DEVELOPMENT OF STRENGTH PERFORMANCE MONITORING SYSTEM FOR LOWER LIMB

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DEVELOPMENT OF STRENGTH PERFORMANCE MONITORING SYSTEM FOR LOWER LIMB

MOHD HANIF BIN RAZALI

Report submitted in partial fulfillment of the requirements
for the award of the degree of
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I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my family,

Razali bin Abdul Rahim, Hamimun binti Dahaman and Ridhwan Hafiz bin Razali

Special dedication to my supervisor,

Prof. Dr. Zahari bin Taha

For his dedication and guidance towards my research

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In the name of Allah, The Most Beneficent, The Most Merciful

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Last but not least, I would like to thank every other people who contributed to my final year project either directly or indirectly. Even though your name is not mentioned here but this does not mean that I have forgotten your help.

ABSTRACT

Strength training is a type of physical exercises that practically involves the usage of resistance or load in order to stimulate muscular contraction which builds the strength of the muscles, anaerobic endurance as well as the size of the skeletal muscles. In strength training, weight load is used as for setting up the resistance for the target muscles to act against. This project provides the detailed steps on the design of strength training performance monitoring system for lower limb. Design and fabrication of leg extension machine was made as the exerciser will be the test rig for this study. Inertial measurement unit sensor was used in measuring the displacement of the knee extension as well as the angular velocity and angular acceleration as the training is performed where it was embedded to the movable link of the exerciser. The data recorded in this study were analysed for strength training analysis and compared with literature review of previous research made by others.

ABSTRAK

Latihan kekuatan adalah sejenis senaman fizikal yang khusus dalam penggunaan rintangan untuk mendorong penguncupan otot bagi membina kekuatan, daya tahan anaerobik, dan saiz otot rangka. Dalam latihan kekuatan, beban berat digunakan ke atas otot yang disasarkan sebagai rintangan untuk ia bertindak balas. Projek ini membentangkan fasa-fasa secara terperinci tentang reka bentuk sistem pemantauan prestasi latihan kekuatan bagi anggota badan di bahagian bawah. Reka bentuk dan proses fabrikasi mesin senaman kaki (leg extension) telah dibuat memandangkan alat senaman tersebut berfungsi sebagai alat untuk ujian dijalankan. Sensor unit pengukuran inersia (IMU) telah dilekatkan pada bahagian alat senaman bagi mengukur sudut anjakan ketika melakukan senaman serta nilai halaju bersudut dan nilai pecutan bersudut. Data yang direkodkan dalam kajian ini telah digunakan bagi tujuan analisis latihan kekuatan lalu dibandingkan dengan kajian literature berdasarkan penyelidikan terdahulu.

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LIST OF SYMBOLS

m	Mass
A	Area
V	Volume
ρ	Density
I	Moment of Inertia
σ	Maximum Stress
Δ	Maximum Deflection
θ	Angular Displacement
$\dot{\theta}$	Angular Velocity
$\ddot{\theta}$	Angular Acceleration
g	Gravitational Acceleration
r	Radius/length
τ	Torque

LIST OF ABBREVIATIONS

EMG	Electromyography
FEA	Finite Element Analysis
I2C	Inter-Integrated Circuit
ICSP	In-Circuit Serial Programming
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
MEMS	Micro-Electro-Mechanical System
MVC	Maximum Voluntary Contraction
USB	Universal Serial Bus

CHAPTER 1

INTRODUCTION

1.0 BACKGROUND OF RESEARCH

Strength training is a type of physical exercises that practically involves the usage of resistance or load in order to stimulate muscular contraction which builds the strength of the muscles, anaerobic endurance as well as the size of the skeletal muscles. (Strength Training, n.d.). It is believed that strength training and weight training shares similarity on how both were developed up until the 20th century. Strength training is advantageous as it could increase the oxygenation in muscles. The supply of oxygen is essential for the muscles to break up the lactic acid that has been built up. Other than that, it is also proven to be able to improve the strength of knee and ankle joint. There are no limitations of particular type of person who can perform strength training as this type of exercises not only can be performed by athletes but also by normal individuals regardless of age and gender. In fact, strength training has shown to be helpful for person with cerebral palsy or stroke in improving their walking pattern.

In strength training, weight load is used as for setting up the resistance for the target muscles to act against. Normally, the number of maximum repetitions that an individual managed to achieve in the training as the load act as variable where it changes with respect to time will be an indicator as to define that individual strength. Successful strength training should involve progressive increment in the intensity where it is supposed to stimulate strength gains which by comparison, should be greater than a person that does not perform the strength training. Thus, this study is to develop a system for monitoring the performance of strength training for lower limb.

1.1 PROBLEM STATEMENT

Strength training is an exercise performed with resistance load in order to develop the muscle strength. A method of measuring certain parameters in order for the user to be able to keep track of their performance while performing the exercise needed to be done. Conventional exerciser does not have the capability of monitoring the strength performance of the user. It can only give a general idealisation of the performance in a way of the user improving the resistance load used for their exercise nevertheless at which point the user decided to maintain the usage of the same load, how else can the performance be defined. Fortunately, current technology has a way of accomplishing this by enabling the muscle force analysis but this has to rely on dynamometer such as Biodex in testing for the muscle strength which normally can only be found in modern physical medicine and rehabilitation.

On that account, a more convenient, easier and affordable way of monitoring the performance of strength while exercising needed to be done. Thus, the development of a system that is able to monitor the performance of strength training for lower limb is necessary.

1.2 PROJECT OBJECTIVES

The main objectives of this project are:

a) To design an exerciser to be used as a test rig for the study.
b) To design a system that can measure and monitor the performance.
c) To analyse the strength measured using the system.

1.3 PROJECT SCOPE

The study is focused on the design and fabrication of a system that is able to measure the strength performance of lower limb muscles by using the gyro and accelerometer sensors which will be attached to the exerciser. The project scope is broken down into the following:

a. Design and FEA simulation of exerciser frame
b. Fabrication of exerciser frame
c. Selection of electrical components and circuit
d. Assembly of mechanical and electrical parts
e. Testing the system
f. Performance evaluation

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discussed about the past research efforts related to strength training in general as well as specified for lower limb, the method and the mechanism of determining the parameters related to the strength of limb. A review of other relevant research studies are also provided which are organized to give an insight to how the past research efforts have laid out the initial groundwork for subsequent studies, including the present research effort. The review is detailed so that the present research effort can be properly tailored to add to the present literature as well as to focus the scope and direction of the present research effort.

