DEVELOPMENT OF FUNCTIONAL ELECTRICAL STIMULATOR WITH MOVEMENT FEEDBACK PARAMETER FOR MUSCLE ACTIVATION LEVEL DETECTION

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ABSTRACT

Functional electrical stimulation (FES) was widely used in rehabilitation for restoring body function by stimulating the muscle with certain amount of current. An alternative of feedback parameter for muscle activation detection was studied. A movement feedback parameter was chosen to detect muscle activation. Two flexible bend sensors were used to detect muscle movement. In this study, consists of three parts. First part, a stimulator would be developed. Second part, flexible bend sensor embedded to the stimulator for muscle movement detection. Third part, stimulator supplied current through stimulation electrodes for muscle activation and muscle movement detected by flexible bend sensor.

Flexible bend sensors were undergo a voluntary and non-voluntary test to observed the voltage output change with the muscle activation relationship. For voluntary test, there are two separate sessions. The first session, a subject was asked to cycle for 20 minutes. For every five minutes, the first three reading displayed on screen will be recorded. The second session, subject also need to do cycling but data recording was different. By using sampling time of five seconds, an output voltage reading from muscle activation was recorded. For non-voluntary test, current was supplied to vastus medialis muscle and the muscle contraction and relaxation were recorded.

In conclusion, muscle activation can be detected by muscle movement sensed by flexible bend sensor. Based on the basic circuit of flexible bend sensor which is voltage divider, when muscle contracted, bending angle and resistance increased, voltage output was low. When muscle relaxes, bending angle ad resistance decreased and voltage output was high.

ABSTRAK

Rangsangan Fungsi Elektrik (FES) telah digunakan secara meluas dalam pemulihan untuk mengembalikan fungsi badan dengan merangsang otot dengan jumlah arus yang tertentu. Parameter maklum balas alternatif untuk mengesan pengaktifan otot telah dikaji. Parameter maklum balas pergerakan telah dipilih untuk mengesan pengaktifan otot. Dua sensor fleksibel digunakan untuk mengesan pergerakan otot. Kajian ini terbahagi kepada tiga bahagian. Bahagian pertama, perangsang dibina. Bahagian kedua, sensor fleksibel digabung bersama perangsang untuk mengesan pergerakan otot. Bahagian ketiga, elektrik dibekal oleh perangsang melalui elektrod rangsangan untuk pengaktifan otot dan pergerakan otot dikesan oleh sensor fleksibel.

Sensor fleksibel menjalani dua ujian secara sukarela dan bukan secara sukarela untuk mengkaji perubahan keluaran voltan dengan hubungan pengaktifan otot. Untuk ujian sukarela, terdapat dua sesi berasingan. Sesi pertama, subjek diminta untuk mengayuh selama 20 minit. Bagi setiap lima minit, tiga bacaan pertama terpapar di skrin akan direkodkan. Sesi kedua, subjek melakukan mengayuh dengan rakaman data yang berbeza daripada sesi pertama. Dengan menggunakan pensampelan masa selama lima saat, bacaan keluaran voltan dari pengaktifan otot direkodkan. Untuk ujian bukan sukarela, elektrik dibekalkan oleh perangsang kepada otot medialis vastus, pengecutan dan pengembangan otot telah direkodkan.

Secara kesimpulannya, pengaktifan otot boleh dikesan oleh pergerakan otot yang dikesan oleh sensor fleksibel. Berdasarkan litar asas sensor liku yang fleksibel iaitu pembahagi voltan, apabila otot mengembang, sudut lenturan dan rintangan meningkat, keluran voltan rendah dan sebaliknya bagi pengecutan otot.

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No.	Symbols and Abbreviations	
1.	FES	Functional Electrical Stimulation
2.	A	Amphere
3.	V	Voltage
4.	Ω	Resistance
5.	rpm	Revolutions per minute
6.	ATP	Adenosine Triphosphate
7.	ADP	Adenosine Diphosphate
8.	P_i	Phosphate
9.	Ca^{2+}	Calcium ions

LIST OF APPENDICES

1.0 INTRODUCTION

1.1 Problem Statement

For almost half of decade, functional electrical stimulation (FES) has been used to restore functions of people who suffer from muscle weakness and paralysis. Stroke and spinal cord injury (SCI) are the causes of muscle weakness and paralysis of human. By applying an acceptable range of current to the muscle, muscle will contract and disabled persons can walk or stand. Continuous current supply to muscle will cause a muscle fatigue. From previous studies, there is several feedback parameters has been developed, but with some limitations in detection of muscle force level.

A new alternative of feedback parameter was developed in this project which is movement of muscle to detect the muscle force level. It is to understand the correlation between muscle movement and declination of muscle force.

1.2 Objective

The main intention in this project is to build a functional electrical stimulation with muscle movement as the feedback parameter which can give the information of muscle fatigue level. Hence, the main objectives for this project are:

i. To reconstruct a functional electrical stimulator (FES) with controllable parameters such as current.
ii. To identify new alternatives feedback parameter - movement for functional electrical stimulator.
iii. To develop the movement sensor embedded in the stimulator system.
iv. To understand the relationship between muscles movement towards muscle activation.

1.3 Hypothesis

In this project, movement of muscle was measured as a feedback parameter. Measurement of the movement gives information of muscle that has been stimulated by current. A stimulator with movement sensor was developed. This stimulator was tested on able-bodied subjects and the relation between force declines in muscle with the muscle movement was observed.

1.4 Scope of Study

The scope of this project is to develop, design and test a functional electrical stimulation with movement feedback parameter to obtain the muscle activation level information. It can be divided into two parts which are:

i. Development and design

A functional electrical stimulator will be developed. A movement sensor will be embedded in the stimulator system. The sensor will give the information of the muscle movement when stimulated by currents.

ii. Test

The stimulator designed with muscle movement sensor will be tested on able-bodied and disable-bodied persons. Current is supplied to stimulate contraction in muscle and hence, initiates the movement of the persons.

1.5 Significance of Study

Nowadays, there are many FES devices available in market since it is popularly applied for muscle activation to restore function. There are a few of feedback parameters such as EMG, stepper motor and force sensor. Though, each of them has their limitations on detection muscle level based on previous studies. This project focuses on a feedback parameter of muscle movement which will be stimulated by current to detect the muscle level. The relationship between muscle movements with activation level of muscle can be comprehended throughout this project.

2.0 LITERATURE REVIEW

2.1 Functional Electrical Stimulation (FES) System

Functional electrical stimulation defines as a technique of applying certain amount of current to paralyzed muscle to stimulate to contract for function restoration (Geoffrey, Adam, & Milos, 2006; T.A & Popovic, 2008). It is a technology for restoring body functions through artificial stimulation of the neuromuscular system (Kim, Schmit, & Youm, 2006).

The functions of FES is to improve impaired function, to slow down or stop bone and muscle deterioration, and to improve circulation in paralyzed limbs. The FES usually use for patient who suffer from spinal cord injury (SCI) and stroke (Geoffrey, et al., 2006).

2.2 Muscle Contraction

The sliding of the filaments is the result of interactions between the myosin cross-bridges and the thin (actin) filaments. The cross-bridges reversibly bind to actin and produce a mechanical impulse which results in force transmission along the filaments, which either results in force production at the tendons, or results in shortening (or a combination of both). The energy for this process comes from the hydrolysis of Adenosine Triphosphate (ATP), resulting in the release Adenosine Diphosphate (ADP) and

(Phosphate) P_i. The link between movement or force and the utilization of ATP is the fundamental aspect of muscle contraction (Baylor & Hollingworth, 2011).

Calcium ions (Ca^{2+}) are released into the myoplasm by the sarcoplasmic reticulum (SR) in response to depolarization of the fibre's exterior membranes, during excitation-contraction coupling in skeletal muscle. Ca^{2+} then diffuses to the thin filaments, where Ca^{2+} binds to the Ca^{2+} regulatory sites on troponin to activate muscle contraction (Baylor & Hollingworth, 2011).

2.3 Muscle Fatigue

The major limitation of FES is that it tends to produce rapid fatigue in muscle. When voluntary muscle force is low and high intensity FES must be used, muscle fatigue occurs after 1 min of stimulation (T.A & Popovic, 2008). Decreasing of force production during FES could be related basically to changes in:

a) Neuromuscular propagation

The M-wave consists of the synchronous sum of all muscle fibre action potentials that are obtained by the electrical stimulation. Changes in the M-wave indicate alterations 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 membranes. Low force - long duration voluntary contractions have been shown to induce greater M-wave depression than high-force contractions (Tepavac & Schwirtlich, 1997).

b) Excitation-contraction coupling

When there is no reduction in the M-wave and there are no significant metabolic changes, fatigue are generally attributed to mechanisms related to excitation-contraction coupling at one of the seven steps linking activation of the muscle fibre membrane and the force exerted by the fibres. Different tasks activate various mechanisms that cause a reduction in force. The relative contributions made by specific mechanisms to the decline in force were also studied by monitoring the recovery from fatigue. Force loss caused by impaired excitation-contraction coupling appears to be most evident after long-duration contractions with slow recovery (30-60 min). Recovery of force loss caused by metabolic changes and from impaired neuromuscular propagation occurs more rapidly less than six minute. (Tepavac & Schwirtlich, 1997)

c) Metabolic change

When energy demands cannot be met by the rate of supply of ATP, and the metabolites generated by the contractile activity influence cross-bridge activity or the supply of energy, muscle force will decrease too. The extent of this dissociation seems to depend on the intensity of the activity. The energy cost of intermittent stimulation also seems to be higher than that of continuous stimulation. Under anaerobic conditions the force elicited with continuous stimulation is more economical than that produced with intermittent stimulation. Supply of energy and the accumulation of metabolites can contribute to force reduction.(Tepavac & Schwirtlich, 1997)

2.4 Feedback Parameter

Feedback parameter is important for effective control of FES systems. The performance of FES assistive systems can be improved by knowing the information of muscle force level. Surface electromyography (sEMG) or percutaneous electromyography (pEMG) can easily record muscle activation. (Tepavac & Schwirtlich, 1997)

2.4.1 Electromyograph (EMG)

Electromyograph signal can be as an indicator of stimulated muscle fatigue in application of functional electrical stimulation. (Chesler & Durfee, 1997) The amplitude of the EMG depends nonlinearly upon the length of muscle, velocity of shortening of the muscle and the fatigue level (Sinkjaer, Haugland, Inmann, Hansen, & Nielsen, 2003). The advantage of using EMG as indicator of muscle state because it is non invasive and reflects the contractile activity of the underlying muscle (Chesler & Durfee, 1997).

Root-mean-square (RMS) of the EMG amplitude and median frequency (MF) of the EMG power spectral content was derived to obtain fatigue-tracking performance (Chesler & Durfee, 1997). Analysis of the EMG signal of each channel was performed with a MATLAB-based program.

Root mean square (RMS), median frequency (MF) and total duration during the muscle was firing are the parameter measured in EMG signal. The segment of muscle firing was calculated by determining the starts and the end of muscle activity. These segments were used to calculate muscle contracting root mean square value and median frequency (Lam, Leong, Li, Hu, & Lu, 2005).

After the raw EMG signals were adjusted to zero mean to remove the offset from the amplifier, the root mean square value (RMS) of each interval was then calculated by the formula:

$$RMS = \frac{1}{n}\sqrt{\sum x^2\,(i)} \tag{1}$$

where n is the total number of samples within the window considered for processing.

After spectral analysis, the median frequency (MF) was calculated with the formula:

$$\sum_{k=0}^{fmedian} P(fk) = \sum_{k=fmedian}^{fc/2} P(fk) \tag{2}$$

where P(f) is the power density spectrum, f_k the frequency and f_c the sampling frequency while f_{median} the median frequency. The median frequency was defined as that frequency that divided the power density spectrum in two regions having the same amount of power (Lam, et al., 2005).

