes, the temperature was recorded and the current amplitude was increment from 0.85mA to 1.15mA. These steps were repeated for each 5 minutes until reach the maximum value of current, 1.55mA.The duration of this whole stimulation was 20 minutes. All the procedures were repeated for the second subject.

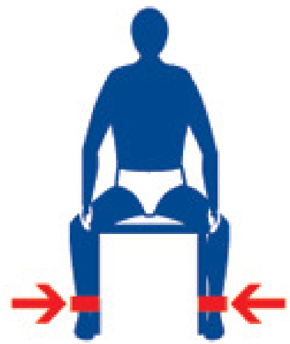


Figure 3.24: Sitting posture for test's subject.
(Adapted from http://www.shopcompex.com/training/electrode-placements/quadriceps)

3.4 Third part: Data analysis

The data obtained from Test 1 was analyzed to study the relationship between the increasing of cycling resistance and the skin temperature. For Test 2, the data obtained to examine the relationship between stimulation current and the skin temperature. All the data were list in tables and plotted into graphs using Microsoft Office Excel to examine the correlation. Then, data between Test 1 and Test 2 were compared to examine the correlation between cycling resistance and stimulation current by observing the respond of skin temperature.

CHAPTER 4: RESULTS

This chapter discussed the outcome of FES stimulator and the results obtained from both Test 1 and Test 2. The output of actual stimulator was compared with the output of simulation stimulator. As for Test 1 and Test 2, both of them showed a relationship between cycling resistance, stimulation current and skin temperature, thus lead to the finding of correlation between muscle activation and the heat produced by the muscle.

4.1 Output of FES stimulator

After the FES stimulator was constructed, the output value was tested first before connected to stimulation electrode and start the stimulation. The value outputs such as pulse frequency, pulse width and current amplitude were displayed using an oscilloscope and ammeter. This was to make sure either the value output were the same as the output of simulation stimulator.

As mention previously in Chapter 3, the 10kΩ digital potentiometer was used to control the level of current amplitude as well as the voltage amplitude. The value of voltage amplitude and pulse frequency was displayed using an oscilloscope. Figure 4.1 and Figure 4.2 shows the maximum and minimum of voltage amplitude and the value of pulse frequency. When the potentiometer was set at the highest value of resistance, the voltage amplitude increased until 9V. As for the opposite, the lowest value of resistance had made the voltage amplitude to decrease until 1.60V and the pulse frequency for both minimum and maximum voltage remained the same, which was already set earlier during the circuit construction.

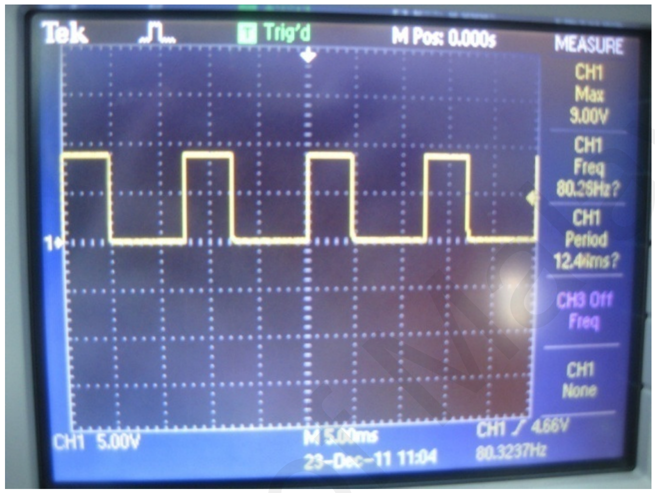


Figure 4.1: Maximum value of voltage amplitude.

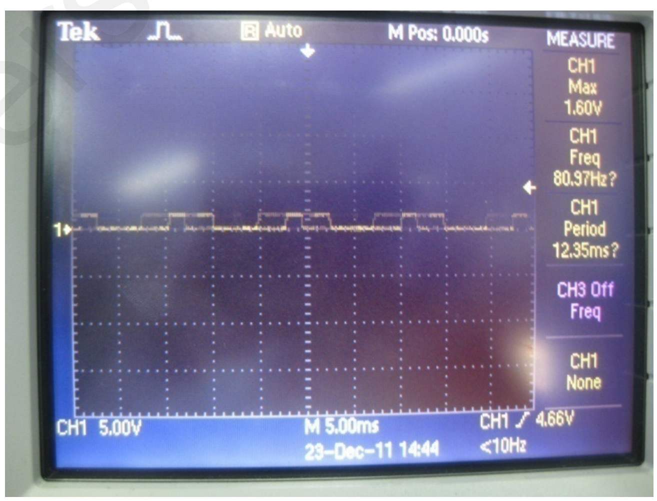


Figure 4.2: Minimum value of voltage amplitude.

For this study, the range of current output that supposedly to be tested was between 10mA and 40mA. As for the testing, the potentiometer was set to the lowest resistance, to display the minimum value of current amplitude. Figure 4.3 shows that the lowest value of current amplitude obtained was around 3mA while in Figure 4.4, it shows the maximum value of current amplitude with 79mA.

Figure 4.3: Minimum value of current amplitude.

Figure 4.4: Maximum value of current amplitude.

4.2 Result of Test 1

For Test 1, both subjects were asked to voluntary cycled for 20 minutes. The cycling speed must be maintained in range of 46 – 52 rpm in order to get good performance. In the experiment, increased value of power indicates the increased of cycling resistance. While maintaining the performance, the cycling resistance will increase due to increased of 1 Watt of power for every five seconds. Through calculation, the value of resistance can be obtained for each time. For example:

1 minute = 60 seconds

10 minutes x 60s = 600 seconds

1 Watt = For every 5 seconds

$$\frac{\mathbf{1}\ \boldsymbol{Watt}}{\mathbf{5}\ \boldsymbol{seconds}} \times \mathbf{600}\ \boldsymbol{seconds} = \mathbf{120}\ \boldsymbol{Watt}$$

Thus, Figure 4.5 shows that the cycling duration is linearly proportional to the cycling resistance.

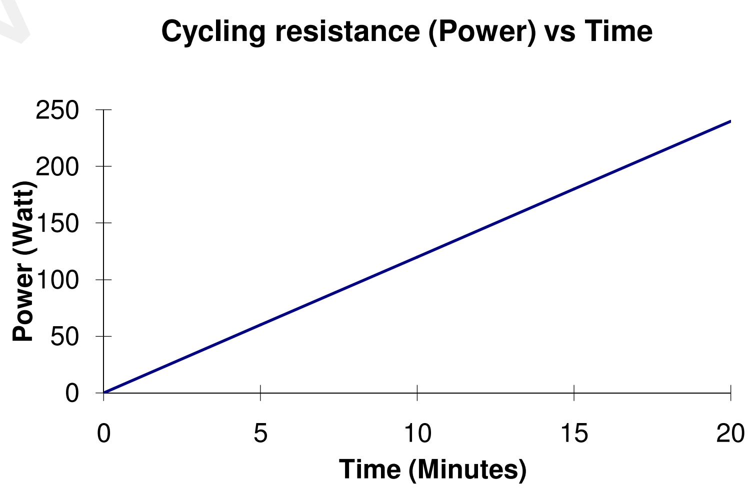


Figure 4.5: Linear graph of cycling resistance versus time of cycling.

Table 4.1 shows the list value of cycling resistance, time of cycling and recorded temperature from five sensors of subject 1. The temperature recorded were the skin temperature of the surface skin above vastus lateralis muscles. For all five sensors, the initial skin temperature was between 28^{o}C and 29^{o}C. As the subject start cycle, the time and cycling resistance were examined. At minute 5 value of power increased to 60 Watt, supposedly the temperature would also increase. However, the temperature value was dropped into a range of 25^{o}C until 28^{o}C for all five sensors. Then, after minute10 until minute 20, the temperature values were increased until reached a range value of 29^{o}C to 31.5^{o}C.

Table 4.1: Temperature recorded of subject 1.

Power (Watt)	**Time**	**Temperature sensor (Degree Celcius)**				
		S1	**S2**	**S3**	**S4**	**S5**
0	Initial	28.12	28.12	28.61	29.1	29.1
60	Minute 5	27.15	26.66	25.63	28.12	27.64
120	Minute 10	28.22	27.15	27.15	28.61	29.1
180	Minute 15	28.61	29.1	29.59	29.59	30.08
240	Minute 20	29.59	31.01	30.08	30.57	31.54

Graph in Figure 4.6 shows the relationship between cycling resistance and the skin temperature of subject 1. From the graph, it showed that the skin temperature was increased as the value of power increased. For the first 5 minute, there might be a problem among the temperature sensors that lead to the reduction of temperature value recorded. For initial value, temperature recorded by S4 and S5 were the highest while temperature recorded by S1 and S2 were the lowest. By the end of the test, it showed that starting from S1 until S5, the temperature recorded was increased. This means that the skin temperature at the distal of vastus lateralis was the lowest and the proximal part of the muscle had the highest temperature.