2.2 STRENGTH TRAINING

2.2.1 History of Strength Training

Historically, the development of strength training was found to be similar to the existence of weight training until the 20th century. The method of strength training had growth since then that it involves progressive resistance training. Earlier in mid-18th century, Boston strongman George Barker Windship had patented his plate loading design. Unfortunately, his sudden death by stroke had caused a decline in strength training for several decades. In the twentieth century, plate loading barbells had quickly become popular aside of dumbbell for both of their adaptability and effectiveness (Jan Todd, 1995). In strength training, the target muscles need to act against set up resistance where the weight load is used for it. Normally, number of maximum repetitions one's can achieve when performing the resistance exercise while the load act as variable where it changes with respect to time will be used to measure the maximum strength that person could achieve. Successful strength training should involve progressive increment in the intensity. (Scholtes et al., 2008).

2.2.2 Classification of Strength

Generally, there are three types of strength which are maximum or absolute strength, elastic strength and endurance strength. Maximum or absolute strength is the greatest force that is possible in a single maximum contraction, or in other words when the maximum weight can be lifted just once (one repetition maximum). An example for this type of strength is weightlifting. Elastic strength is the ability to exert maximum force in a short time period which also the product of strength and speed. This found to be common in explosive sports involving sprinting, jumping and throwing. Endurance strength is the capacity to exert a force repeatedly over an extended time which is required in swimming, rowing and cross-country skiing. (Mackenzie, B., 1997).

The force exerted during strength training is proportional to the type and force of the muscular contractions. The three different types of muscular contraction are isotonic where a force against an external load that remains constant throughout the movement, isometric where a force performed at a constant angle against an immovable load, and isokinetic where a force generated during movement at a pre-set, fixed speed throughout the range of motion of the joint.

2.2.3 Effect of Strength Training on the Oxygenation in Muscles

Strength training can be beneficial to be performed by individuals as oxygenation of exercising muscles can be increased when performing strength training. A research has been done by Ušaj et al. in order to determine the effect of strength training on the oxygenation in muscles where the participants of ice climbers were divided into two groups, Group A and Group B performing an ice axe grasping using axe of weight 750 g and 150 N isometric hand squeezing of dynamometer respectively until fatigue. Both group then underwent similar interval training consisted of squeezing a rubber ring isometrically before they repeated the test as before until exhaustion.

Table 2.1: The influence of training on duration of two groups of exercises.

Duration of exercise	**Before training (s)**	**After training (s)**	**∆t (s)**	**∆t (%)**
Group A (grasping)	113 ± 25	117 ± 18	4 ± 14	5 ± 11
Group B (150 N)	263 ± 82	350 ± 84	86 ± 57	39 ±37

Values are mean ± SD

Differences between pre- and post-training (**P < 0.01)

Source: Ušaj et al. (2007)

According to the finding in the above table, it was found that muscle strength-endurance training has increased performance of forearm muscles as well as the increment in oxygenation of the exercising muscles for test performed by Group B while the training did not significantly influence the duration of ice-axe-grasping in group A. Therefore it can be concluded that strength endurance interval training has increased oxygenation of exercising muscles. When contraction intensity during testing exceeds the training intensity, then the increased oxygenation achieved during training did not accompany endurance performance of exercising muscles. When lower than training intensity contraction of 150 N (20–25% MVC) was performed, the oxygenation was accompanied by increased endurance performance. Less contracted forearm muscles presented more of an open system, lower intramuscular tissue pressure, and less restricted blood flow. Training increased both perfusion and blood flow. This in turn increased oxygenation, fuel availability and wash-out of metabolic products. Altogether, this may contribute in prolonging the contraction, and thus endurance.

2.2.4 Strength Training Improving Strength of Ankle and Knee Joint

According to research conducted by Kim K. et al. on elderly adults, significant improvements had been shown on the concentric isokinetic strength on the ankle and knee joints in both the right and left legs prior to and after training through functional performance tests.

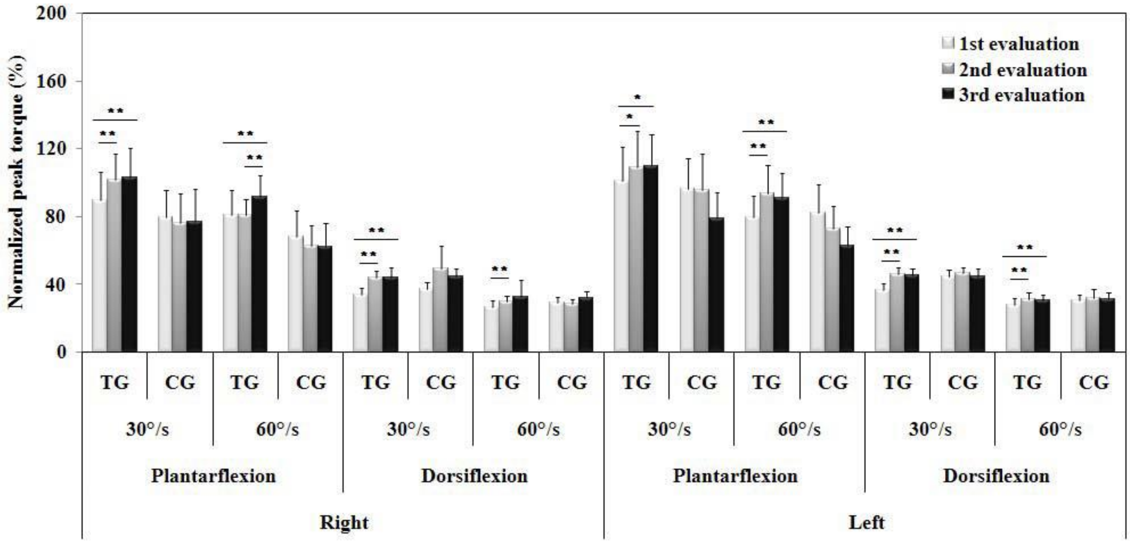

Figure 2.1: Normalized peak torque by body mass of ankle joints in both legs before and after training (*P<0.05, **P<0.001)