Stable and artifact-free recordings are major challenges on using EMG as feedback signal. The stimulus artifact is one or more orders of magnitude larger than EMG signal and its effects can remain if EMG amplifier saturates. Special stimulation and recording apparatus must be used to achieve effective artifact reduction. (Chesler & Durfee, 1997)

2.5 Flexible Bend Sensor

The study done by Saba Bakhshi et. al is on development of wearable sensors and smart cloth to measure human motion and joint angles. It is shown in Figure 2.1 below, the finding of Saba Bakhshi et. al on the relationship between voltage and time during flexion and extension of knee (Saba Bakhshi, et al., 2011).

There are some disadvantages of flex sensors in an experiment conducted by Saba Bakhshi et. al. The flex sensor can be damaged if not gently and properly attached to subject. The lifetime of the sensors are not high, and can result of fatal breaking. The available flex sensors are wide and affixing more than two sensors is not practical (Saba Bakhshi, et al., 2011).

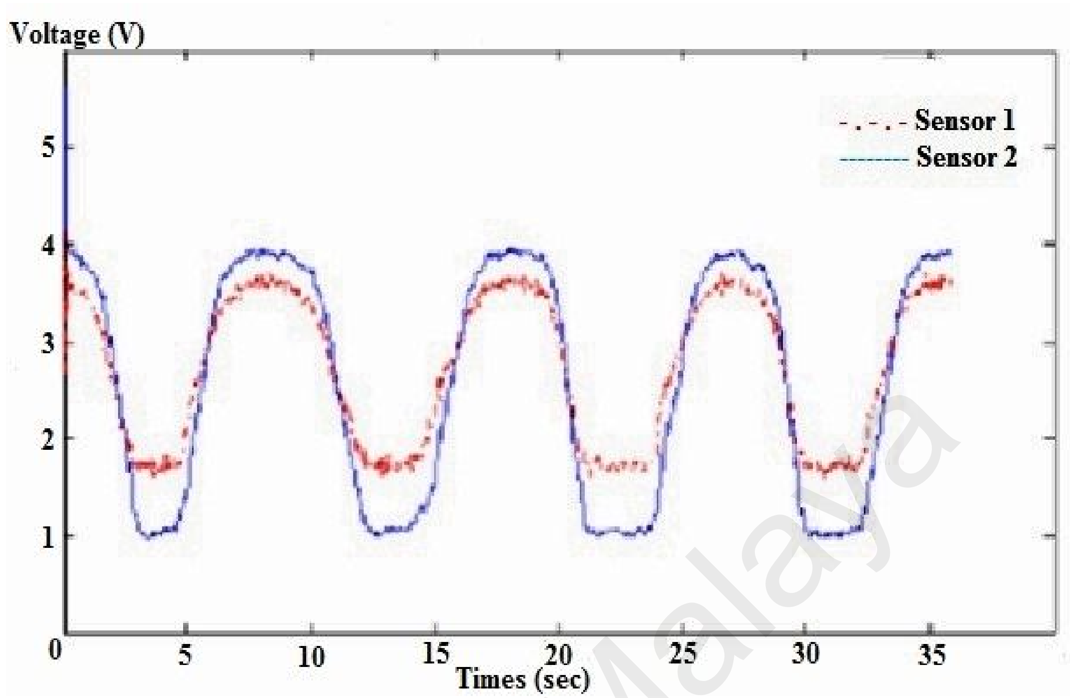

Figure 2.1: Relationship of voltage and time for flexion and extension of knee (Saba Bakhshi, et al., 2011)

3.0 METHODHOLOGY

In this part, the ways of initializing, conducting and analyzing throughout the project was discussed. The flow chart shown in Figure 3.1 below showed the process of conducting this project. Initially the FES stimulator was constructed in Multisim software before being constructed on board. After that, the flex sensor circuit constructed. To display the voltage output from sensor circuit, a microcontroller board that connects to a computer via USB cable, called Arduino, was used. The reading of the voltage change was display on the laptop's screen.

Tests for sensor were conducted in two ways which are voluntary and non-voluntary. For voluntary, subject was asked for cycling in 20 minutes as the resistance of Aerobike was increasing by time. For non-voluntary, current was supply by stimulator in the range of 0.70mA to 1.55mA by slowly increment to muscle. The output voltage of both activities was analyzed and compared.

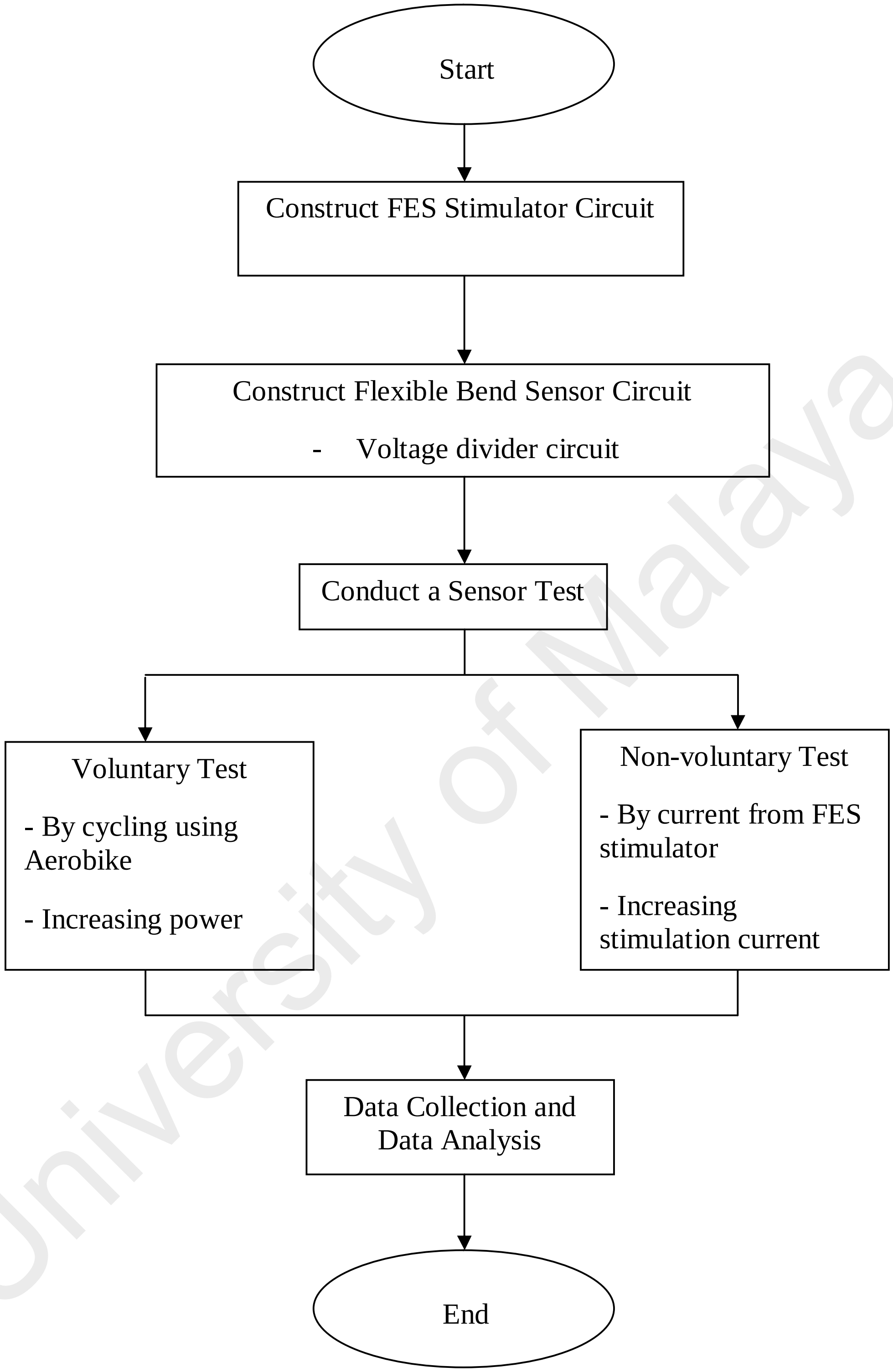

Figure 3.1: Process Flowchart

3.1 Stimulator Circuit

In this project, a stimulator circuit was constructed by using Multisim software. The construction of FES stimulator circuit as shown in Figure 3.2 can be divided into 3 parts. The first part was LM555 timer circuit to control pulse, second part was potentiometer push buttons circuit to control current with two PNP transistor and the third part was the connection of stimulation electrode with the stimulator for current supply to muscle.

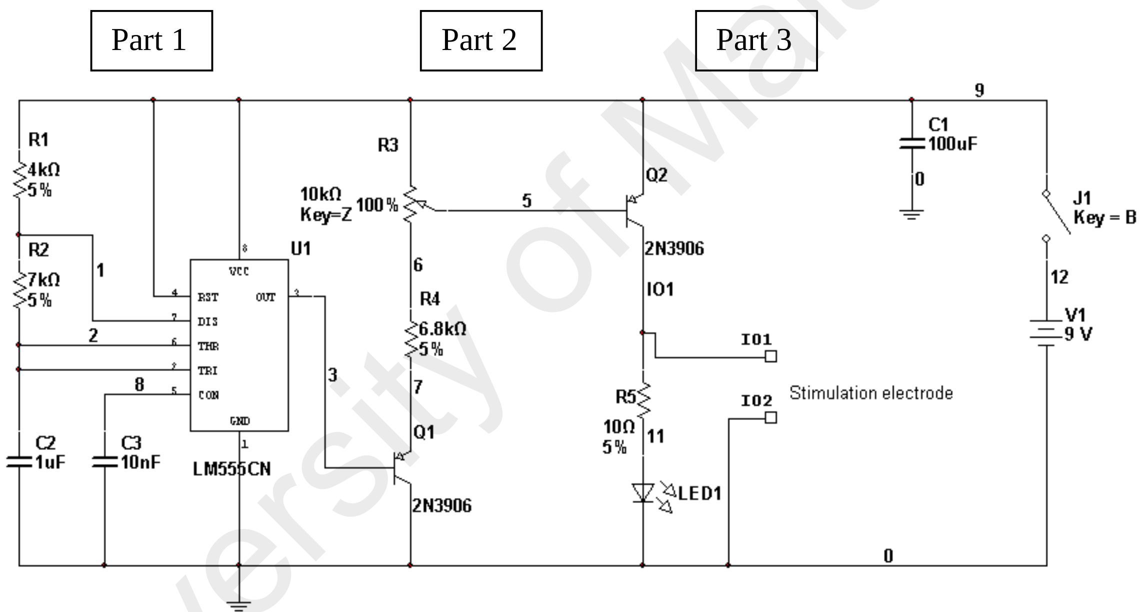

Figure 3.2: Stimulator Circuit (Adapted from http://www.diy-electronic-projects.com/p231-Muscular-Bio-Stimulator).

3.1.1 LM555 Timer

LM555 is a device used for generating accurate time delays or oscillation. For time delay mode's operation, one external resistor and capacitor precisely controls the time. For astable operation as an oscillator, two external resistors and capacitor are accurately controlled free running frequency and duty cycle. The applications of LM555 were pulse generation, pulse width modulation and precision timing in this project.

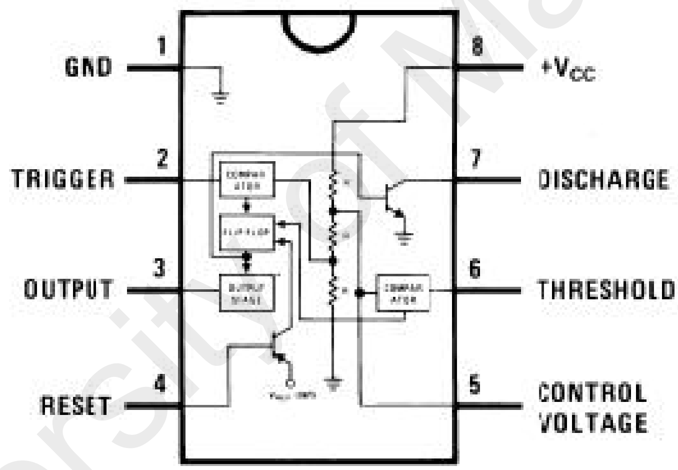

Figure 3.3: Top view of LM555 (Adapted from Datasheet National Semiconductor LM555 Timer)

Figure 3.3 above shows the top view of LM555. In this project, 80Hz of frequency was required. Based on Tepavac et al study, 10 – 100Hz frequency was used for the stimulator. So, 80Hz was chosen which it lies in the range of 10 – 100Hz and also considering the electronic components available in lab. 80Hz of frequency can be calculated by determine value of RA, RB and C using the formula of frequency of oscillation,

$$f = \frac{1}{T} = \frac{1.44}{(RA+2RB)C} \qquad (3)$$

$$f = \frac{1.44}{(4k\Omega + 2(7k\Omega))1\mu F}$$

f = 80Hz

3.1.2 AD5220 Digital Potentiometer

From the LM555 timer's output pin 3, it was connected to Q1. Q1 acts as a buffer to control the flow of current and Q2 inverts the pulses polarity. 10kΩ potentiometer functions to controls the amplitude of pulse current and approximately displayed by the brightness of LED1.