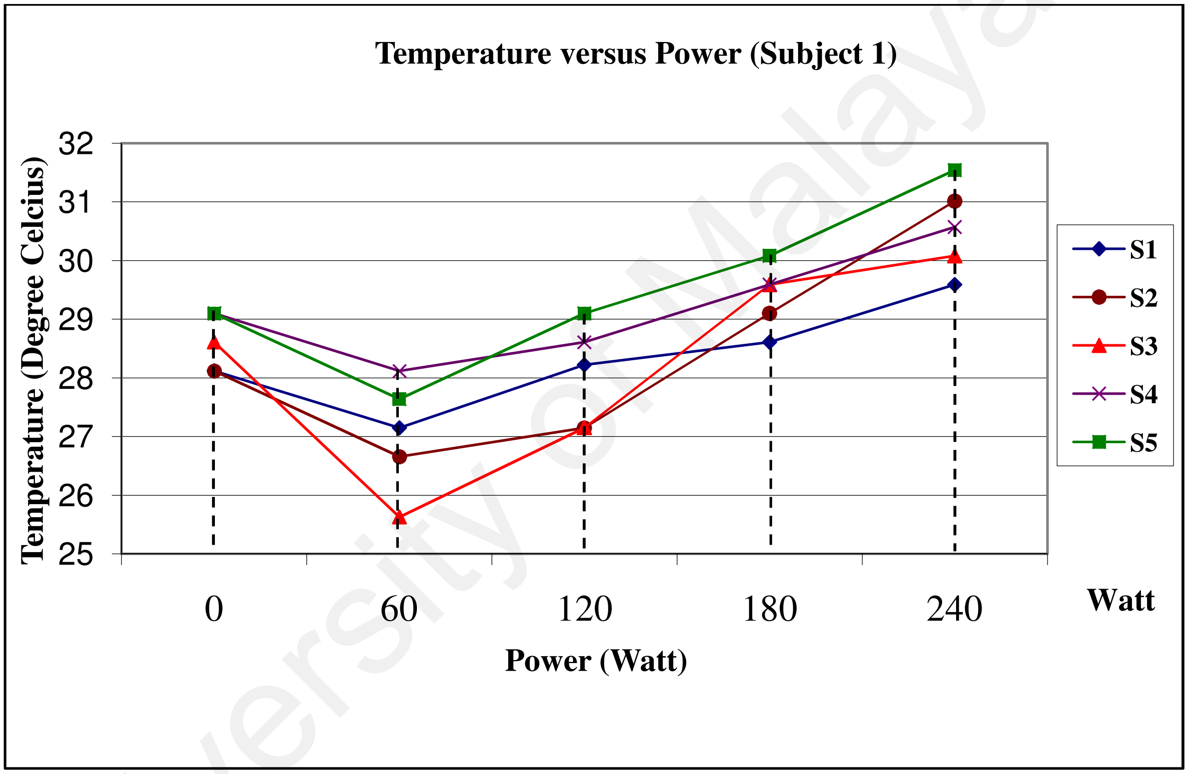


Figure 4.6: Graph of temperature versus power of cycling of subject 1.

Temperature recorded for all five sensors of subject 2 were listed in the Table 4.2. The initial skin temperature of subject 2 was in range of 24^{o}C to 26^{o}C. Five minute after cycling was started; the temperature for each sensor was increased. As the time of cycling reach 10 minutes, the temperature still increased. However, as it reached 15 minutes of cycling, temperature value from S2 and S4 still maintained the same and the value from S5 was dropped nearly 1^{o}C. While temperature value of S1 and S3 still increased. End of the test, there was a change in the performance of each sensor. S1 gave out a same temperature as before, value of S2 was slightly increased, value of S3 was slightly decreased, and value of S4 and S5 was increased. The mean temperature that recorded by five sensors was about 28.07^{o}C.

Table 4.2: Temperature recorded of subject 2.

Power (Watt)	Time	Temperature sensor (Degree Celcius)				
		S1	**S2**	**S3**	**S4**	**S5**
0	Initial	24.71	25.68	24.22	25.68	26.17
60	Minute 5	26.66	28.12	25.68	26.66	27.64
120	Minute 10	27.15	28.12	26.66	28.12	28.12
180	Minute 15	27.64	28.12	27.64	28.12	27.15
240	Minute 20	27.64	28.61	27.15	28.64	28.31

Figure 4.7 shows that the pattern of temperature increased of subject 2 was slightly different compared to subject 1. The skin temperature was theoretically increased linearly with the increased of power value of cycling resistance and time of cycling. However, in the relationship graph of subject 2, the temperature recorded was not constantly increased as some of the sensors gave out a decreased of temperature during cycling. For the initial temperature, value of S5 was the highest while value of S3 was the lowest. Yet, at the end S4 gave out the highest value and S3 remained the lowest.

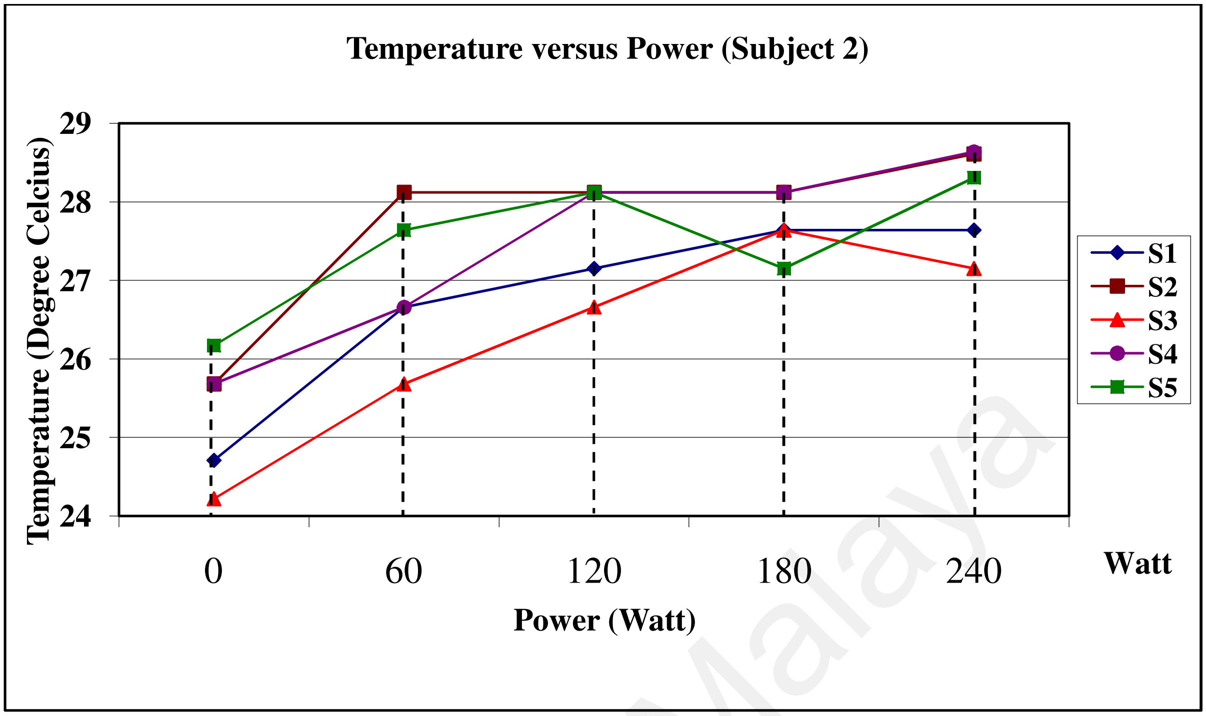


Figure 4.7: Graph of temperature versus resistance of subject 2.

The mean and standard deviation graph in Figure 4.8 shows that pattern of temperature increased of subject 2 was better than subject 1. For subject 2, the mean temperature keep increased when power increased. For subject 1, the temperature decreased during the power value of 60Watt. But after that, start to increased back until the maximum value of power. Then, the mean difference between end temperature and initial temperature of subject 1 and subject 2 were different. For subject 1, the mean difference was approximate to 2^{o}C while for subject 2, the mean difference was nearly 3^{o}C. It showed that during the 20 minutes cycling, the rate of increased temperature for subject 2 was slightly higher than subject 1. The standard deviation among the five sensors for both subject 1 and subject 2 was different for each value of resistance where the temperature was recorded.