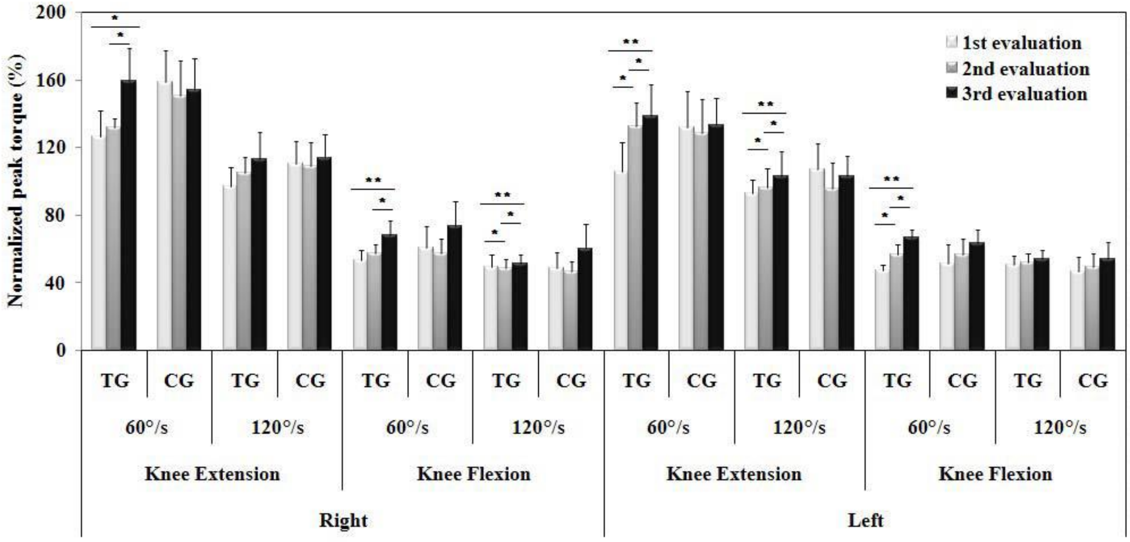

Figure 2.2: Normalized peak torque by body mass of knee joints in both legs before and after training (*P<0.05, **P<0.001)

Source: Kim K. et al (2010)

Figure 2.1 shows the normalized peak torque by body mass at different speeds of ankle joints in both the right and left legs prior to and after training. The normalized peak torque of the ankle joints in two legs at both 30°/s and 60°/s speeds were increased significantly after training in the training group, and not in the control group. Figure 2.2 shows the normalized peak torque by body mass at different speeds in the knee joints in both the right and left legs prior to and after training. The normalized peak torque of the knee joints in both legs at speeds of both 60°/s and 120°/s were increased significantly after training in the training group, but not in the control group. The experimental results show that the training could successfully effect a gradual improvement in the concentric isokinetic strength of the ankle and knee joints of the participants.

2.2.5 Strength Training Improving Walking Pattern

Many adults with cerebral palsy claimed to experience early-onset decline in mobility and independence. Strength training plays a role in battling this by showing positive gains in muscle strength. (Ross S. M. et al, 2016). A study of determining the effects of strength training on walking in persons with stroke also had been done by

Kim C. M. et al, where it involve 20 individuals with chronic stroke divided into two groups which are experimental and control group. Both groups underwent 6 weeks intervention with experimental group had to perform study of maximal isokinetic strengthening while the control group went with passive range of motion. Although at the end both groups had shown increment in muscle strength after the intervention, there was a trend for the experimental group to show greater improvement.

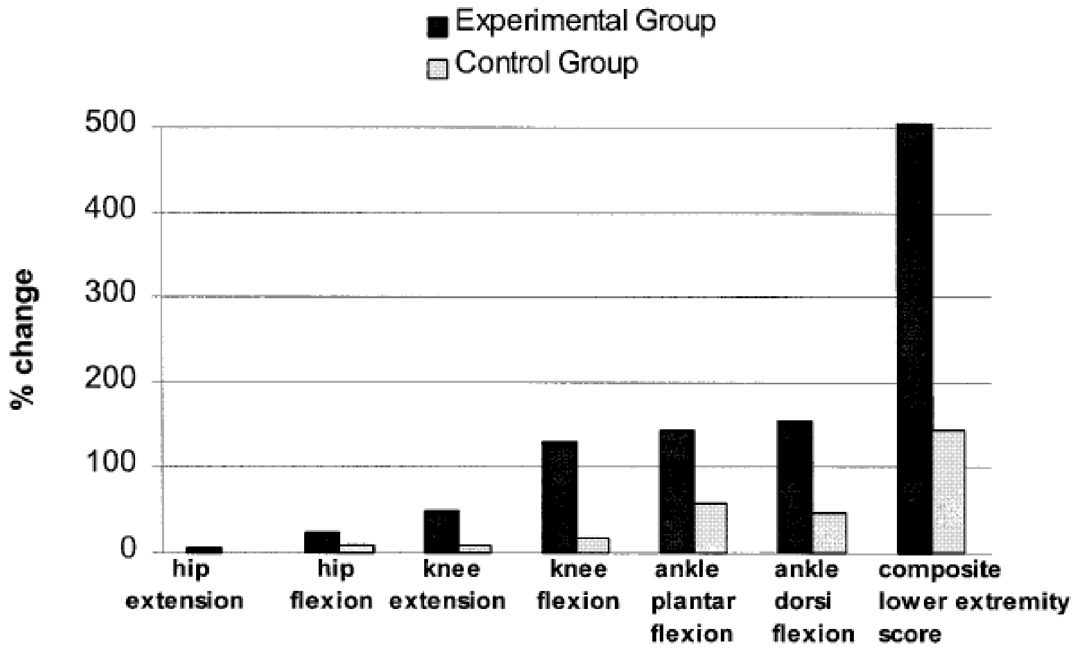

Figure 2.3: Mean percentage change in average torque (Nm/kg) of each muscle group and for the composite lower extremity score on the paretic side in the experimental and control groups (N 10 per group) following 6 weeks of training.

Source: Kim C. M. et al (2001)

Figure 2.3 above has shown the difference of improvement of both experimental and control groups involved in the study. It also proven that individuals with stroke can improve the strength of their paretic limb with maximal isokinetic strength training.

2.3 LEG EXTENSION

Leg extension is a training involving resistance weight training exercise. This exercise consists of bending the knee of the leg then extends the legs. The position of the legs then needed to be lowered to its original position. It is the best exercise for isolating the quadriceps. The greater the angle of the backrest, the farther toward the pelvic rotates. This exercise stretches the rectus femoris, which is the midline biarticular portion of the quadriceps, which makes the work on it more intense while extending the legs.