To increase and decrease value of resistance, application of push button in AD5220 was used. Switch J1 in Figure 3.4 was used to control the increment or decrement of the resistance's value. As switch connecting to Up/Down (U/D) pin, pressing the push button repeatedly increases the value of resistance, hence reduced the brightness of LED1. If the switch connected to the ground, again pushing the push button repeatedly decreases the value of resistance. Thus, LED1 will become brighter.

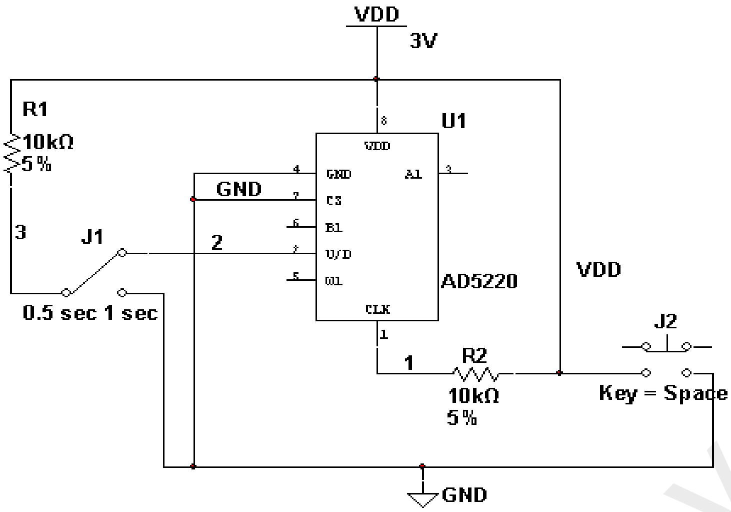

Figure 3.4: Typical Push-Button Control Application (Adapted from Datasheet Analog Devices AD5220 Digital Potentiometer)

After testing the output current from the Multisim software, a circuit was constructed on the breadboard to ensure the connection is correct as shown in Figure 3.5. In Figure 3.6, the stimulator circuit was then connected to oscilloscope to observe the voltage, frequency and duty cycle of the circuit.

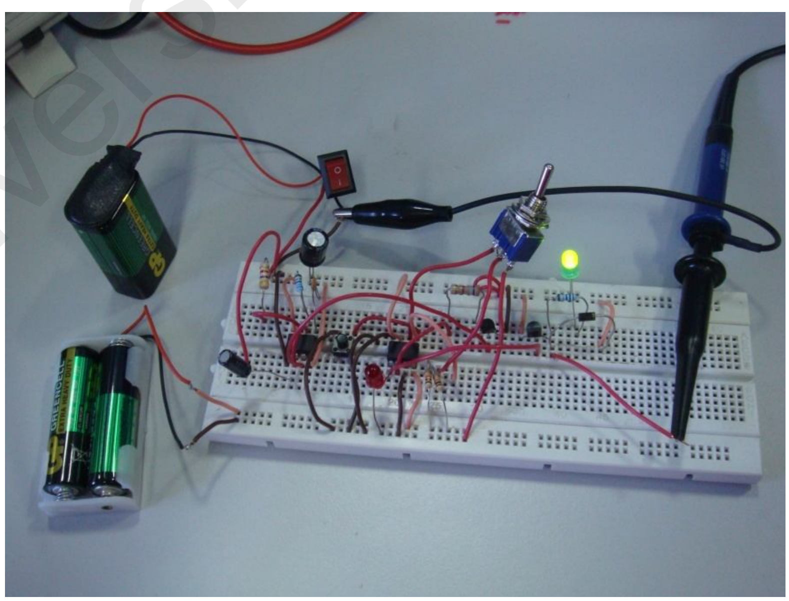

Figure 3.5: Circuit constructed on breadboard

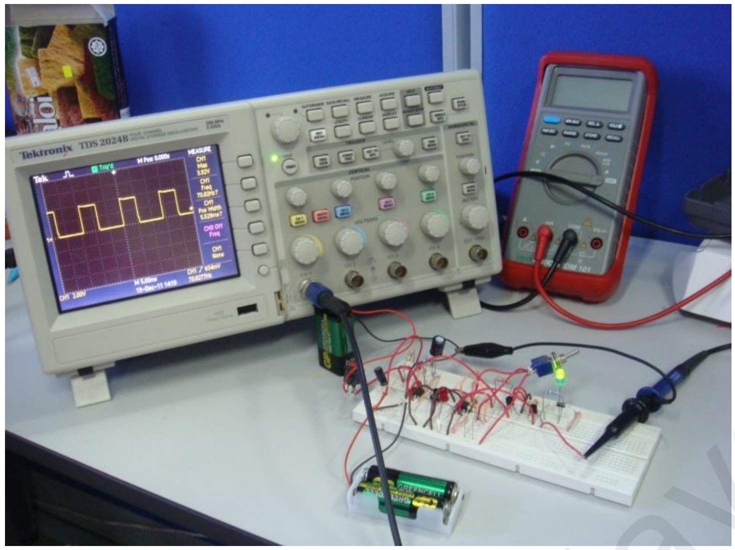

Figure 3.6: Stimulator circuit and Oscilloscope

3.1.3 Connection of Stimulation Electrode

A stimulation electrode was connected to stimulator circuit to supply the current to stimulate the muscle. The electrode used was reusable and some conductive gel application was required for better electrical conduction.

3.2 Sensor Circuit

Flexible bend sensor was chosen to detect muscle movement due to its smaller size, not heavy and it is only a thin film that easier to attach on muscle. The basic circuit of flex sensor was used a voltage divider. This sensor was based on the resistance change over the bending angle.

3.2.1 Resistance Test

In this study, flexible bend sensor was used for detection of muscle activation when stimulated with current. As the sensor is flexed, the resistance across the sensor increases as in Figure 3.7 below. By using multimeter, the resistance of sensor could be tested. The bending angle increases leads to the increment of the sensor resistance. From the reading of multimeter, it can be summarized as in Table 3.1 below:

Table 3.1: Value of resistance respective with bending angle

Angle	Resistance (Ω)
0˚	~ 10k
45˚	~ 12k
90˚	~ 14k

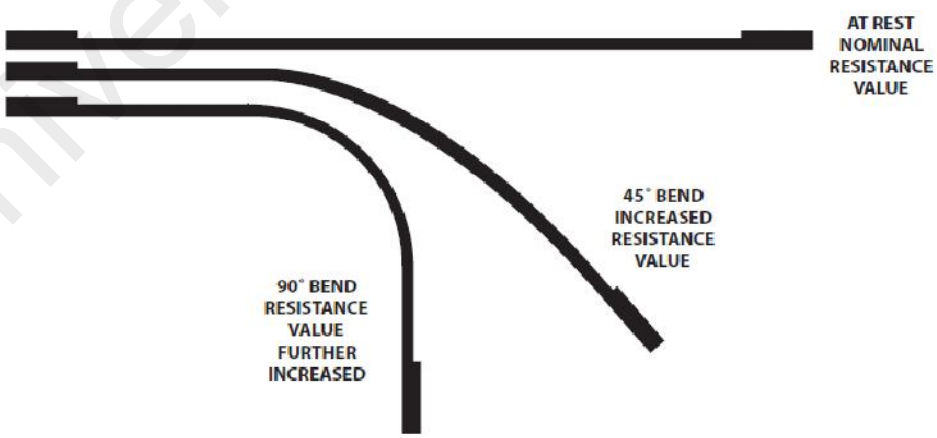

Figure 3.7: Resistance of sensor increase with the bending angle (Adapted from Datasheet Spectrasymbol Flexible Bend Sensor)

3.2.2 Resistance Convert to Voltage

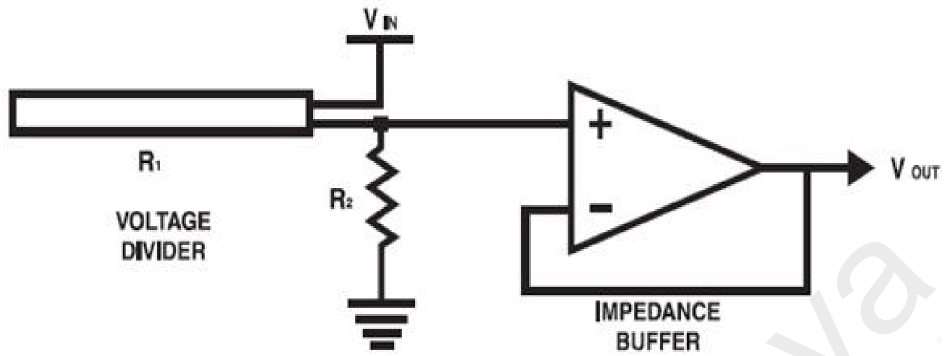

Figure 3.8: Basic Circuit of Flexible Bend Sensor (Adapted from Datasheet Spectrasymbol Flexible Bend Sensor)

$$Vout = \frac{R2}{R1+R2} V_{in} \qquad (4)$$

According to Figure 3.8 above, voltage divider circuit was used for converting resistance into voltage reading. R_1 is a flexible bend sensor. R_2 is 10kΩ resistor connected to ground and V_{in} is 5V. Both resistor and flex sensor were connected to operational amplifier and the output voltage was displayed.

3.2.3 Sensor Placement

Two flexible bend sensors were attached to subject's inner thigh. The sensors must be fixed on vastus medialis muscle. As shown in Figure 3.9, the sensors were placed parallel with the stimulation electrodes to calculate the stimulated muscle movement. In this experiment, Sensor_0 was placed on the distal part of vastus medialis muscle which is near to stimulation electrode while for the Sensor_1 was placed approximately center of the muscle.

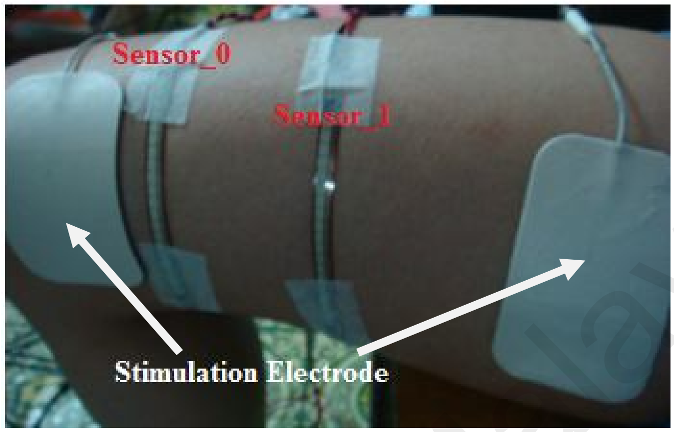

Figure 3.9: Subject with attachment of sensor

3.3 Muscle and Electrode

For this project, the muscles concern in the experiment is quadriceps. Quadriceps is a large group of muscle. All four quadriceps are powerful extensors of the knee joint. They are crucial in walking, running, jumping and squatting. It is comprised of four muscles which are Rectus Femoris, Vastus Lateralis, Vastus Medialis and Vastus Intermedius as shown in Figure 3.10. The exact muscle for electrodes and sensors placement is on Vactus Medialis which located inner part of thigh.