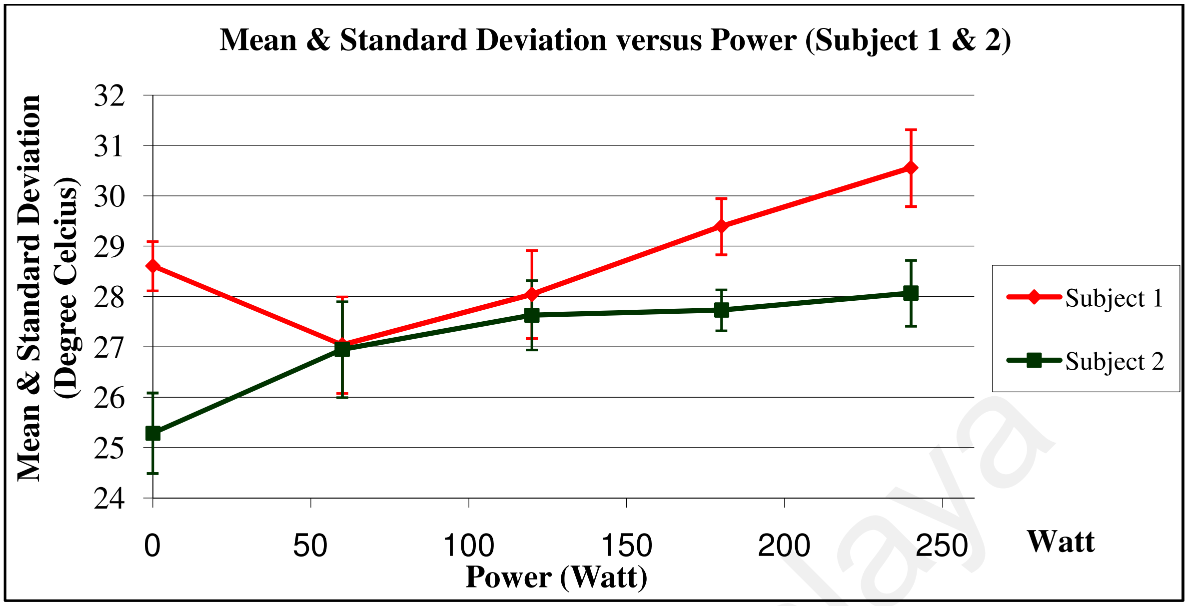


Figure 4.8: Graph of mean and standard deviation of skin temperature for subject 1 and subject 2.

4.3 Result of Test 2

For Test 2, both subjects were not asked to do any voluntary training, instead they were applied with a stimulate current to stimulate their vastus lateralis muscles. As mentioned before, the stimulator that have been constructed had failed to be applied on human muscle, thus been replaced with another stimulator to carry on this test.

The new stimulator was set to the maximum value of pulse frequency was 17Hz and the output voltage pulse was ≈7V. As for the output current, the maximum value was 1.55mA. Thus, the initial skin temperature was taken before started the stimulation.

Table 4.3 shows the recorded temperature from five sensors of subject 3. For all sensors, the initial skin temperature for subject 3 was between 24°C and 27°C. For starting, the stimulator was set to give out 0.85mA for about 5 minutes. At the end of 5 minutes, value of temperature was recorded. Supposedly the temperature was increased for all sensors, but S5 gave out a slightly decreased value. Then, the output current was increased to 1.15mA for another 5 minutes. This went on until minute 20 with the maximum current of 1.55mA. At the end, it showed that temperature for all sensors were increased into a range of 25^{o}C until 28^{o}C.

Table 4.3: Temperature recorded of subject 3.

Current (mA)	Time	Temperature sensor (Degree Celcius)				
		S1	**S2**	**S3**	**S4**	**S5**
0	Initial	25.68	26.66	26.17	27.12	24.71
0.85	Minute 5	25.68	26.66	26.66	28.12	24.23
1.15	Minute 10	26.66	27.12	27.12	29.01	25.11
1.35	Minute 15	26.02	27.64	27.17	28.64	25.21
1.55	Minute 20	26.17	27.66	27.66	28.62	25.68

Figure 4.9 shows the graph of a relationship between current amplitude and the skin temperature of subject 3. From the graph, it showed that the skin temperature was increased as the current amplitude increased. However, the increased pattern of temperature was not linear with the increased of current amplitude as some of the sensors detect a decreased value of temperature during the stimulation. For initial temperature value, S4 gave out the highest value while temperature detected by S5 was the lowest. As the muscles were stimulated with 1.55mA, seems that S4, S2, and S3 gave out a higher reading temperature

compared to S1 and S5. Concluded that both proximal and distal muscles that located near the electrodes produced lower temperature while the medial muscle which is far from both electrodes produced a higher temperature.

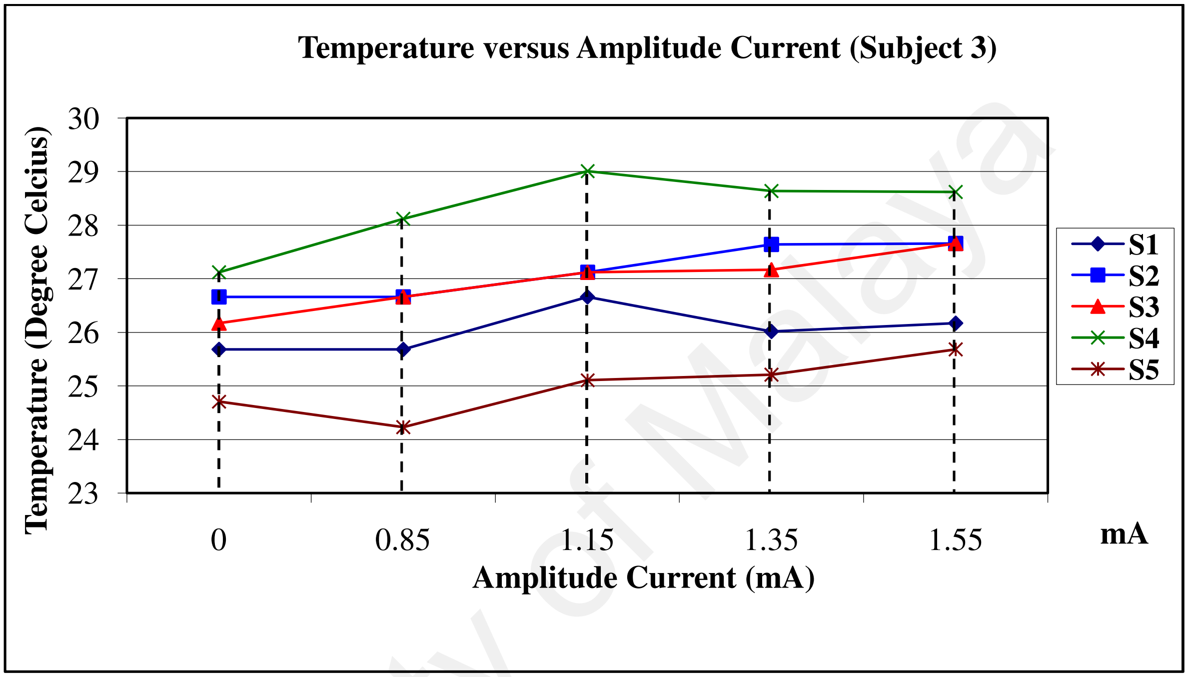


Figure 4.9: Graph of temperature versus amplitude current of subject 3.

For subject 4, the list of temperature recorded for were listed in the Table 4.4. The initial skin temperature of subject 4 was in range of 26°C to 28°C. Five minute after stimulation started; temperature for three sensors were increased while the other two were remained the same as the initial reading. When the current increased for another five minutes, most of temperature was increased except temperature at S5 was decreased. The current increased and time has reached 15 minutes of stimulation, temperature value from S3 maintained the same and the others increased. End of stimulation, S1 and S5 gave a difference of 1°C higher compared to other sensors. Thus, the range of temperature reading was between 28°C and 29°C.

Table 4.4: Temperature recorded of subject 4.

Current (mA)	Time	Temperature sensor (Degree Celcius)				
		S1	**S2**	**S3**	**S4**	**S5**
0	Initial	27.15	26.59	27.64	26.66	27.64
0.85	Minute 5	28.12	26.66	27.64	28.12	27.64
1.15	Minute 10	29.1	28.12	29.1	29.1	26.66
1.35	Minute 15	29.59	28.61	29.1	27.64	28.61
1.55	Minute 20	29.59	28.64	28.12	28.12	29.1

Figure 4.10 shows that the pattern of temperature increased of subject 4 was different compared to subject 3. The graph shows that the performance of sensor to detect temperature was not any better. The temperature detected was not constantly increased as some of the sensors gave out a decreased of temperature during stimulation. But by the end, the temperature still increased as predicted when the stimulation current increased. For the initial temperature, value of S3 and S5 were the highest while value of S2 and S4 were the lowest. Yet, at the end of stimulation, S1 gave out the highest value whereas S3 and S5 are the lowest.