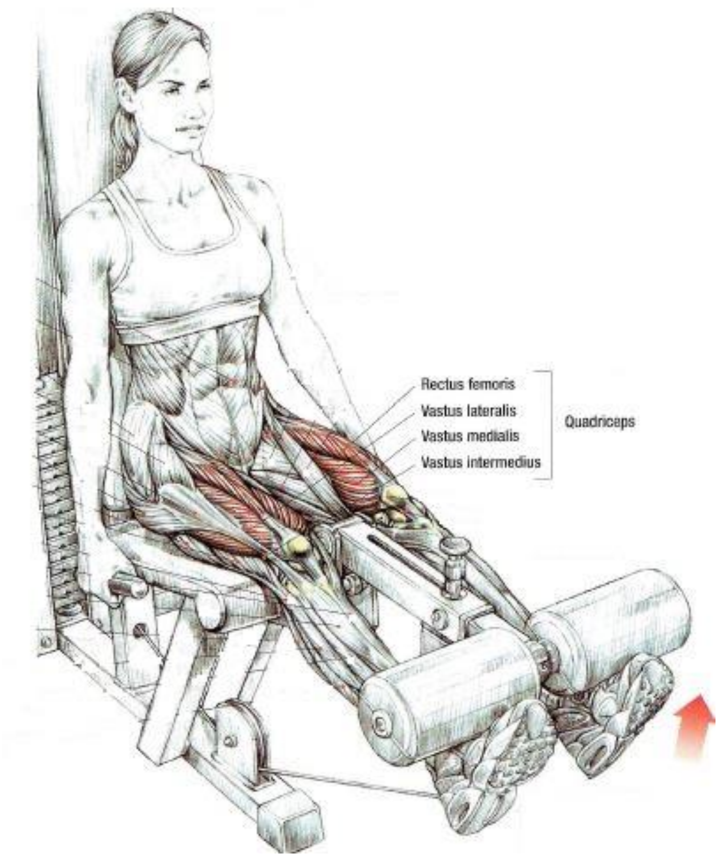

Figure 2.4: Quadriceps muscles involved during leg extension exercise

Source: Delavier (2005)

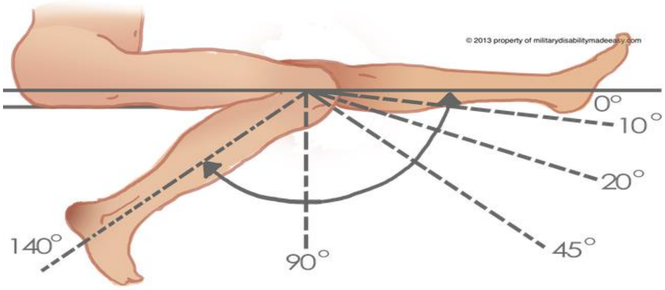

Figure 2.5: The degree of knee extension/flexion

Source: www.militarydisabilitymadeeasy.com/kneeandleg.html

To measure degrees of flexion, the zero is on the ankle and the 180 degree is on the hip. Thus the full extension is zero degrees while the right-angle at the knee being 90 degrees.

2.3.1 Design of Leg Extension

For the purpose of coming up with the design of the exerciser, current commercialised designs has been used as a reference. The followings are several designs that were convenient and applicable rather than the other complex designs that were not included in the list. The term applicable for the design is of the design that does not contain complexity in the mechanical parts that might cause trouble in the fabrication process later on in this study. Hence, only a simpler designs and capable to fabricate were taken into account.

Figure 2.6: Powerline Leg Extension Curl Machine

Source: www.amazon.com/Powerline-PLCE165X-Extension-Curl-Machine/dp/B000VDF6YG

The design of Figure 2.6 was designed to protect the joints from the stress. This design is also suitable for performing both upright and prone leg extensions and curls. It has a decline bench which is stationary and fixed. Leg Extension in Figure 2.7 below is designed to isolate and fully engage quadriceps muscles with the best workload distribution according to movement trajectory and the optimum torque throughout the complete range of motion.

Figure 2.7: Pure Strength Leg Extension

Source: www.technogym.com/gb/leg-extension-purestrength-11.html

Design in Figure 2.8 below has an easy and convenient step-in design using heavy gauge steel frame with all-4-side welded construction. In terms of load placement, this design is found to be quite similar with the Figure 2.6 design.

Figure 2.8: Body Solid Leg Curl Extension

Source: www.fitnesszone.com/product/Body-Solid-GLCE365-Leg-Curl-Extension-Station.html?Old_CatCode=commercial-free-weight-benches

2.4 ANALYSIS OF ACCELERATION

Inertial acceleration sensors are able to record movement which later can be expressed in terms of velocity, displacement, angular velocity, acceleration, force etc. There were numerous efforts in understanding the acceleration related to human body (O'Donovan et al., 2005) as well as the implementation usage in sports such as to study the acceleration movement of cricket bats (Sarkar et al., 2011) and tennis racquet (Rowlands et al., 2012).

Two accelerometers had been used by O'Donovan to determine if the calf muscle pump has been active or not. These accelerometers were attached to the heel of the foot and the lateral side of the lower leg. Signals produced by these accelerometers were then compared to their threshold respectively in order to distinguish between level of high activity and the level of low activity. The MATLAB computing program was used for all post trial analysis where the raw EMG signal and the accelerometer signals were band pass filtered.