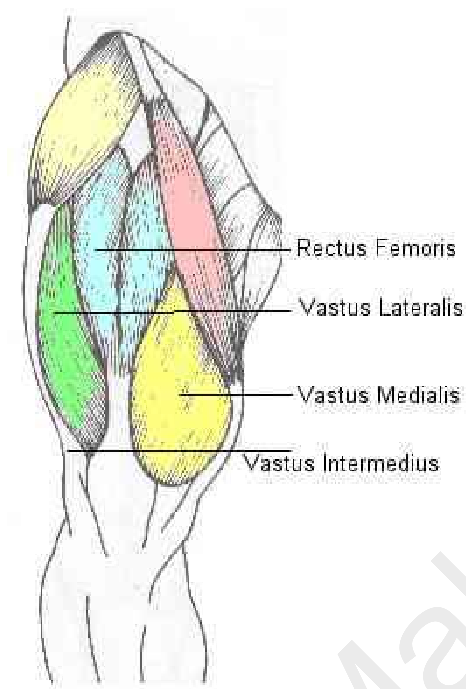

Figure 3.10: Quadriceps muscle (Adapted from http://forum.bodybuilding.com/showthread.php?t=116634911&page=1)

In this study, a gel electrode as shown in Figure 3.11 was used. The stimulation electrode used is Empi Stimcare. A conductive gel was used for better electrical conduction. It is reuseable and non sterile. The stimulation electrodes were placed perpendicular with the Vactus Medialis muscles for wider electrical stimulation acceptance as in Figure 3.12.

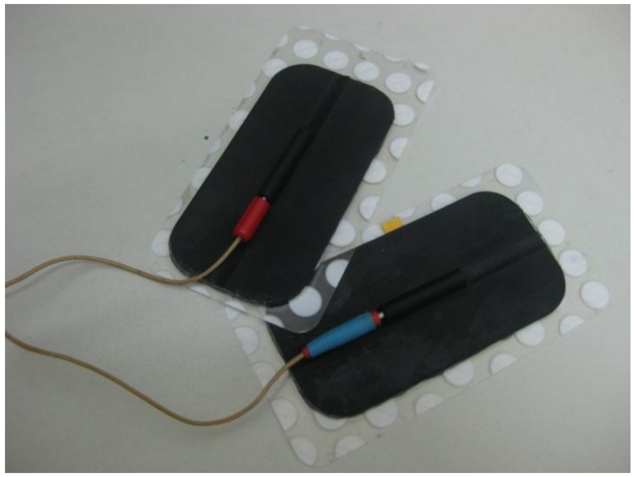

Figure 3.11: Stimulation Electrode Used

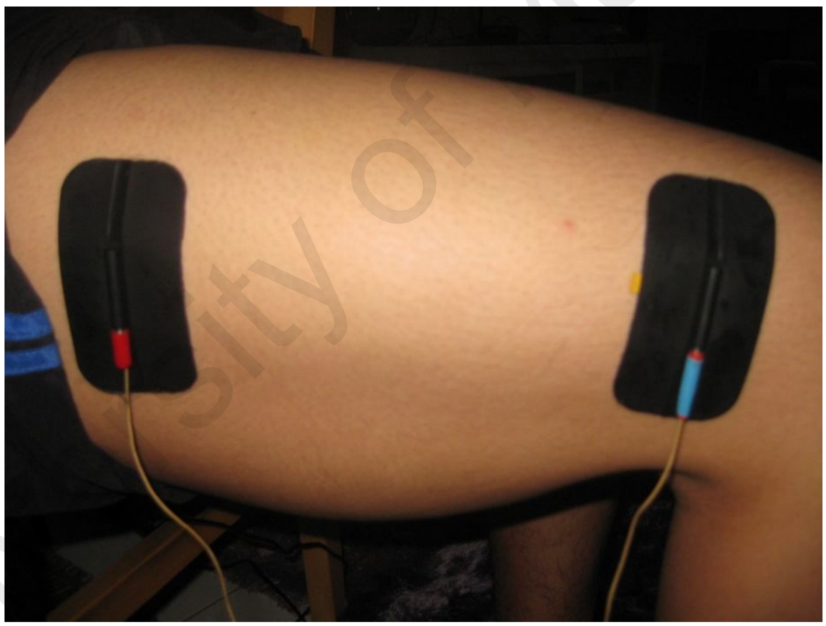

Figure 3.12: Electrode Placement on Subject's Thigh

3.4 Equipment Used

Figure 3.13: Aerobike 75XL II for cycling

Figure 3.13 above shown cycling equipment that was used in sensor's performance testing. Some information such as gender, weight and age need to be keyed in before the start of the cycling session. Subject need to cycle for 20 minutes and they should make sure that their cycling is maintained in the range of 'GOOD' displayed on the screen. For every 5 seconds, the power was increased by 1 Watt. As the power increased, subject feels harder to cycle. The ranges of revolutions per minute (rpm) display on screen are between 47- 53rpm to maintain at GOOD indicator as shown in Figure 3.14.

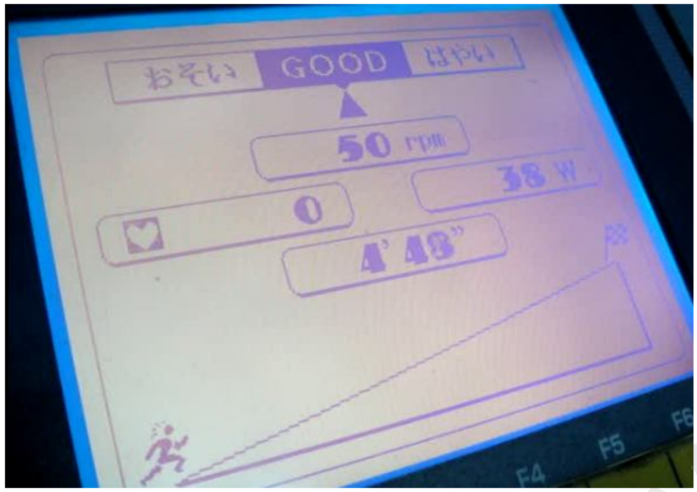

Figure 3.14: GOOD indicator range

3.5 Study Protocol

In this study, the flex sensor was tested on able bodied subject due to time constraint and safety of the patient. Below are the study protocols for this experiment:

3.5.1 Voluntary Exercise

1. Subject must be a man and must take their meal 2 hours before the experiment.
2. Subject must wear short pants to avoid touching with the sensors.
3. Subject need to cycle for 20 minutes during experiment.
4. Subject must maintain the cycling in the range of GOOD display on the screen.
5. Placement of sensor on thigh of the subject attached directly to the skin with the use of tape to avoid misplacement.

3.5.2 Non-voluntary Exercise

1. Subject must be a man and must take their meal 2 hours before the experiment.

2. Subject must wear short pants to avoid touching with the sensors.

3. Subject will be stimulated by current for 10 minutes during experiment.

4. Placement of sensor on thigh of the subject attached directly to the skin with the use of tape to avoid misplacement.

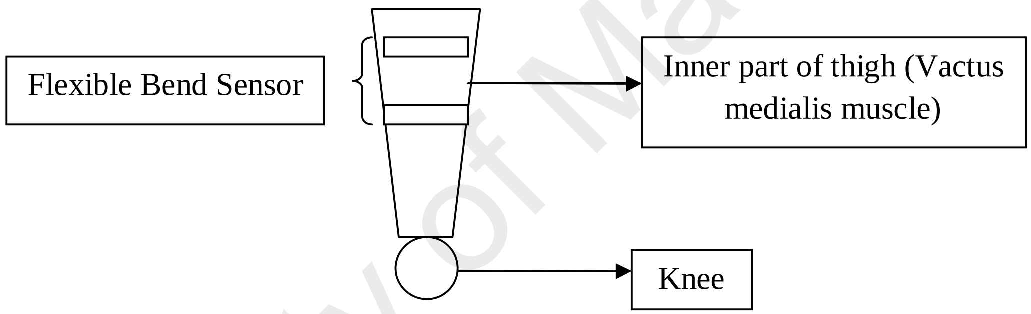

Figure 3.15: Illustration of flexible bend sensor placement

3.6 Display Connection

Arduino is an interface device between voltage divider circuit and computer display. Voltage divider circuit was connected to Arduino as shown in Figure 3.16. After the Arduino was connected to laptop for display as in Figure 3.17, programming as shown in Appendix 7.1 need to be compiled and upload to the input output board before it can be display on the laptop's screen as shown in Figure 3.18.

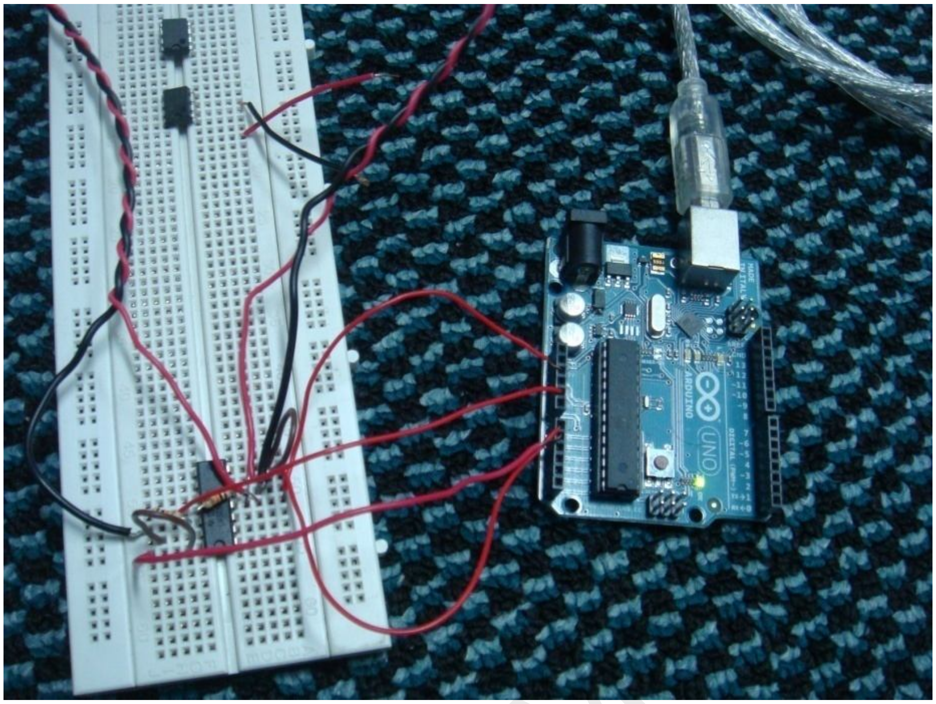

Figure 3.16: Circuit connected to Arduino

Since there are only two flex sensors were used in this experiment, hence, the voltage output connected only to output pin 0 and output pin 1. Input for the circuit connected to 5V on board and ground for both sensor connect from operational amplifier to board.