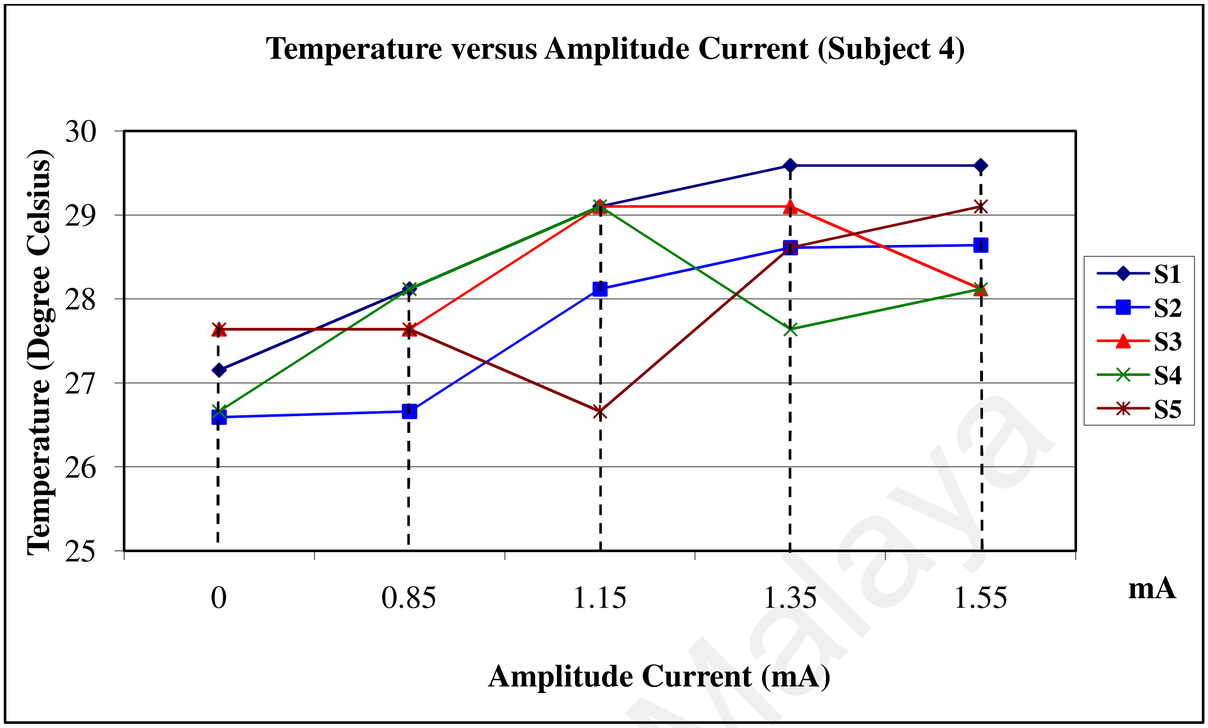


Figure 4.10: Graph of temperature versus amplitude current of subject 4.

Figure 4.11 shows the mean and standard deviation graph of skin temperature of subject 3 and subject 4. From the graph, the pattern of temperature increased of subject 3 was better than subject 4. But, both shows an increased of mean temperature as the current amplitude increased. Yet, the mean difference between end temperature and initial temperature of subject 3 and subject 4 were different. For subject 3, the mean difference was 1.09^{o}C while for subject 4, the mean difference was 1.58^{o}C. It showed that during the 20 minutes stimulation, the rate of increased temperature for subject 4 was slightly higher than subject 3. The standard deviation among the five sensors for both subject 3 and subject 4 was different for each value of current amplitude where the temperature was recorded. Before stimulation, the standard deviation of temperature recoded was lower while when the stimulation current was set at 1.15mA, the standard deviation of temperature between the sensors was the highest.

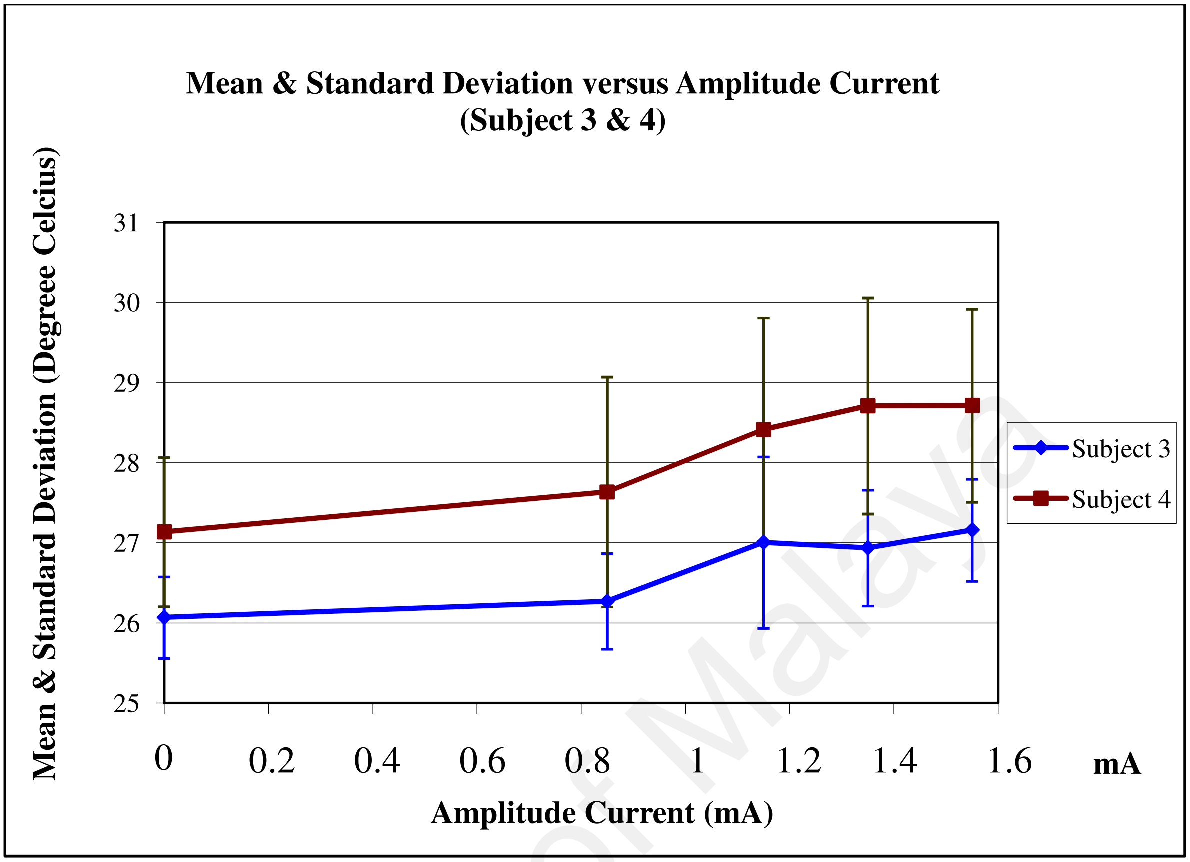


Figure 4.11: Graph of mean and standard deviation of skin temperature for subject 3 and subject 4.

CHAPTER 5: DISCUSSION

This project was to develop a heat feedback parameter of FES stimulator. Thus, temperature sensor was used to detect the changes of skin temperature during the stimulation muscles. One of the objectives was to examine the correlation between activation of muscle and the heat produced by the muscles. This project had two parts which were first part involved with the construction of FES stimulator and second part involved with the testing of the temperature sensor.

For the first part, the FES stimulator was build to give an output of 80Hz, 32% of duty cycle, and the current amplitude can be modulate to 40mA or more. After successfully construct the stimulator circuit, the output was displayed and as predicted, it produced a satisfying output. The current amplitude was set in range of 40mA to 70mA because this project used only able-bodied subject. The values were half of the range of value used to stimulate a SCI patient. Previous studies used a range of 120mA to 140mA current amplitude to stimulate the muscles of SCI patients (Decker et al., 2010; Szecsi et al., 2008).