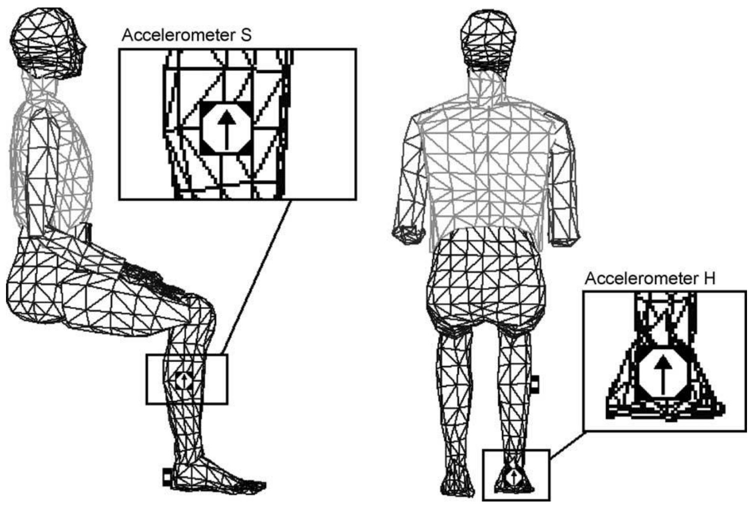

Figure 2.9: Accelerometer set-up for calf muscle pump activity detection

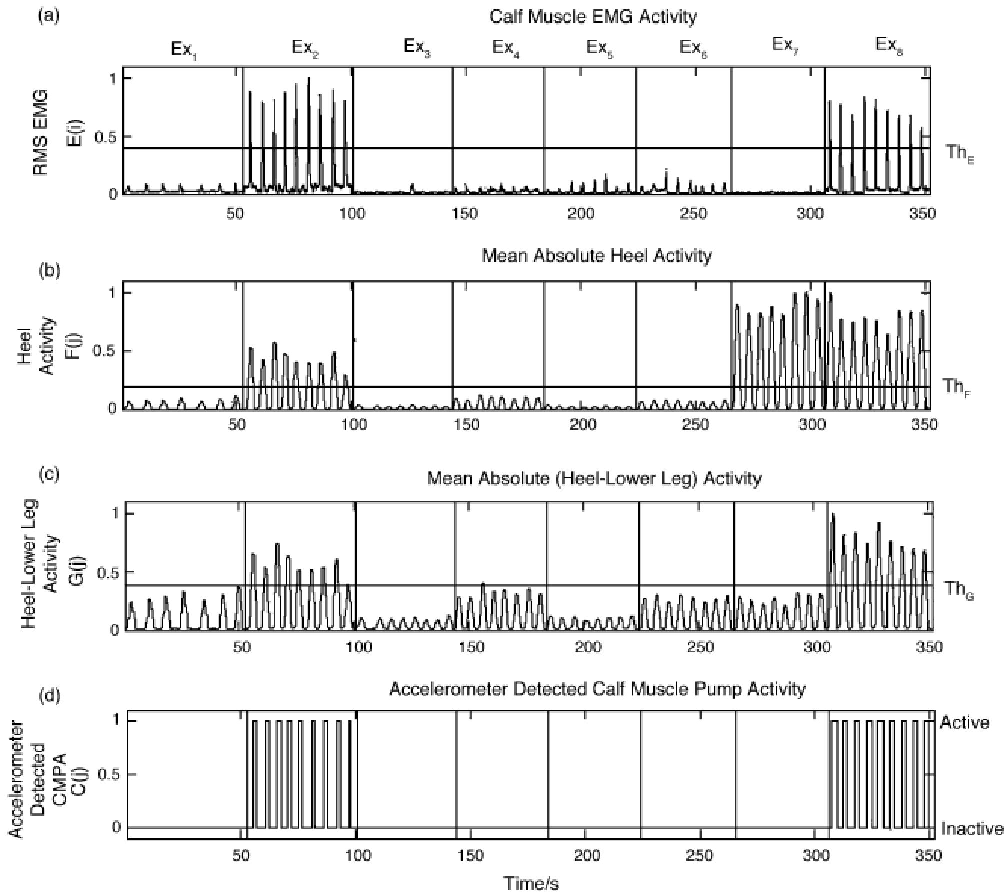

Figure 2.10: Calf muscle EMG and derived signals F(j), G(j) and C(j)

Source: O'Donovan et al. (2005)

Okita and Sommer had fabricated an IMU with two sensors where both contained a gyroscope and an accelerometer. The IMU was secured to the dorsal surface of the shoe with a shoe lace.

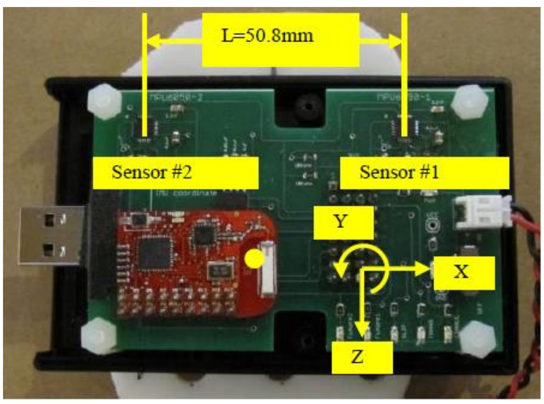

Figure 2.11: Top view of the IMU

Figure 2.12: IMU secured to the shoe

Source: Okita and Sommer

Angular acceleration was calculated using MATLAB using both of the respective formula for accelerometer and gyro.

$$\alpha_{accel,i} = \frac{a_{y1,i} - a_{y2,i}}{L}$$
$$\alpha_{gyro,i} = \frac{d\omega_z}{dt} = \frac{\omega_{i+1} - \omega_{i-1}}{2\Delta t}$$

a_{y1} and a_{y2} were the vertical accelerations from sensor #1 and #2, L was the distance between the sensors, and ω_z was angular velocity about the medial-lateal axis measured by gyro.

A method by Dejnabadi et al. in measuring joint angle had used the combination of accelerometers and gyroscopes. The model is based on estimating acceleration of the joint center of rotation. Since it is not physically possible to place accelerometers at the joint center of rotation, virtual sensors are used by mathematically shifting the location of the physical sensors.

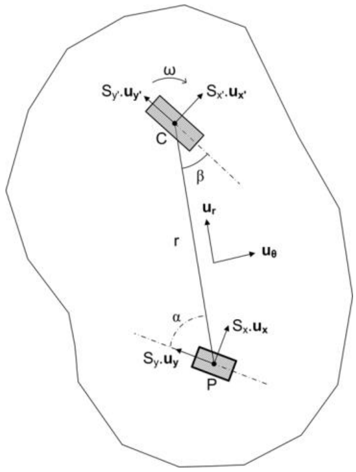

Figure 2.13: A physical sensor module at point P, and a virtual sensor module on point C on a 2-D rigid body. Each sensor module consists of 2-D accelerometers and a gyroscope.

In order to calculate the knee angle (flexion-extension) in their research, two sensor modules that have two accelerometers and a gyroscope had been used.