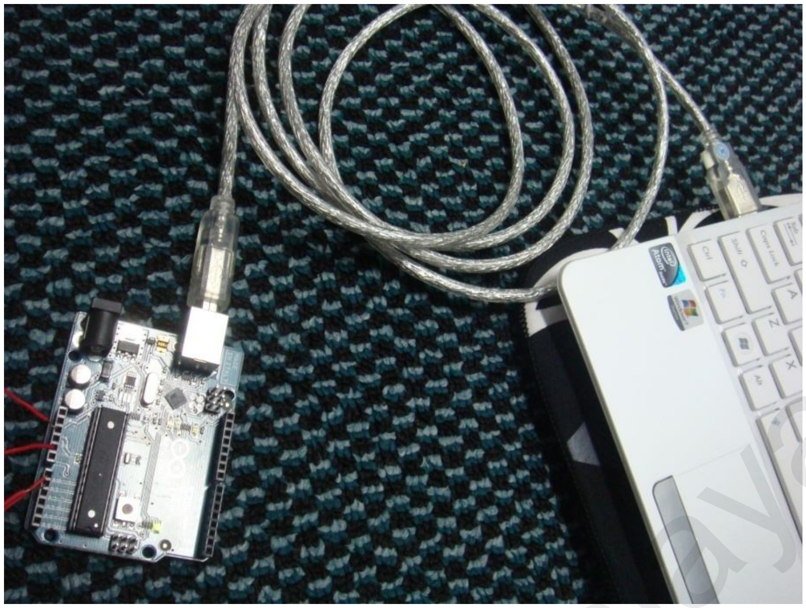

Figure 3.17: Arduino connected to laptop

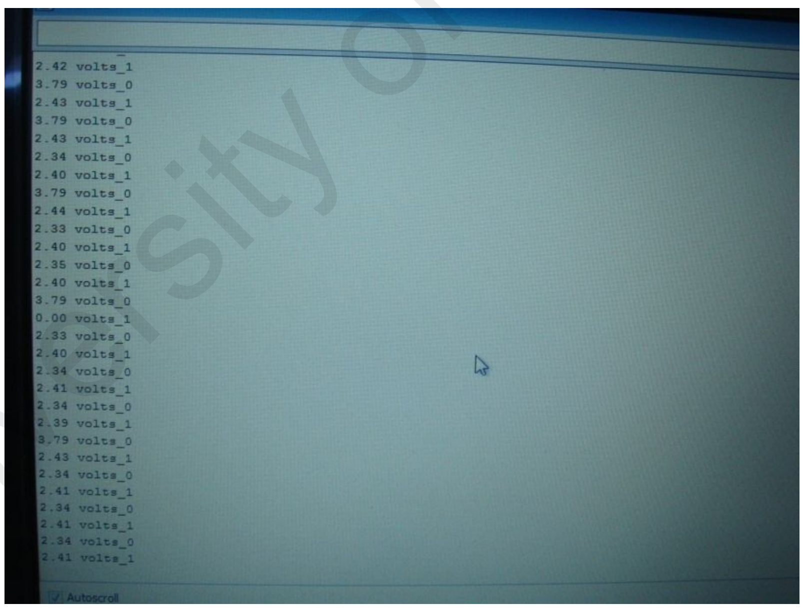

Figure 3.18: Output Display

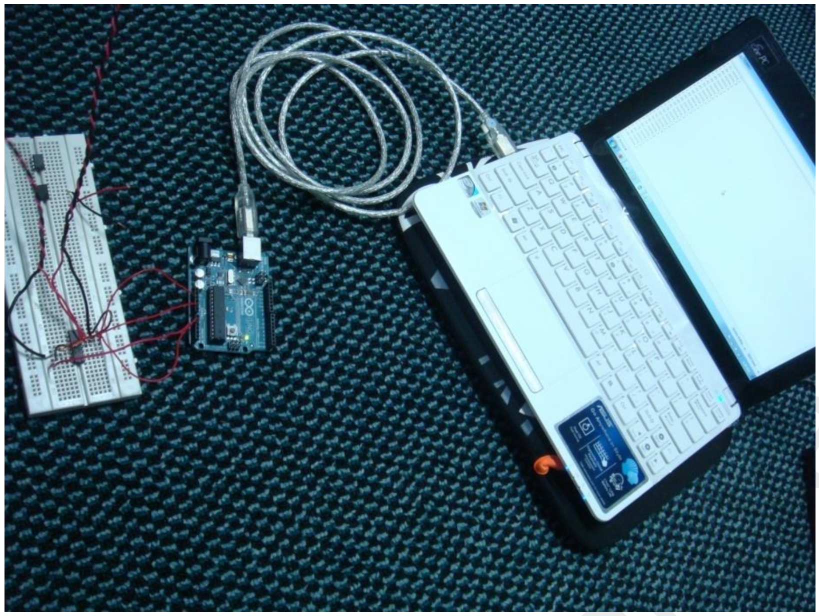

Figure 3.19: The circuit and display

4.0 RESULTS

In this chapter, the result of FES stimulator and results obtained from test 1 and test 2 was discussed. A comparison was made between simulation stimulation with the actual stimulator output. For voluntary test, two different procedures were conducted to observe the relation between time and output voltage with muscle contraction or with muscle fatigue. And for non-voluntary test, a current from stimulator was supplied to muscle and the voltage output was recorded.

4.1 FES Stimulator

FES stimulator constructed on the breadboard and the output value was displayed using oscilloscope and multimeter. The value of output voltage, frequency, pulse width and current amplitude were compared with the value obtained from the simulation stimulator.

A 10kΩ of digital potentiometer was used to control the current amplitude in the stimulator. Frequency and pulse width were tested in oscilloscope as shown in Figure 4.1 and Figure 4.2 which showed the maximum and minimum value of voltage and pulse frequency. Pulse frequency is same for both maximum and minimum value of voltage. The changed of maximum value of voltage which was 9V due to the setting of digital potentiometer to the high resistance. And the minimum value of voltage which was 1.6V by setting the potentiometer to the lowest resistance. Figure 4.3 and Figure 4.4 showed the minimum and maximum values of current amplitude displayed on multimeter.

Figure 4.1: Maximum value of voltage and minimum value of pulse frequency from oscilloscope.

Figure 4.2: The minimum value of voltage and the maximum value of pulse frequency from oscilloscope.

Figure 4.3: Minimum reading of current amplitude from multimeter.

Figure 4.4: Maximum reading of current amplitude from multimeter.

4.2 Result of Voluntary Test

4.2.1 Muscle Fatigue Test

For this test, both of the subjects were asked to cycle for 20 minutes. The subject need to cycle and maintained the rpm in the range of 47 – 53 for a GOOD performance. The reading of voltage output displayed was recorded for every 5 minutes, the first three voltage reading for each time frame was taken. For every 5 second of cycling, the power of cycling was increased by 1 Watt. Hence, for 20 minutes of cycling, the power of cycling has increased to 240 Watt as show in the calculation below:

For every 5 sec, there will be increment of 1 Watt.

Hence, for 1200 sec the power is:

$$\frac{1200\,\text{sec} \times 1\,Watt}{5\,sec} = \mathbf{240\ Watt}$$

So, the power of cycling is proportional with time. As time increased, cycling power was increased. The linear graph of this relationship was shown in Figure 4.5.

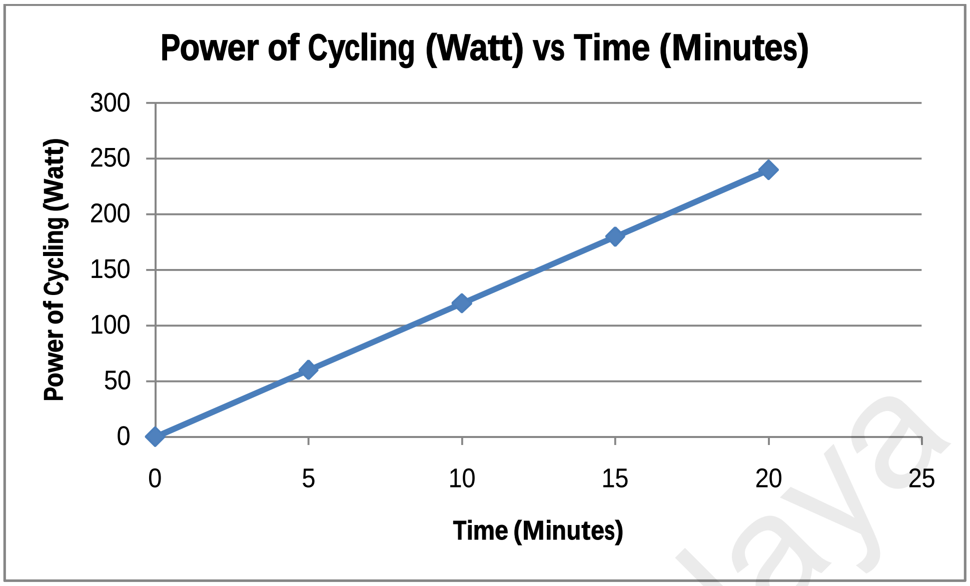

Figure 4.5: Relationship between power of cycling and time.

The result from Table 4.1 showed cycling time and average voltage output reading of flexible bend sensor for subject 1. The reading was obtained from the flexible bend sensor which was attached to surface of vactus medialis muscle. For every five minutes, the first three reading from output display were recorded then calculated for average voltage reading. The initial voltage reading for Sensor_0 and Sensor_1 are 2.29V and 2.33V respectively. As time of cycling increased, the average voltage reading for both sensors were increased. Average voltage reading for Sensor_1 is slightly higher than Sensor_0.

Table 4.1: Result for Subject 1

Time (Minute)	**Sensor_0**				**Sensor_1**			
	Reading 1	Reading 2	Reading 3	**Average Reading (V)**	Reading 1	Reading 2	Reading 3	**Average Reading (V)**
0	2.29	2.3	2.29	**2.29**	2.32	2.34	2.33	**2.33**
5	2.3	2.32	2.31	**2.31**	2.34	2.36	2.37	**2.36**
10	2.35	2.33	2.34	**2.34**	2.36	2.35	2.39	**2.37**
15	2.33	2.35	2.34	**2.34**	2.4	2.37	2.39	**2.39**
20	2.35	2.37	2.34	**2.35**	2.39	2.42	2.4	**2.4**

As can be observed form graph of voltage output versus time in Figure 4.6, the value of average voltage output is increasing with the increment of time. As muscle contracted with time, the bending angle of flex sensor was increased hence voltage increased. Sensor_1 showed the higher reading of output voltage compared to Sensor_0. So, it is showed that Sensor_1 which placed on middle of vactus medialis has less muscle contraction compare to Sensor_0 which was placed distal to vactus medialis muscle by concluded from the average output voltage from each sensors.

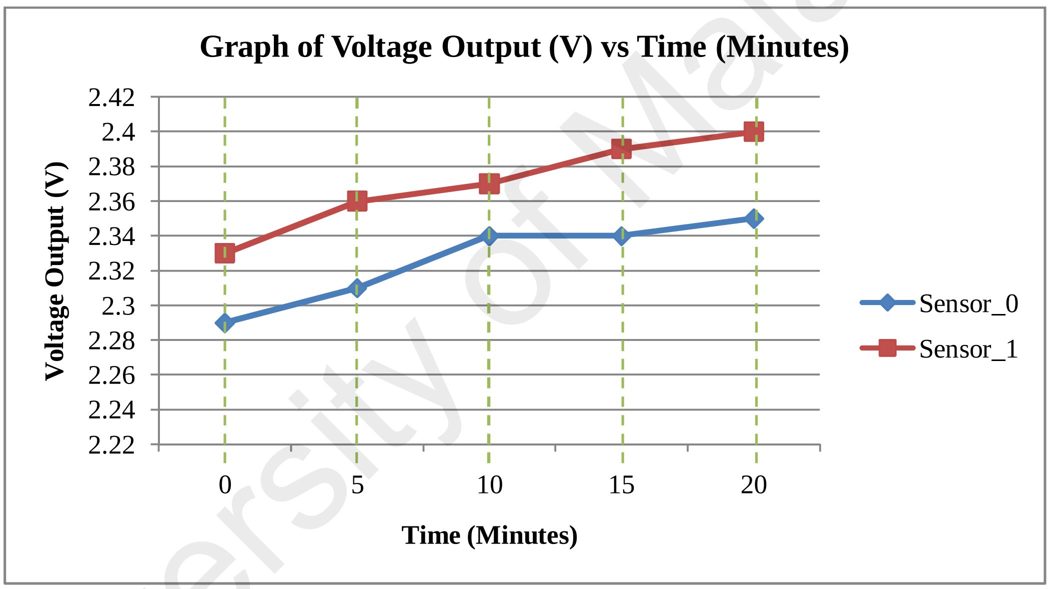

Figure 4.6: Graph of voltage output versus time for subject 1

The same procedures were applied to subject 2. Table 4.2 showed cycling time and average of output voltage. As the increment of time, the average output voltage reading for both sensors were increased. Sensor_1 has higher reading of average voltage output compare to Sensor_0. At time 15 minutes, there were slight decreased of average output voltage.