However, when the stimulator was connected to the stimulation electrode and tested it to the subject, the subject did not feel any tingling sensation. This means that the current output did not stimulate the subject's muscles. After completing few modifications towards the stimulator circuit, it still gave out a same result. It can be assume that there were few reasons that lead to the problem. First, maybe because of the amplitude voltage was not high enough to activate the stimulation of pulse current. The voltage output for the stimulator was only 9V compared to the FES stimulators within the market; they produced more than 100V of voltage amplitude. Second, the stimulation electrode and electrode gel have their own resistance that the current amplitude must pass through. Thus, it might have reduced the current output. Third, maybe the current output could not go through the skin impedance of human skin as the current output had been reduced. The resistance of human skin was in range of 500Ω to 2kΩ depends on any part of the body. In the end, the stimulator was successful to produce a satisfying output but still failed to stimulate the muscles. It was concluded that the stimulator could not be used in Test 2 to stimulate the muscle.

There were a few suggestions that might be able to overcome the problem faced by the stimulator circuit. First, the output of stimulator can be connected to a transformer to step-up the pulse voltage amplitude form 9V to over than 100V. This might produce a strong stimulation pulse to stimulate the muscle. Second, if the output of transformer produces low current amplitude, the value of resistor within the circuit can be change in order to get higher current amplitude. By lowering the value resistor, it can increase the amplitude of current output.

As the constructed stimulator has failed, it has been decided to replace the stimulator with a previous FES stimulator that has been done by an undergraduate student. However, the output of the previous stimulator was different than the constructed stimulator. The pulse frequency produced was approximate to ≈17Hz, the amplitude voltage was ≈7V and maximum current amplitude was only 1.55mA. But the stimulator did success to stimulate the muscles. Thus, Test 2 used the previous stimulator to stimulate the muscles for 20 minutes.

For this project, only four men were used as the subjects. This is because it had been mentioned in a previous study that women have a thicker layer of fat under their skin compared to men. Although the skin thickness was not significantly different between men and women, but women have a thicker subcutaneous fat in average of 0.7cm at the thigh area while men only 0.51cm. It also showed that as the subcutaneous fat increased, the stimulation current also needs to be increased (Petrofsky et al., 2008).

As seen the result in Chapter 4, the initial temperature of skin thigh for each subject was different. The minimum temperature recorded was 24^{o}C and the maximum value was 29^{o}C. Previous study mentioned that the skin temperature for thigh was 31^{o}C. But there are a few factors that lead to the change of skin temperature without any voluntary exercise. The main factor was the temperature environment. A study proved that when a person wears heavy clothing, the skin temperature increased because it received the inner body temperature, whereas when the clothes were loosen, the skin temperature was decreased to the environment temperature (Benedict et al., 1919). This explains the reason why the temperature of thigh of the subjects displayed in range of temperature lower than 31^{o}C.

Thus, the temperature sensor used in this project was not accurate enough to only detect the true skin temperature. It was proposed in previous study, an apparatus which is nearly instantaneous in action and sufficiently protected from the environment should be used to record the true skin temperature, not the resultant of skin and environmental temperature (Benedict et al., 1919). However, all five sensors used in this project indeed success in detecting the increased of skin temperature for both Test 1 and Test 2.

Test 1 and Test 2 were carried out in order to examine the correlation between resistance of cycling, current amplitude and skin temperature. For Test 1, theoretically when the resistance increased, subject must give more effort to maintain the performance of the cycling, thus the activation of thigh muscles especially vastus lateralis was increased. Thus, it expected that the heat produced by muscle will change the skin temperature. As mentioned before, this test was voluntary experiment. As for Test 2, it involved non-voluntary experiment. Theoretically, as the amplitude current increased, the stimulation towards the muscles also increased and forced the muscles to activate more. Previously mentioned for Test 1, as muscle activation increased, heat produced by muscle would increase.

During the 20 minutes of experiment for both tests, it was expected that the temperature increased as resistance and current amplitude increased. However, the mean difference of temperature value between end value and initial value was different for both Test 1 and Test2. The mean difference of skin temperature for Test 1 was between 2^{o}C and 3^{o}C while for Test 2, the mean difference was only between 1^{o}C to 1.59^{o}C. The only factor that leads to the different of those values was because of the muscle activation. For Test 1, as the resistance increased, the subject was voluntarily put an effort towards the muscles to overcome the resistance, thus muscle activation increased. A study mentioned that the skin temperature was affected by the skin blood flow. The temperature rises as the skin blood flow increased (Petrofsky et al., 2008). Thus, it have been assumed that, when muscle activation increased, blood would flow more to the muscles to transfer some oxygen from the blood to the muscles, thus lead to the increased of skin temperature.

For Test 2, the mean difference between initial temperature and final temperature was lower because the current amplitude used was not strong enough to increase the activation of muscles. During the stimulation, indeed the subjects feel the presence of pulse current but as the current amplitude increased, the subjects only feel a little pain. Supposedly, as current amplitude increased, subject would feel more pain. This concludes that the maximum current of 1.55mA cannot be used in a test to examine the muscle activation; it should be increased to 40mA or more as it had been proposed for able-bodied person through a previous study (Decker et al, 2010). By doing this, in an increase the muscle force thus will result an increase of muscle activation.

CHAPTER 6: CONCLUSION

6.1 Summary

In summary, for the first part of this project, the objective of building a FES stimulator has failed due to some reasons. First, due to the lower value of amplitude voltage that was not enough to activate the stimulation of pulse current. Second, due to the resistance of stimulation electrode and electrode gel, it might have reduced the stimulation current. Third, the reduced stimulation current could not go through the skin impedance of human skin. The stimulator indeed success produced a satisfying output with a pulse frequency of 80Hz and current amplitude above 40mA, but unfortunately the current produce did not reach to the subject's muscles thus failed to stimulate the muscles. Supposedly, the stimulator would be used for Test 2, but it was replaced by the previous stimulator done by an undergraduate student.

Yet, this project successfully reached its objectives to detect the muscle contraction level using heat as the feedback parameter and to examine the relationship between muscle contraction level and heat production by the muscle. The hypothesis has been proven that when the contraction level increased, the heat produced by muscle increased and the skin temperature increased.

Test 1 and Test 2 showed that there was a correlation between resistances of cycling, current amplitude and the skin temperature. For Test 1, as resistance increased, the skin temperature increased. For Test 2, as the current amplitude increased, the skin temperature also increased. But the result performance of Test 1 was better than Test 2 because Test 2 was only used a small value of current amplitude. By the end, making the muscle activation level increased, the increased of heat produced by stimulated muscles was transferred to skin surface, thus also increased the skin temperature.

6.2 Recommendation for Future Work

For a future work, the stimulator that has failed will be modulated in order to success produce pulse current and can stimulate the muscle. For examining the muscle contraction level of other muscles, the output will be multiplex to stimulate other muscles at the same time. Multiplexer will be used in advance.

Current study was using an open-looped system of FES stimulator; means that the user need to manually modulate the current amplitude. For future work, a feedback circuit with a microcontroller will be designed for a closed-looped system of FES stimulator. It would remove the need for time uncontrollable manual adjustment. However, for this application, it is important to calculate the expected accuracy of the detected sensor in order to integrate this information into the parameter's controller design. Thus, a more sensitive temperature sensor will be used to read the true temperature of the skin surface.

APPENDIX A

Arduino programming for TMP36:

```
//TMP36 Pin Variables
int sensorPin0 = 0;     //the analog pin the TMP36's Vout (sense) pin is connected to
int sensorPin1 = 1;                     //the resolution is 10 mV / degree centigrade with a
int sensorPin2 = 2;                     //500 mV offset to allow for negative temperatures
int sensorPin3 = 3;
int sensorPin4 = 4;

/*
 * setup() - this function runs once when you turn your Arduino on
 * We initialize the serial connection with the computer
 */
void setup()
{
  Serial.begin(9600);  //Start the serial connection with the computer
                       //to view the result open the serial monitor
}

void loop()                    // run over and over again
{
 //getting the voltage reading from the temperature sensor
 int reading0 = analogRead(sensorPin0);
 int reading1 = analogRead(sensorPin1);
 int reading2 = analogRead(sensorPin2);
 int reading3 = analogRead(sensorPin3);
 int reading4 = analogRead(sensorPin4);

 // converting that reading to voltage, for 3.3v arduino use 3.3
 float voltage0 = reading0 * 5.0;
 voltage0 /= 1024.0;

 float voltage1 = reading1 * 5.0;
 voltage1 /= 1024.0;

 float voltage2 = reading2 * 5.0;
 voltage2 /= 1024.0;
```

```
 float voltage3 = reading3 * 5.0;
 voltage3 /= 1024.0;

 float voltage4 = reading4 * 5.0;
 voltage4 /= 1024.0;

 // now print out the temperature
 float temperatureC0 = (voltage0 - 0.5) * 100 ;  //converting from 10 mv per degree wit 500
mV offset
 float temperatureC1 = (voltage1 - 0.5) * 100 ;
 float temperatureC2 = (voltage2 - 0.5) * 100 ;
 float temperatureC3 = (voltage3 - 0.5) * 100 ;
 float temperatureC4 = (voltage4 - 0.5) * 100 ;  //to degrees ((volatge - 500mV) times 100)

 Serial.print(temperatureC0); Serial.println(" degrees C0");
 Serial.print(temperatureC1); Serial.println(" degrees C1");
 Serial.print(temperatureC2); Serial.println(" degrees C2");
 Serial.print(temperatureC3); Serial.println(" degrees C3");
 Serial.print(temperatureC4); Serial.println(" degrees C4");

 delay(3000);                                  //waiting a second
}
```

APPENDIX B

Datasheet of LM555 timer

National Semiconductor

July 2006

LM555
Timer

General Description

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200mA or drive TTL circuits.