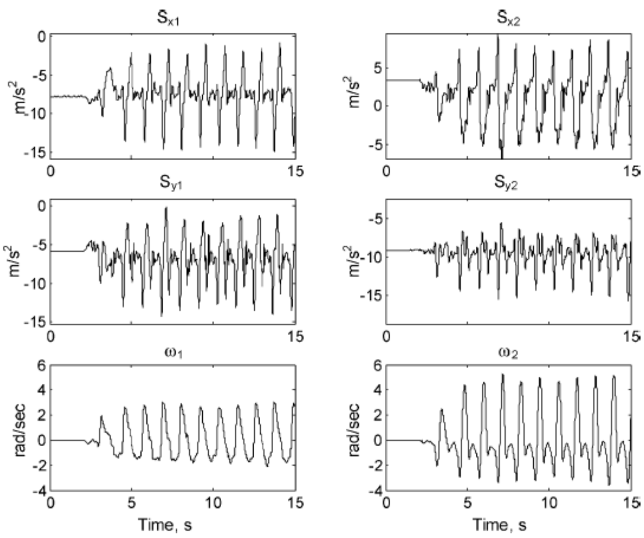

Figure 2.14: Physical accelerometers and gyroscopes (raw data) readings during walking at 3 km/h

Figure above shows the physical accelerometer and gyroscopes reading that were placed on thigh and shank. The site on thigh consists of two accelerometers (S_{x1} and S_{y1}) and a gyroscope (ω_1). Similarly, there are two accelerometers (S_{x2} and S_{y2}) and a gyroscope (ω_2) on a shank module as well.

2.5 ELECTRONIC COMPONENTS

2.5.1 Microcontroller

Nowadays, most of machinery, devices and appliances products are designed with built-in microcontroller. It is a small computer on a single integrated circuit which contains a processing core, memory, and programmable input/output peripherals. Its ability to control instruments has become the reason for it's widely usage.

The Uno is a microcontroller board that has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. It can be used easily by simply connect it to a computer with a USB cable.

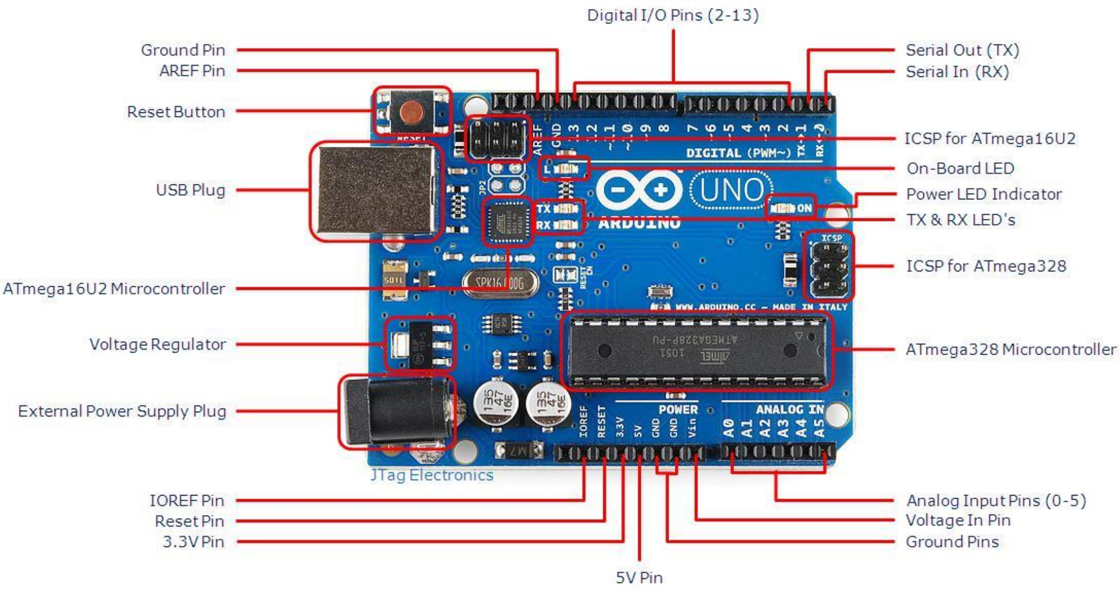

Figure 2.15: pins mapping on Arduino Uno board

2.5.2 IMU Sensor

An inertial measurement unit (IMU) is an electronic device that measures a body's specific force and angular rate using a combination of accelerometers and gyroscopes. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs), among many others, and spacecraft, including satellites and landers. Recent developments allow for the production of IMU-enabled GPS devices.

The InvenSense MPU-6050 sensor contains a MEMS accelerometer and a MEMS gyro in a single chip. It is very accurate, as it contains 16-bits analog to digital conversion hardware for each channel. Therefor it captures the x, y, and z channel at the same time. The sensor uses the I2C-bus to interface with the Arduino.

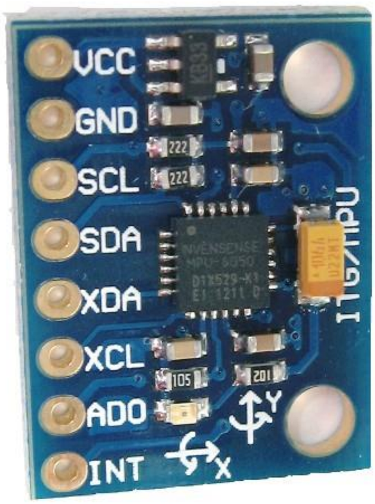

Figure 2.16: InvenSense MPU6050 board

Source: MPU-6050 Accelerometer + Gyro, n.d.

2.6 MECHANICS OF SWINGING THE HUMAN LEG

In the study conducted by Doke J. et al., how much of metabolic energy is expended to swing a human leg was studied. For this study, equation of torque needed to be derived as for it will be the parameter in the study. Since the part of the leg that will be considered for the calculation is only from knee to ankle, therefore, the leg can be modelled as a simple pendulum moving back and forth.

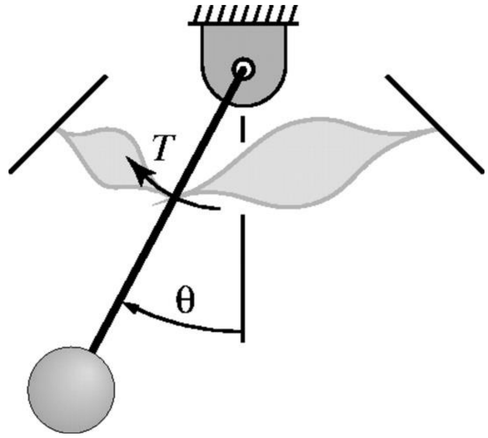

Figure 2.17: Isolated leg was modelled as a simple pendulum.

Source: Doke J. et al. (2004)

Equation of motion by employing a small angle approximation and measuring the angular displacement from vertical,

$$\ddot{\theta} + {\omega_n}^2\theta = T \tag{2.1}$$

Where ω_n is the perpendicular natural frequency and T is moment of applied muscle force normalized by leg inertia. The pendulum is assumed to be driven approximately sinusoidal with fixed amplitude A and frequency $\omega \triangleq 2\pi f$,

$$\theta(t) = A\cos\omega t \tag{2.2}$$

Active movement of the leg requires muscle force or torque, increasing with the square of swing frequency. By combining both of the equation above, the torque is

$$T(t) = A(-\omega^2 + {\omega_n}^2)\cos\omega t \tag{2.3}$$

Based on the setup of a simple pendulum,

$$I\ddot{\theta} = \tau \quad (2.4)$$

Where I is the moment of inertia of the mass, and τ is the torque acting on the system. For this, $I = ml^2$.