Table 4.2: Result for Subject 2

Time (Minute)	Sensor_0				Sensor_1			
	Reading 1	Reading 2	Reading 3	**Average Reading (V)**	Reading 1	Reading 2	Reading 3	**Average Reading (V)**
0	2.31	2.32	2.31	**2.31**	2.35	2.36	2.36	**2.36**
5	2.33	2.25	2.34	**2.31**	2.4	2.32	2.39	**2.37**
10	2.35	2.33	2.34	**2.34**	2.42	2.42	2.42	**2.42**
15	2.32	2.34	2.33	**2.33**	2.41	2.40	2.39	**2.40**
20	2.35	2.33	2.34	**2.34**	2.45	2.43	2.43	**2.44**

Graph in Figure 4.7 showed the result of output voltage obtained from subject 2. Both sensors have a slight increment of voltage output from initial time to minutes 10. After 10 minutes, both sensors showed a slight decrement of voltage output value.

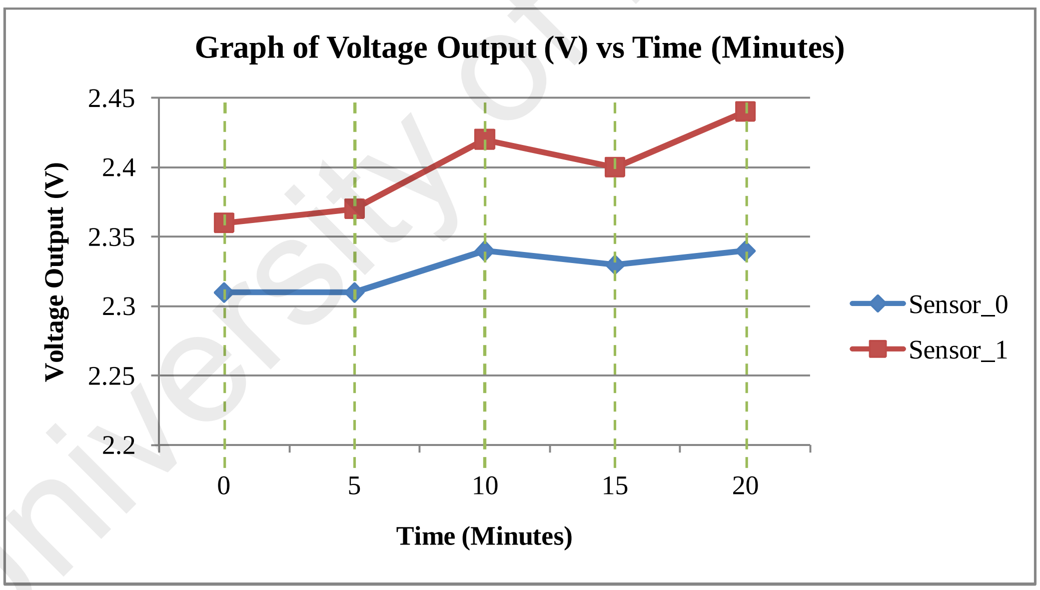

Figure 4.7: Graph of voltage output versus time for subject 2

4.2.2 Muscle Contraction and Relaxation Test

In this test, subject was asked to cycle for ten minutes. Voltage output was recorded for every five seconds displayed on the laptop's screen. The same requirement again, subject need to maintained their cycling in the range of 47 – 53 rpm which showed as GOOD performance. The variations in values represent muscle contraction detected every 5 seconds. Figure 4.8 showed the voltage output for Sensor_0 and Sensor_1 in 600 seconds which equal to ten minutes cycling. It is showed that Sensor_0 has higher value of voltage output compare to Sensor _1. The range of Sensor_0 is between 2.87 V to 3.1 V while for Sensor_1, the range of output voltage is between 2.5 V to 2.85 V.

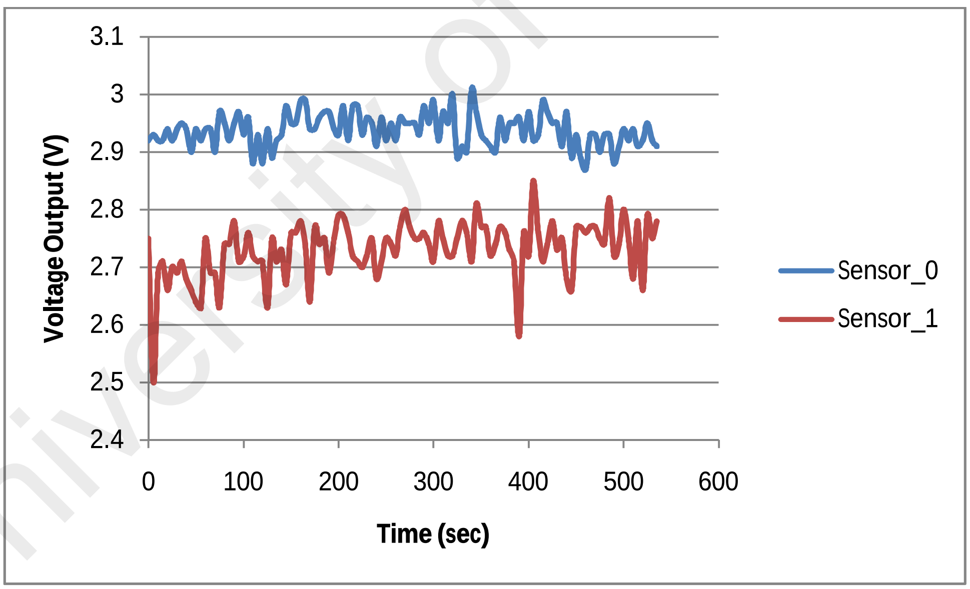

Figure 4.8: Graph of voltage output versus time for 10 minutes of cycling with 5 seconds of sampling time

4.3 Result of Non-voluntary Test

A stimulator was connected to electrodes which placed on the surface of subject's vactus medialis muscle. Current from stimulator was supplied for 10 minutes to stimulate the muscle. A voltage output was recorded and display on screen. In this test, for every 100 seconds of current supply to muscle was increase to observe the muscle contraction.

As shown in Figure 4.9, it is the combination of output voltage versus time from initial time to 600 seconds. Both sensors showed a slightly constant of output voltage range. Sensor_0 have higher output voltage than Sensor_1 as shown in graph.

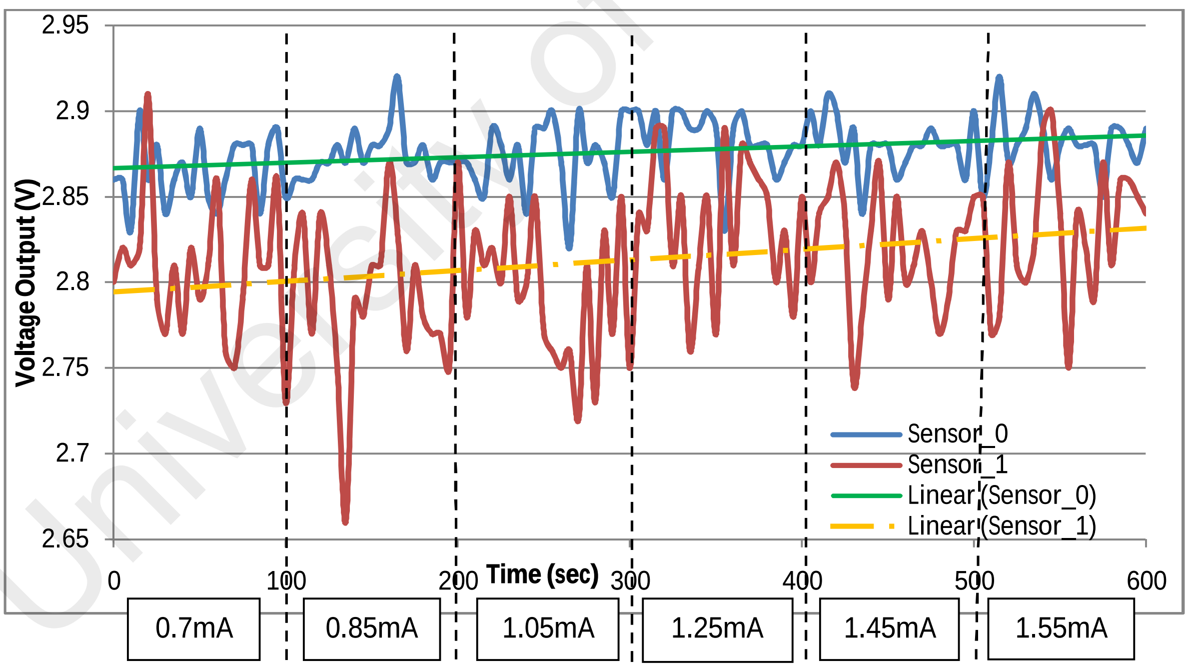

Figure 4.9: Graph of voltage output vs time (sec) for 10 minutes of stimulation

Current was applied on muscle from minimum value until it starts to stimulate the muscle contraction. For this test, 0.70mA of current value was started to activate the muscle. Current was supplied continuously for 100 sec and the voltage outputs were recorded. Figure 4.10 showed the output voltage when 0.70mA of current was supplied to muscle for the first 100 seconds. Sensor_0 showed the higher output voltage compare to Sensor_1.

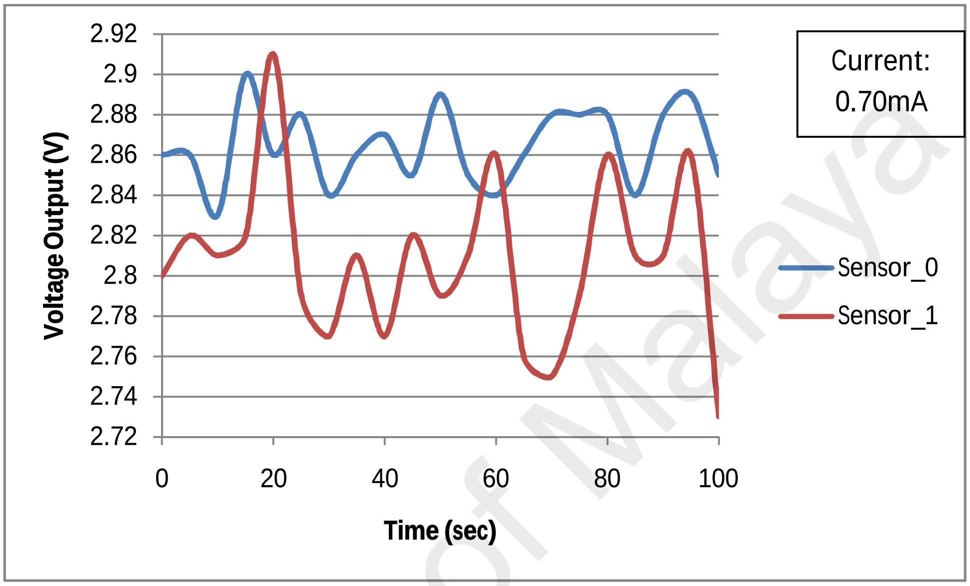

Figure 4.10: Graph of voltage output vs time (sec) for 0.70mA stimulation

For 101 seconds until 200 seconds, current supplied to muscles increased to 0.85mA. Sensor_0 has higher output voltage compare to Sensor_1. The range of output voltage for Sensor_0 was smaller than range of output voltage for Sensor_1 as shown in Figure 4.11. Sensor_0 showed 2.86 V to 2.93 V of output voltage range while Sensor_1 showed 2.66 V to 2.87 V of output voltage range.