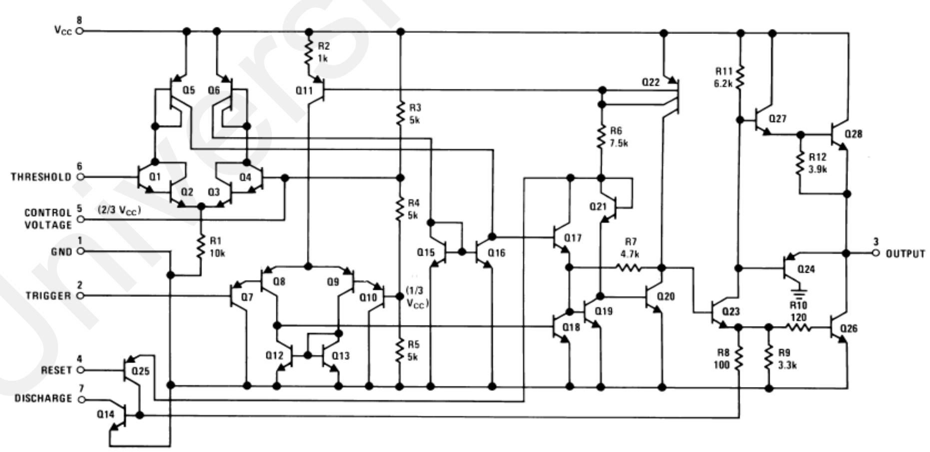
Features

- Direct replacement for SE555/NE555
- Timing from microseconds through hours
- Operates in both astable and monostable modes
- Adjustable duty cycle
- Output can source or sink 200 mA
- Output and supply TTL compatible
- Temperature stability better than 0.005% per °C
- Normally on and normally off output
- Available in 8-pin MSOP package

Applications

- Precision timing
- Pulse generation
- Sequential timing
- Time delay generation
- Pulse width modulation
- Pulse position modulation
- Linear ramp generator

Schematic Diagram



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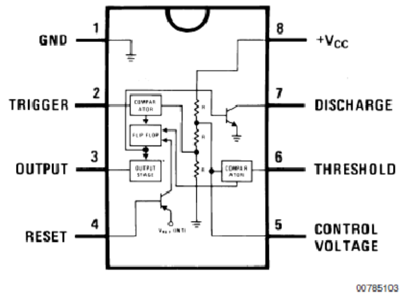
Connection Diagram

Dual-In-Line, Small Outline
and Molded Mini Small Outline Packages



Top View

Ordering Information

Package	Part Number	Package Marking	Media Transport	NSC Drawing
8-Pin SOIC	LM555CM	LM555CM	Rails	M08A
	LM555CMX	LM555CM	2.5k Units Tape and Reel	
8-Pin MSOP	LM555CMM	Z55	1k Units Tape and Reel	MUA08A
	LM555CMMX	Z55	3.5k Units Tape and Reel	
8-Pin MDIP	LM555CN	LM555CN	Rails	N08E

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Supply Voltage	+18V
Power Dissipation (Note 3)	
LM555CM, LM555CN	1180 mW
LM555CMM	613 mW
Operating Temperature Ranges	
LM555C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C

Soldering Information	
Dual-In-Line Package	
Soldering (10 Seconds)	260°C
Small Outline Packages	
(SOIC and MSOP)	
Vapor Phase (60 Seconds)	215°C
Infrared (15 Seconds)	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics (Notes 1, 2)

(T_A = 25°C, V_{CC} = +5V to +15V, unless othewise specified)

Parameter	Conditions	Limits			Units
		LM555C			
		Min	Typ	Max	
Supply Voltage		4.5		16	V
Supply Current	V_{CC} = 5V, R_L = ∞ V_{CC} = 15V, R_L = ∞ (Low State) (Note 4)		3 10	6 15	mA
Timing Error, Monostable Initial Accuracy Drift with Temperature Accuracy over Temperature Drift with Supply	 R_A = 1k to 100kΩ, C = 0.1µF, (Note 5)		 1 50 1.5 0.1		 % ppm/°C % %/V
Timing Error, Astable Initial Accuracy Drift with Temperature Accuracy over Temperature Drift with Supply	 R_A, R_B = 1k to 100kΩ, C = 0.1µF, (Note 5)		 2.25 150 3.0 0.30		 % ppm/°C % %/V
Threshold Voltage			0.667		x V_{CC}
Trigger Voltage	V_{CC} = 15V V_{CC} = 5V		5 1.67		V V
Trigger Current			0.5	0.9	µA
Reset Voltage		0.4	0.5	1	V
Reset Current			0.1	0.4	mA
Threshold Current	(Note 6)		0.1	0.25	µA
Control Voltage Level	V_{CC} = 15V V_{CC} = 5V	9 2.6	10 3.33	11 4	V
Pin 7 Leakage Output High			1	100	nA
Pin 7 Sat (Note 7) Output Low Output Low	 V_{CC} = 15V, I_7 = 15mA V_{CC} = 4.5V, I_7 = 4.5mA		 180 80	 200	 mV mV

Applications Information

MONOSTABLE OPERATION

In this mode of operation, the timer functions as a one-shot (*Figure 1*). The external capacitor is initially held discharged by a transistor inside the timer. Upon application of a negative trigger pulse of less than 1/3 V_{CC} to pin 2, the flip-flop is set which both releases the short circuit across the capacitor and drives the output high.

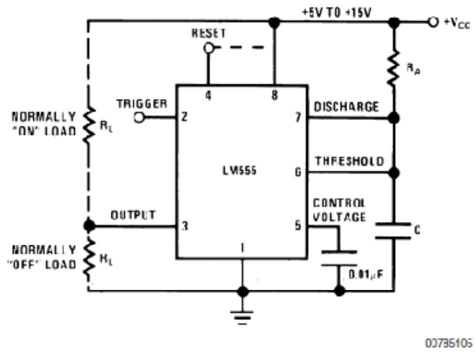
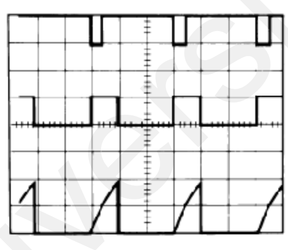


FIGURE 1. Monostable

The voltage across the capacitor then increases exponentially for a period of $t = 1.1\ R_A\ C$, at the end of which time the voltage equals 2/3 V_{CC}. The comparator then resets the flip-flop which in turn discharges the capacitor and drives the output to its low state. *Figure 2* shows the waveforms generated in this mode of operation. Since the charge and the threshold level of the comparator are both directly proportional to supply voltage, the timing interval is independent of supply.



$V_{CC} = 5V$ Top Trace: Input 5V/Div.
TIME = 0.1 ms/DIV. Middle Trace: Output 5V/Div.
$R_A = 9.1k\Omega$ Bottom Trace: Capacitor Voltage 2V/Div.
C = 0.01μF

FIGURE 2. Monostable Waveforms

During the timing cycle when the output is high, the further application of a trigger pulse will not effect the circuit so long as the trigger input is returned high at least 10μs before the end of the timing interval. However the circuit can be reset during this time by the application of a negative pulse to the reset terminal (pin 4). The output will then remain in the low state until a trigger pulse is again applied.

When the reset function is not in use, it is recommended that it be connected to V_{CC} to avoid any possibility of false triggering.

Figure 3 is a nomograph for easy determination of R, C values for various time delays.

NOTE: In monostable operation, the trigger should be driven high before the end of timing cycle.