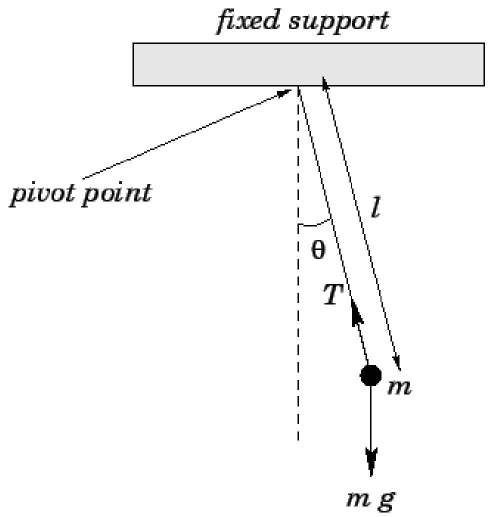

Figure 2.18: A simple pendulum

Source: Fitzpatrick P. (2006)

The two forces acting on the mass are the downward gravitational force, $m\,g$, and the tension, T, in the string however the tension makes no contribution to the toque.

$$\tau = -mgl\sin\theta \quad (2.5)$$

2.7 PARAMETERS FOR STUDY

The following figures are showing graph of results obtained from several study related to this study. These results will be used later on this study as for comparison with the result obtained from this study itself. It will be as a validation for the results obtained through the conduct of this study. Included following will be the graph for angular position or simply angle, angular velocity, angular acceleration as well as the torque graph. Firstly presented here are results from Dejnabadi. Note that their study was for gait analysis, nevertheless the results still can be used for comparison as it also involves the result for knee flexion and extension although the value might be different for this study later.

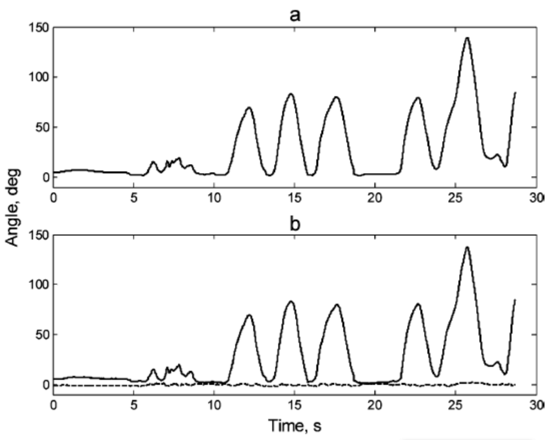

Figure 2.19: Absolute knee angle during a freely arbitrary flexion and extension of knee

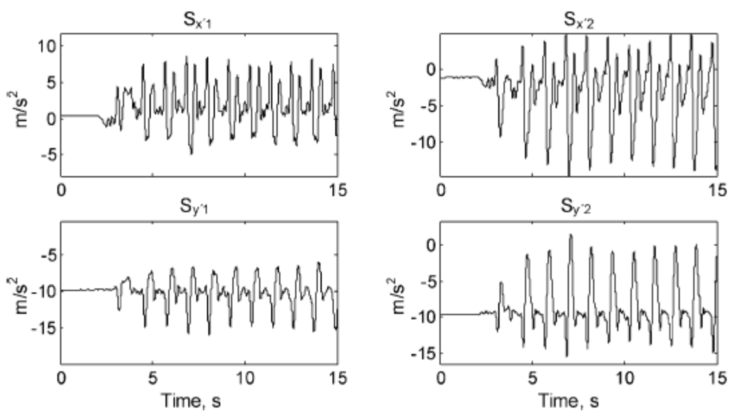

Figure 2.20: Virtual accelerometers readings placed at the knee center of rotation on the adjacent segments.

The following is the graph of comparison of knee angle estimates using camera and IMU data which was obtained from the research of Cooper G., et al. where two IMUs were used (one placed at the thigh and one placed at the shank).

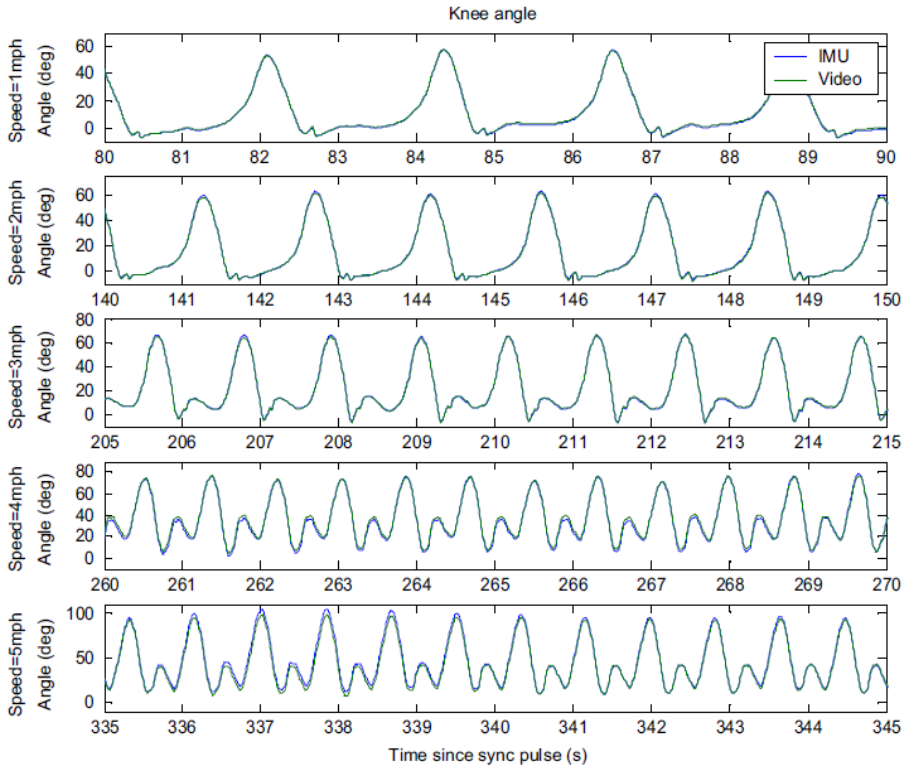

Figure 2.21: Comparison of knee angle estimates using camera and IMU data for subject 1

In the study conducted by Nozaki D., et al. on the knee joint torque, the following result was obtained.