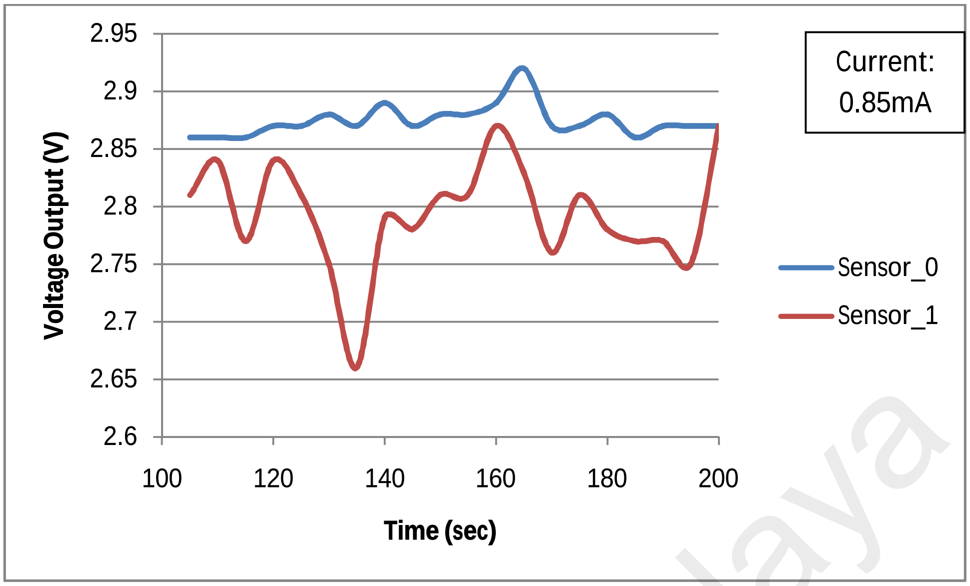

Figure 4.11: Graph of voltage output vs time (sec) for 0.85mA stimulation

In Figure 4.12, it is showed the voltage output of time 201 seconds until 300 seconds when stimulated with 1.05mA of current. For Sensor_1, there are a dropped of voltage started from 240 seconds until 270 seconds. Output voltage increased back after 270 seconds.

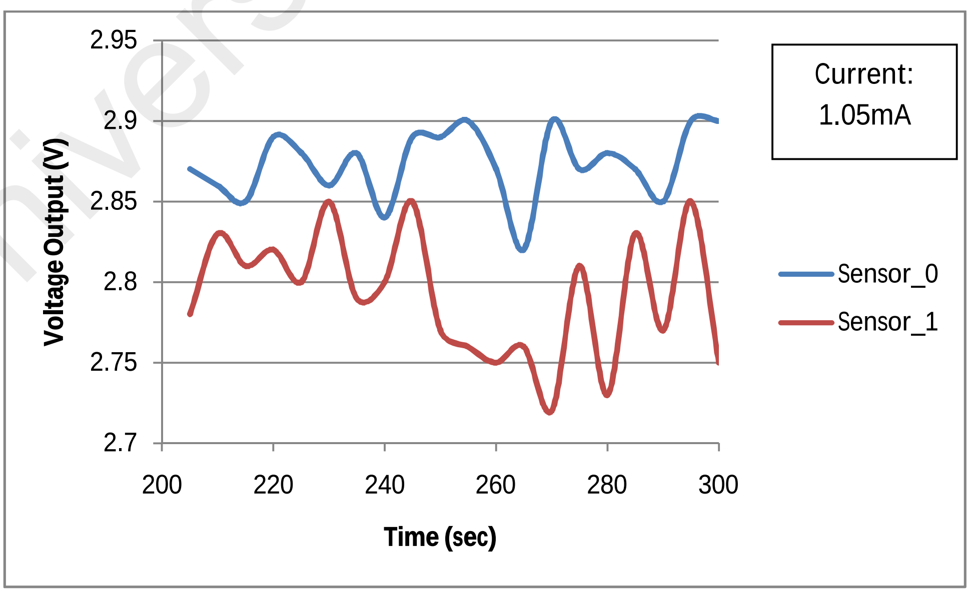

Figure 4.12: Graph of voltage output vs time (sec) for 1.05mA stimulation

At 301 seconds until 400 seconds, 1.25mA of current input was supplied to muscle. Sensor_ 0 has higher range of output voltage compare to Sensor_1 as shown in Figure 4.13. Range of output voltage for Sensor_1 was 2.76 V to 2.89 V compare to Sensor_1 range of output voltage from 2.83 V to 2.9 V. After first 20 seconds of stimulation, output voltage for Sensor_1 was decreased.

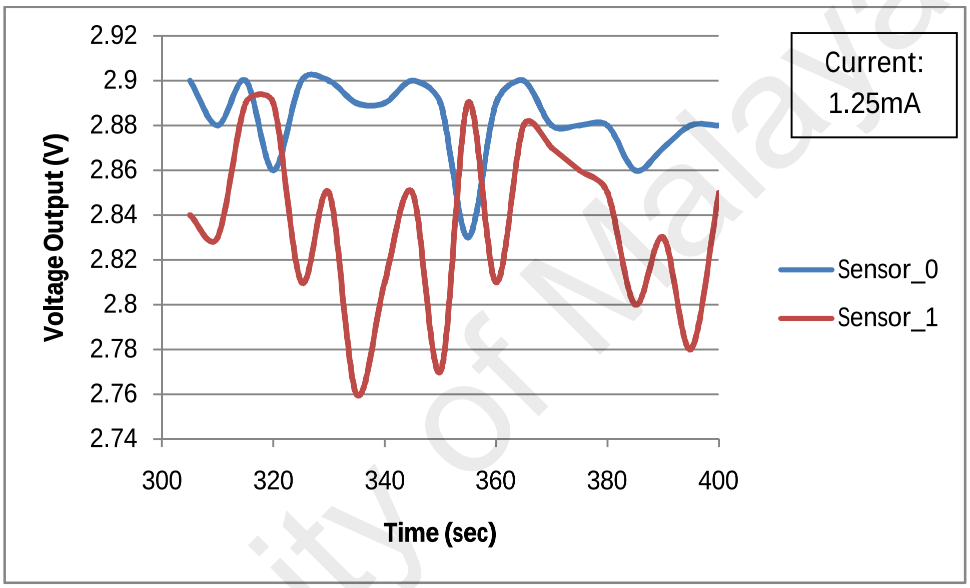

Figure 4.13: Graph of voltage output vs time (sec) for 1.25mA stimulation

For Figure 4.14, 1.45mA of current input was stimulated the muscle. The output voltage presented with time as shown in the graph. At 420 seconds until 430 seconds, there are higher decrements of voltage output for both sensors.

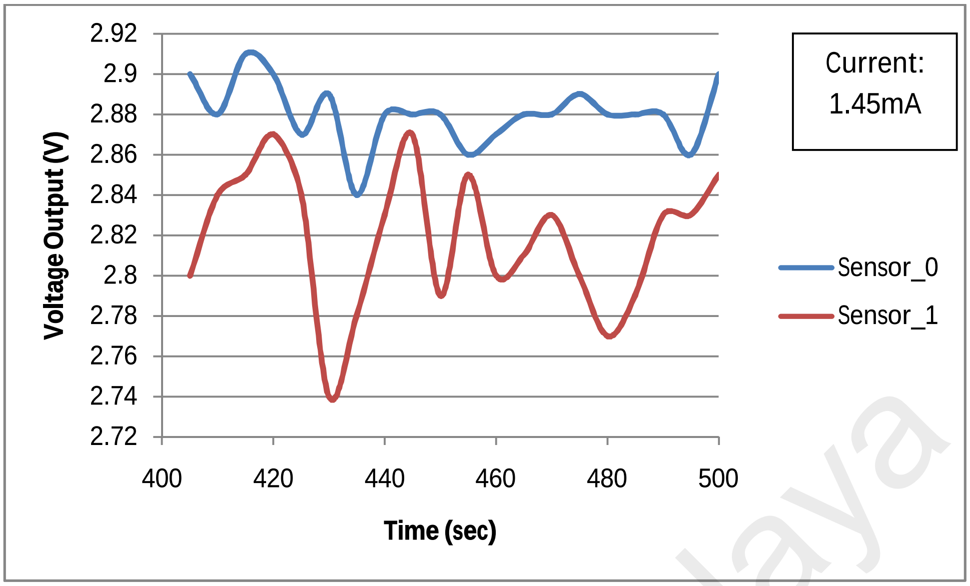

Figure 4.14: Graph of voltage output vs time (sec) for 1.45mA stimulation

A maximum of 1.55mA was supplied to muscle for the time of 501 seconds until 600 seconds. The output voltage versus time was plotted as shown in Figure 4.15. In this period, the output voltage is opposite for both sensors. When Sensor_0 has high value of voltage, Sensor_1 has low value of output voltage.

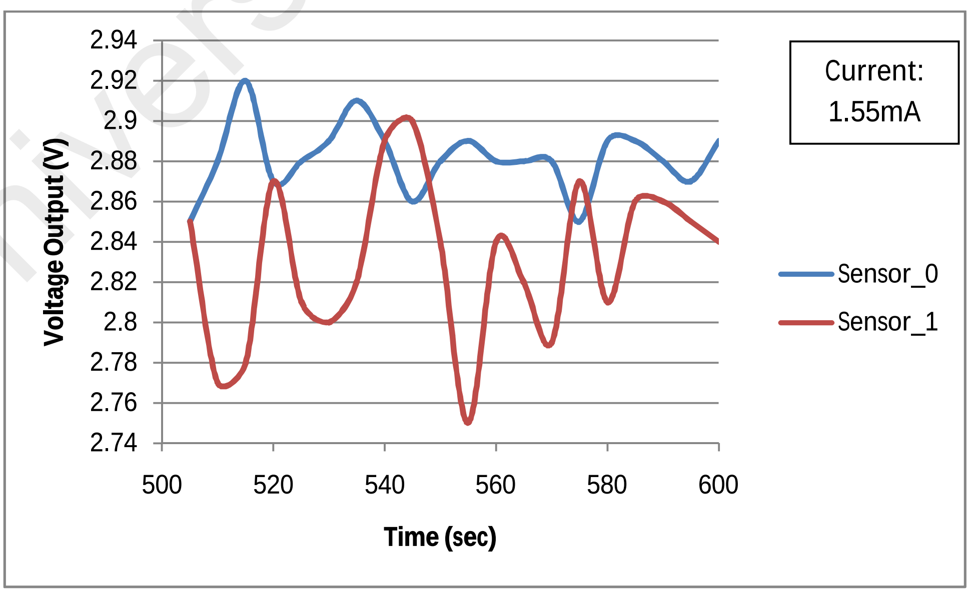

Figure 4.15: Graph of voltage output vs time (sec) for 1.55mA stimulation

5.0 DISCUSSION

This research project was concerned on the development of functional electrical stimulator (FES) with movement feedback parameter for muscle activation detection. In this project, a functional electrical stimulator is used for current supplied to muscle was build with controllable parameter of frequency and current amplitude. A new alternative of feedback parameter which is movement has been identified for muscle activation detection. A movement sensor embedded in the stimulator system was developed. This is used for the purpose of understand the relationship between muscle movement towards muscle activation.

5.1 Stimulator Circuit

For this project, it can be divided into two parts which are circuit construction and sensor testing. The first part for circuit construction, Multisim software was used to virtually construct a stimulator circuit. After completed the circuit construction in Multisim to test the connection, the real circuit was constructed on the breadboard. In this project, flexible bend sensor was used as a movement feedback parameter and it required a voltage divider circuit for converted resistance change to voltage output reading. Sensor was tested on able bodied for cycling session and with current stimulator session.

The stimulator that was developed gives the reading of more than 40mA of current and 80Hz of frequency amplitude when connected to oscilloscope. Usually, for rehabilitation purpose the electrical stimulator available in market should supply up to 140mA maximum of current to muscle. In this project, the stimulator circuit is successes to construct and give the reading on multimeter and oscilloscope. Unfortunately, when connect the stimulator with electrodes they cannot supplied any current to stimulate the muscle.

Stimulator cannot supply current to stimulate muscle maybe due to these problems. First, the voltage supply for stimulator is not large enough to produce the current. According to the previous studied, up to 100 V of voltage was supplied to produce higher current. Based on Ohm's Law, I=V/R it is show that relationship between current and voltage is directly proportional. Second, stimulation electrode and conductive gel have resistance. Due to this resistance, the current supply was reduced. Thirdly, since the current was reduced hence it cannot penetrate human muscle to stimulate it due to high skin resistance. Human skin resistance is in the range of 500 Ω to 2k Ω. In the end, the stimulator circuit was constructed on the breadboard but failed to generate current supplied to stimulate muscle.