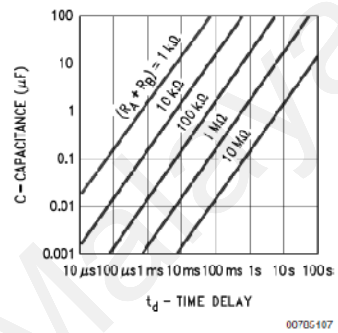


FIGURE 3. Time Delay

ASTABLE OPERATION

If the circuit is connected as shown in *Figure 4* (pins 2 and 6 connected) it will trigger itself and free run as a multivibrator. The external capacitor charges through $R_A + R_B$ and discharges through R_B. Thus the duty cycle may be precisely set by the ratio of these two resistors.

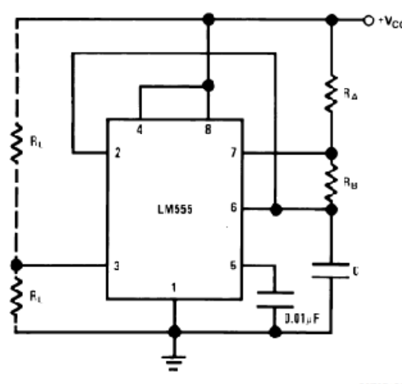
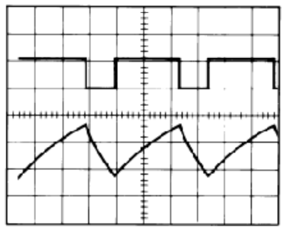


FIGURE 4. Astable

In this mode of operation, the capacitor charges and discharges between 1/3 V_{CC} and 2/3 V_{CC}. As in the triggered mode, the charge and discharge times, and therefore the frequency are independent of the supply voltage.

Applications Information (Continued)

Figure 5 shows the waveforms generated in this mode of operation.



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V_{CC} = 5V
TIME = 20μs/DIV.
R_A = 3.9kΩ
R_B = 3kΩ
C = 0.01μF

Top Trace: Output 5V/Div.
Bottom Trace: Capacitor Voltage 1V/Div.

FIGURE 5. Astable Waveforms

The charge time (output high) is given by:

$$t_1 = 0.693\ (R_A + R_B)\ C$$

And the discharge time (output low) by:

$$t_2 = 0.693\ (R_B)\ C$$

Thus the total period is:

$$T = t_1 + t_2 = 0.693\ (R_A + 2R_B)\ C$$

The frequency of oscillation is:

$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2\,R_B)\,C}$$

Figure 6 may be used for quick determination of these RC values.

The duty cycle is:

$$D = \frac{R_B}{R_A + 2R_B}$$

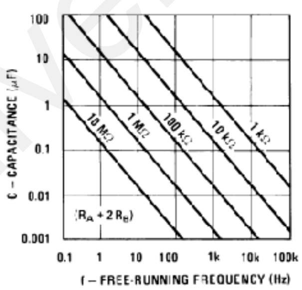

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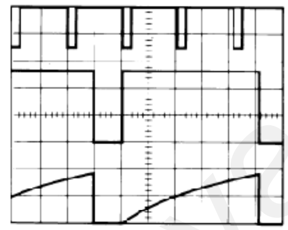
FIGURE 6. Free Running Frequency

FREQUENCY DIVIDER

The monostable circuit of *Figure 1* can be used as a frequency divider by adjusting the length of the timing cycle. *Figure 7* shows the waveforms generated in a divide by three circuit.



00785111

V_{CC} = 5V
TIME = 20μs/DIV.
R_A = 9.1kΩ
C = 0.01μF

Top Trace: Input 4V/Div.
Middle Trace: Output 2V/Div.
Bottom Trace: Capacitor 2V/Div.

FIGURE 7. Frequency Divider

PULSE WIDTH MODULATOR

When the timer is connected in the monostable mode and triggered with a continuous pulse train, the output pulse width can be modulated by a signal applied to pin 5. *Figure 8* shows the circuit, and in *Figure 9* are some waveform examples.

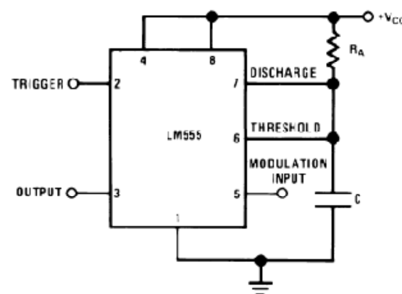


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FIGURE 8. Pulse Width Modulator

APPENDIX C

Datasheet of AD5220 Digital Potentiometer

ANALOG DEVICES

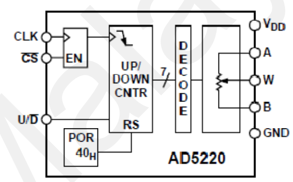
Increment/Decrement Digital Potentiometer

AD5220

FEATURES
128 Position
Potentiometer Replacement
10 kΩ, 50 kΩ, 100 kΩ
Very Low Power: 40 µA Max
Increment/Decrement Count Control

APPLICATIONS
Mechanical Potentiometer Replacement
Remote Incremental Adjustment Applications
Instrumentation: Gain, Offset Adjustment
Programmable Voltage-to-Current Conversion
Programmable Filters, Delays, Time Constants
Line Impedance Matching
Power Supply Adjustment

FUNCTIONAL BLOCK DIAGRAM



GENERAL DESCRIPTION

The AD5220 provides a single channel, 128-position digitally controlled variable resistor (VR) device. This device performs the same electronic adjustment function as a potentiometer or variable resistor. These products were optimized for instrument and test equipment push-button applications. A choice between bandwidth or power dissipation are available as a result of the wide selection of end-to-end terminal resistance values.

The AD5220 contains a fixed resistor with a wiper contact that taps the fixed resistor value at a point determined by a digitally controlled UP/DOWN counter. The resistance between the wiper and either end point of the fixed resistor provides a constant resistance step size that is equal to the end-to-end resistance divided by the number of positions (e.g., R_{STEP} = 10 kΩ/128 = 78 Ω). The variable resistor offers a true adjustable value of resistance, between the A terminal and the wiper, or the B terminal and the wiper. The fixed A-to-B terminal resistance of 10 kΩ, 50 kΩ, or 100 kΩ has a nominal temperature coefficient of 800 ppm/°C.

The chip select $\overline{CS}$, count CLK and U/$\overline{D}$ direction control inputs set the variable resistor position. These inputs that control the internal UP/DOWN counter can be easily generated with mechanical or push button switches (or other contact closure devices). External debounce circuitry is required for the negative-edge sensitive CLK pin. This simple digital interface eliminates the need for microcontrollers in front panel interface designs.

The AD5220 is available in both surface mount (SO-8) and the 8-lead plastic DIP package. For ultracompact solutions selected models are available in the thin µSOIC package. All parts are guaranteed to operate over the extended industrial temperature range of –40°C to +85°C. For 3-wire, SPI compatible interface applications, see the AD7376/AD8400/AD8402/AD8403 products.

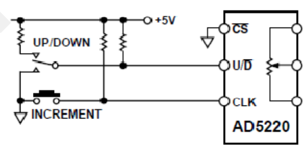


Figure 1. Typical Push-Button Control Application

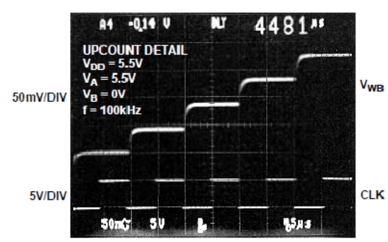


Figure 2a. Stair-Step Increment Output

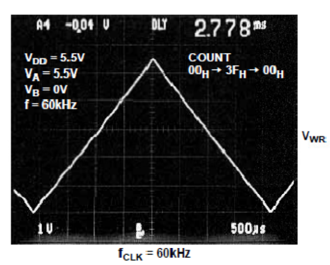


Figure 2b. Full-Scale Up/Down Count

REV. 0

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
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AD5220–SPECIFICATIONS