Since the constructed stimulator was not functioning well, a stimulator from previous undergrade student was used to supply current to stimulate muscle contraction (How, 2011). As for this stimulator, it has different frequency, amplitude and voltage supply. Current output from this circuit was supplied to vastus medialis for contraction and tested with flexible bend sensor.

5.2 Voluntary and Non-voluntary Test

For conducting the voluntary and non-voluntary test, subject chosen was male. It is because male have only thin layer of fat compare to women. The greater the layer of fat, the more current needed to elicit the muscle contraction. Fat layer is a barrier to transfer the current from skin to tissue. With the barrier, if current increase it would shift more current between the electrodes (Petrofsky, 2008). Hence, muscle contraction in men can be seen clearly compared to women and the feedback sensor would give more reliable result of the contraction. From the test, it can be concluded that the sensors affect the output of voltage cause by (i) placement of sensor with muscle anatomically (ii) current stimulation input to muscle.

5.2.1 Placement of sensor with muscle anatomically

Placement of sensors on muscle played an important role on giving the output voltage reading for muscle. In the test, sensors were placed on vastus medialis muscle. Sensor_0 was placed exactly on the muscle belly of vastus medialis while for Sensor_1 was placed proximal to vastus medialis. The higher contraction was produced on muscle belly which Sensor_0 was located. Hence, the voltage output reading for Sensor_0 was higher compare than Sensor_1. For the best reading of voltage output, the stimulation electrode should be place exactly on proximal and distal end of the targeted muscle – vastus medialis as shown in Figure 5.1. In this test, the placement of stimulation electrodes was placed slightly higher than the proximal part of vastus medialis hence the contraction of muscle on proximal part was interfere with other muscle nearby and gave smaller contraction.

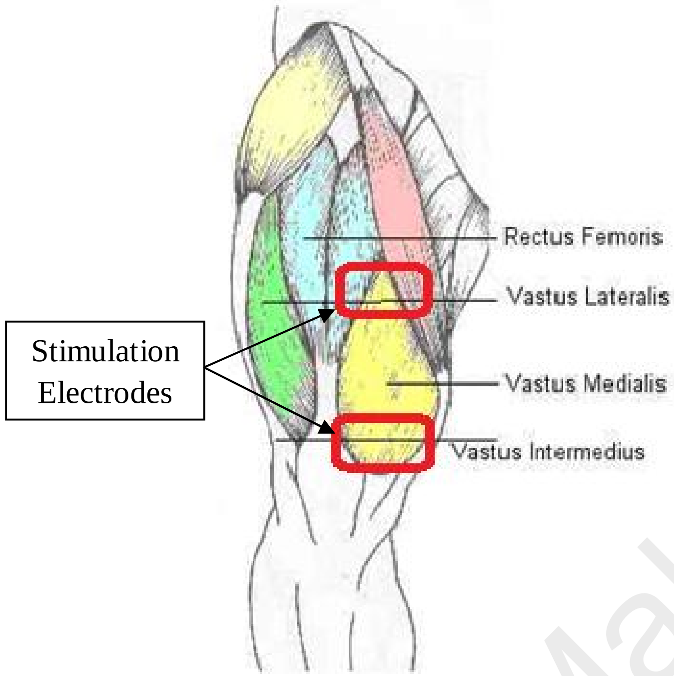

Figure 5.1: Stimulation electrodes placement (Adapted from http://forum.bodybuilding.com/showthread.php?t=116634911&page=1)

5.2.2 Current stimulation input to muscle

There are clear gap ranges between voltage output from Sensor_1 and Sensor_0 for voluntary test and non-voluntary test as shown in Figure 5.2 and Figure 5.3 below. For non-voluntary test, muscle did not get enough stimulation current to contract more since the input current from stimulator to muscle was too small which was 1.55mA for maximum. Hence, it cannot show the clear muscle contraction detection as clearly seen in voluntary test. On the other hand, from the graph observed it is showed an increment pattern of voltage output of Sensor_1 for both tests as shown by yellow dotted line in the graph. It means, when stimulation current increased or more effort needed to contract the muscle goes with time, the voltage output was increased. As for Sensor_0 voltage output pattern for both test, there were only minimal changes of voltage output hence the graph only has a little increased and the graphs looks constantly changed in the same range as shown by straight green line in the graph.

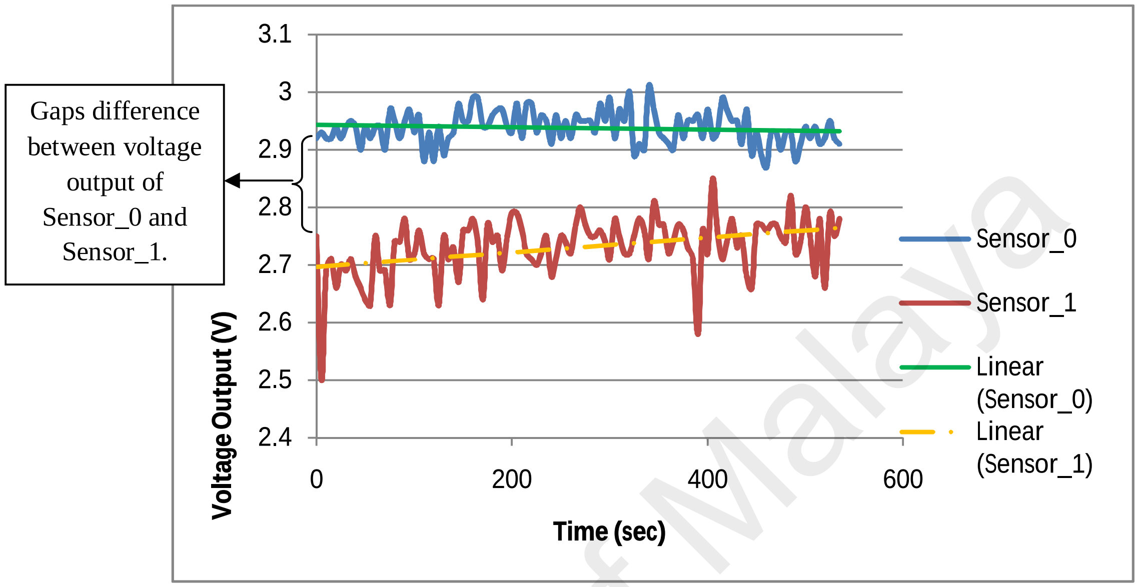

Figure 5.2: Result of voluntary test

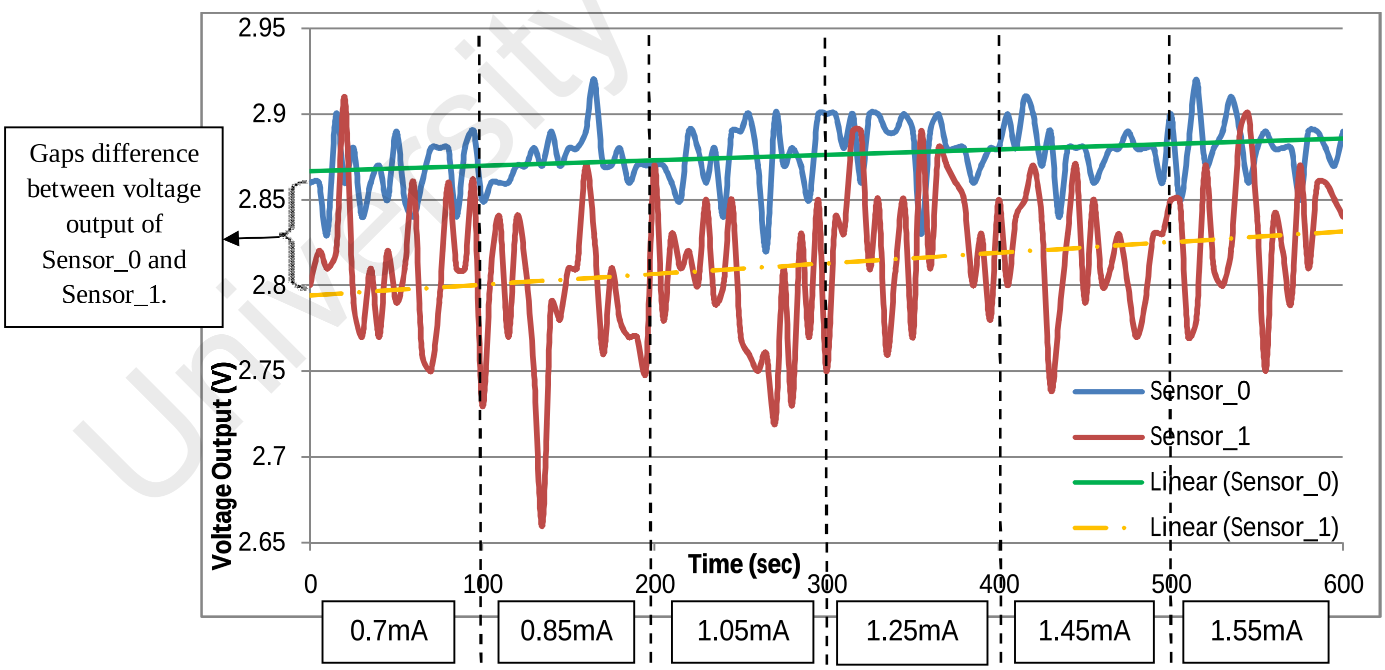

Figure 5.3: Result of non-voluntary test

For voluntary test of muscle fatigue, it can be observed that when increased the time, the voltage output is increased. Based on the voltage divider equation,

$$Vout = \frac{R2}{R1+R2}V_{in} \tag{5}$$

R1 is resistance change of flexible sensor. When bending angle higher, resistance change increased, hence voltage output was decreased. When time increased, the bending angle decreasing slightly, resistance decreased and output voltage increased. Bending angle decreased due to the less contraction of muscle because of subject felt tired and slowed his cycling. At this time, muscle becomes fatigue and produces less bending angle to flexible sensor.

6.0 CONCLUSION

In the end of this project, it is showed that the feedback parameter for muscle activation detection can be measured by muscle movement. The stimulated muscle was applied by certain amount of current which induced the muscle activation. By using flexible bend sensor, the amount of muscle can be measured by the changing of resistance on sensor through bending angle. When the muscle was contracted so do the angles of flexible bend sensor also change. The increment of angle change affects the increasing value of resistance change. Since the flexible bend sensor using the principle of voltage divider, the output voltage was showed that the voltage also increases by changes of resistance.

From the voluntary and non-voluntary test, it is observed the relationship between muscle movement feedbacks towards muscle activation. For this study, the simulation stimulator in Multisim software was successes to obtained required frequency, current and voltage required but failed when current was send to stimulation electrodes to stimulate muscle.

For the future work, the stimulator that failed to supplied current to muscle need to be construct again so that it can give the stimulation current require to muscle. A feedback parameter circuit will be adding to the stimulator and sensor circuit to give an automatic controlled of parameters. Since the flexible sensor is easy to break, for the future need a supporter for the sensor to maintain its performance.

7.0 APPENDICES

7.1 Program Listing

```
//Flexible Bend Sensor Pin Variables
int sensorPin_0 = 0;   //the analog pin of Flexible Bend Sensor 's Vout pin is connected to
int sensorPin_1 = 1;   //the analog pin of Flexible Bend Sensor 's Vout pin is connected to

/*
 * setup() - this function runs once when turn the 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 opens the serial monitor
}

void loop()            // run over and over again

{
 // getting the voltage reading from the Flexible Bend Sensor
 int reading_0 = analogRead(sensorPin_0);
 int reading_1 = analogRead(sensorPin_1);

 // converting that reading to voltage, for 5.0V arduino use 5.0
 float voltage_0 = reading_0 * 5.0;
 voltage_0 /= 1024.0;

 float voltage_1 = reading_1 * 5.0;
 voltage_1 /= 1024.0;

 // print out the voltage
 Serial.print(voltage_0); Serial.println("volts_0");
 Serial.print(voltage_1); Serial.println("volts_1");

delay(6000);           //waiting a second
}
```

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