ELECTRICAL CHARACTERISTICS (V_{DD} = +3 V ± 10% or +5 V ± 10%, V_A = +V_{DD}, V_B = 0 V, –40°C < T_A < +85°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ[1]	Max	Units
DC CHARACTERISTICS RHEOSTAT MODE Specifications Apply to All VRs						
Resistor Differential NL[2]	R-DNL	R_{WB}, V_A = NC, R_{AB} = 10 kΩ	–1	±0.4	+1	LSB
		R_{WB}, V_A = NC, R_{AB} = 50 kΩ or 100 kΩ	–0.5	±0.1	+0.5	LSB
Resistor Nonlinearity[2]	R-INL	R_{WB}, V_A = NC, R_{AB} = 10 kΩ	–1	±0.5	+1	LSB
		R_{WB}, V_A = NC, R_{AB} = 50 kΩ or 100 kΩ	–0.5	±0.1	+0.5	LSB
Nominal Resistor Tolerance	ΔR	T_A = +25°C	–30		+30	%
Resistance Temperature Coefficient	$\Delta R_{AB}/\Delta T$	V_{AB} = V_{DD}, Wiper = No Connect		800		ppm/°C
Wiper Resistance	R_W	I_W = V_{DD}/R, V_{DD} = +3 V or +5 V		40	100	Ω
DC CHARACTERISTICS POTENTIOMETER DIVIDER MODE Specifications Apply to All VRs						
Resolution	N		7			Bits
Integral Nonlinearity[3]	INL	R_{AB} = 10 kΩ	–1	±0.5	+1	LSB
		R_{AB} = 50 kΩ, 100 kΩ	–0.5	±0.2	+0.5	LSB
Differential Nonlinearity Error[3]	DNL	R_{AB} = 10 kΩ	–1	±0.4	+1	LSB
		R_{AB} = 50 kΩ, 100 kΩ	–0.5	±0.1	+0.5	LSB
Voltage Divider Temperature Coefficient	$\Delta V_W/\Delta T$	Code = 40_H		20		ppm/°C
Full-Scale Error	V_{WFSE}	Code = $7F_H$	–2	–0.5	0	LSB
Zero-Scale Error	V_{WZSE}	Code = 00_H	0	+0.5	+1	LSB
RESISTOR TERMINALS						
Voltage Range[4]	V_A, V_B, V_W		0		V_{DD}	V
Capacitance[5] A, B	C_A, C_B	f = 1 MHz, Measured to GND, Code = 40_H		10		pF
Capacitance[5] W	C_W	f = 1 MHz, Measured to GND, Code = 40_H		48		pF
Common-Mode Leakage	I_{CM}	V_A = V_B = V_W		7.5		nA
DIGITAL INPUTS AND OUTPUTS						
Input Logic High	V_{IH}	V_{DD} = +5 V/+3 V	2.4/2.1			V
Input Logic Low	V_{IL}	V_{DD} = +5 V/+3 V			0.8/0.6	V
Input Current	I_{IL}	V_{IN} = 0 V or +5 V			±1	µA
Input Capacitance[5]	C_{IL}			5		pF
POWER SUPPLIES						
Power Supply Range	V_{DD}		2.7		5.5	V
Supply Current	I_{DD}	V_{IH} = +5 V or V_{IL} = 0 V, V_{DD} = +5 V		15	40	µA
Power Dissipation[6]	P_{DISS}	V_{IH} = +5 V or V_{IL} = 0 V, V_{DD} = +5 V		75	200	µW
Power Supply Sensitivity	PSS			0.004	0.015	%/%
DYNAMIC CHARACTERISTICS[5, 7, 8]						
Bandwidth –3 dB	BW_10K	R_{AB} = 10 kΩ, Code = 40_H		650		kHz
	BW_50K	R_{AB} = 50 kΩ, Code = 40_H		142		kHz
	BW_100K	R_{AB} = 100 kΩ, Code = 40_H		69		kHz
Total Harmonic Distortion	THD_W	V_A =1 V rms + 2.5 V dc, V_B = 2.5 V dc, f = 1 kHz		0.002		%
V_W Settling Time	t_S	V_A = V_{DD}, V_B = 0 V, 50% of Final Value, 10K/50K/100K		0.6/3/6		µs
Resistor Noise Voltage	e_{NWB}	R_{WB} = 5 kΩ, f = 1 kHz		14		$nV/\sqrt{Hz}$
INTERFACE TIMING CHARACTERISTICS Applies to All Parts[5, 9]						
Input Clock Pulsewidth	t_{CH}, t_{CL}	Clock Level High or Low	25			ns
$\overline{CS}$ to CLK Setup Time	t_{CSS}		20			ns
$\overline{CS}$ Rise to Clock Hold Time	t_{CSH}		20			ns
$U/\overline{D}$ to Clock Fall Setup Time	t_{UDS}		10			ns

NOTES

[1] Typicals represent average readings at +25°C and V_{DD} = +5 V.

[2] Resistor position nonlinearity error R-INL is the deviation from an ideal value measured between the maximum resistance and the minimum resistance wiper positions. R-DNL measures the relative step change from ideal between successive tap positions. Parts are guaranteed monotonic. See Figure 29 test circuit.

[3] INL and DNL are measured at V_W with the RDAC configured as a potentiometer divider similar to a voltage output D/A converter. V_A = V_{DD} and V_B = 0 V. DNL specification limits of ±1 LSB maximum are guaranteed monotonic operating conditions. See Figure 28 test circuit.

[4] Resistor terminals A, B, W have no limitations on polarity with respect to each other.

[5] Guaranteed by design and not subject to production test.

[6] P_{DISS} is calculated from (I_{DD} × V_{DD}). CMOS logic level inputs result in minimum power dissipation.

[7] Bandwidth, noise and settling time are dependent on the terminal resistance value chosen. The lowest R value results in the fastest settling time and highest bandwidth. The highest R value results in the minimum overall power consumption.

[8] All dynamic characteristics use V_{DD} = +5 V.

[9] See timing diagrams for location of measured values. All input control voltages are specified with t_R = t_F = 1 ns (10% to 90% of V_{DD}) and timed from a voltage level of 1.6 V. Switching characteristics are measured using both V_{DD} = +3 V or +5 V.

Specifications subject to change without notice.

ABSOLUTE MAXIMUM RATINGS*
(T_A = +25°C, unless otherwise noted)

V_{DD} to GND . . . . –0.3 V, +7 V
V_A, V_B, V_W to GND . . . . 0 V, V_{DD}
A_X–B_X, A_X–W_X, B_X–W_X . . . . ±20 mA
Digital Input Voltage to GND . . . . 0 V, V_{DD} + 0.3 V
Operating Temperature Range . . . . –40°C to +85°C
Maximum Junction Temperature (T_J MAX) . . . . +150°C
Storage Temperature . . . . –65°C to +150°C
Lead Temperature (Soldering, 10 sec) . . . . +300°C
Package Power Dissipation . . . . (T_J max–T_A)/θ_{JA}
Thermal Resistance θ_{JA}
P-DIP (N-8) . . . . 103°C/W
SOIC (SO-8) . . . . 158°C/W
μSOIC (RM-8) . . . . 206°C/W

*Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

PIN CONFIGURATION

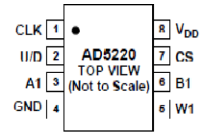

Table I. Truth Table

CS	CLK	U/D	Operation
L	↓	H	Wiper Increment Toward Terminal A
L	↓	L	Wiper Decrement Toward Terminal B
H	X	X	Wiper Position Fixed

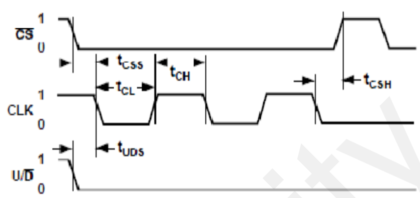

Figure 3. Detail Timing Diagram

PIN FUNCTION DESCRIPTIONS

Pin No.	Name	Description
1	CLK	Serial Clock Input, Negative Edge Triggered
2	U/D	UP/DOWN Direction Increment Control
3	A1	Terminal A1
4	GND	Ground
5	W1	Wiper Terminal
6	B1	Terminal B1
7	CS	Chip Select Input, Active Low
8	V_{DD}	Positive Power Supply

ORDERING GUIDE

Model	kΩ	Temperature Range	Package Descriptions	Package Options
AD5220BN10	10	–40°C to +85°C	8-Lead Plastic DIP	N-8
AD5220BR10	10	40°C to +85°C	8-Lead (SOIC)	SO-8
AD5220BRM10	10	–40°C to +85°C	8-Lead μSOIC	RM-8
AD5220BN50	50	–40°C to +85°C	8-Lead Plastic DIP	N-8
AD5220BR50	50	–40°C to +85°C	8-Lead (SOIC)	SO-8
AD5220BRM50	50	–40°C to +85°C	8-Lead μSOIC	RM-8
AD5220BN100	100	–40°C to +85°C	8-Lead Plastic DIP	N-8
AD5220BR100	100	–40°C to +85°C	8-Lead (SOIC)	SO-8
AD5220BRM100	100	–40°C to +85°C	8-Lead μSOIC	RM-8

NOTE
The AD5220 die size is 37 mil × 54 mil, 1998 sq mil; 0.938 mm × 1.372 mm, 1.289 sq mm. Contains 754 transistors. Patent Number 5495245 applies.

CAUTION
ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the AD5220 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

WARNING!
ESD SENSITIVE DEVICE

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