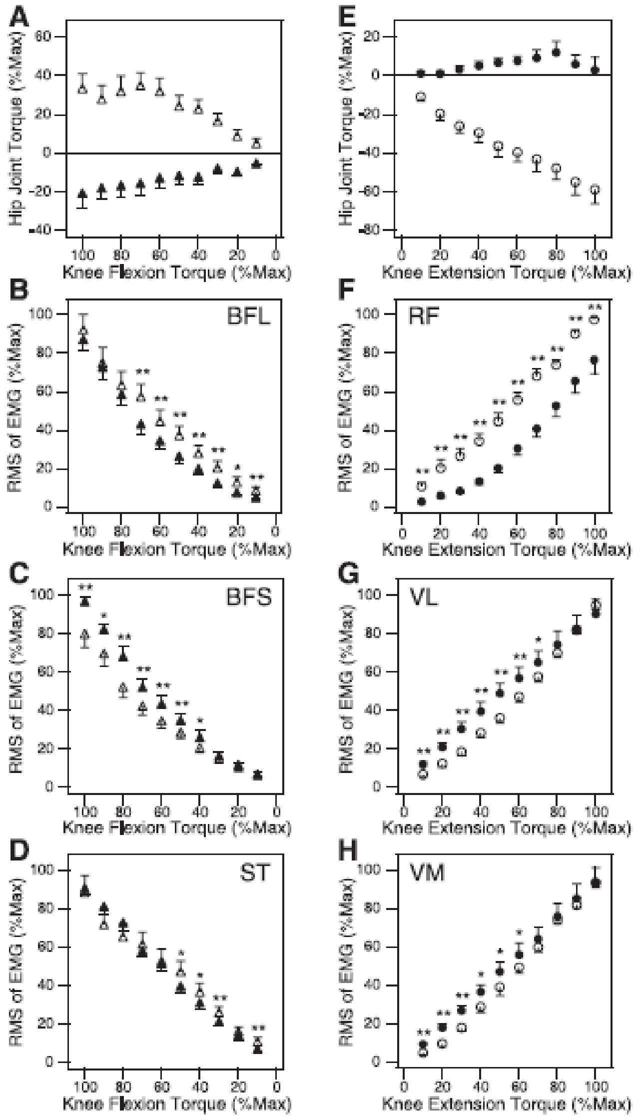

Figure 2.22: Effect of the change in the strategy on the muscle activity.

A and E: relationship between the hip and knee joint torque in the knee flexion and knee extension tasks, respectively. Each of the closed and open markers corresponds to each of the 2 strategies that the subjects used. The smaller one of the maximal knee joint torques in the Free and Control conditions is used as a normalization factor for the knee and hip joint torques (%Max). B–D and F–H: muscle activity with respect to each knee joint torque level averaged over all subjects. BFL, biceps femoris long head; BFS, biceps femoris short head; ST, semitendinosus; RF; rectus femoris; VL, vastus lateralis; VM, vastus medialis; RMS, root mean square; EMG, electromyography. The RMS of EMG is normalized (%Max) to the maximal value obtained in the range of knee joint torque from 0 to 100%.

2.8 CONCLUSION

This chapter, which is the literature review from the past research is important as the reference to organize the current research. The research related to strength training that had been done previously is review as the resource. The past research shows the importance of strength training and how certain improvement of muscle strength shown when performing the strength training.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discussed on the methods used to carry out this research. This research was done to identify methods of measuring and monitoring the strength performance of lower limb. The procedure in carrying out this research is first to design the system properly. The design consists of hardware part which is the frame of the test rig and the software part where it involves the programming for the sensor in getting the reading data. From the design process, then fabrication process will proceed. An experiment will need to be set up subsequently as to determine the system well-functioning and as to get the data for further analysis. The result obtained from the experiment will be then analysed for performance evaluation. For a better view and understanding of the methodology, the flow chart in Figure 3.1 is presented.

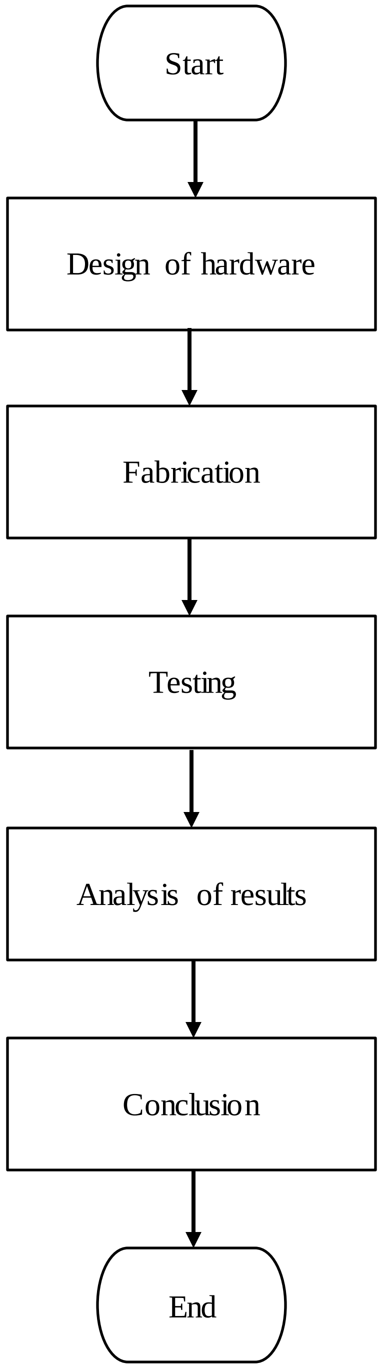

Figure 3.1: Methodology flow chart

3.2 DESIGN OF THE SYSTEM

In order to measure the strength performance of the lower limb, a system needs to be designed that will be able to measure the angular displacement (position), angular velocity and the angular acceleration of swinging action of the leg while it performing knee extension as a certain amount of load act against the leg.

3.2.1 Exerciser

The exerciser made in this study is a leg extension machine which is to be used as a test rig for this study. In designing the frame, material selection is important since it affects the strength capability of the frame to withstand heavy load. The one listed below is the necessary material properties in designing the exerciser:

a. High strength
b. Rigid, does not excessively deform under loading
c. Easily fabricated

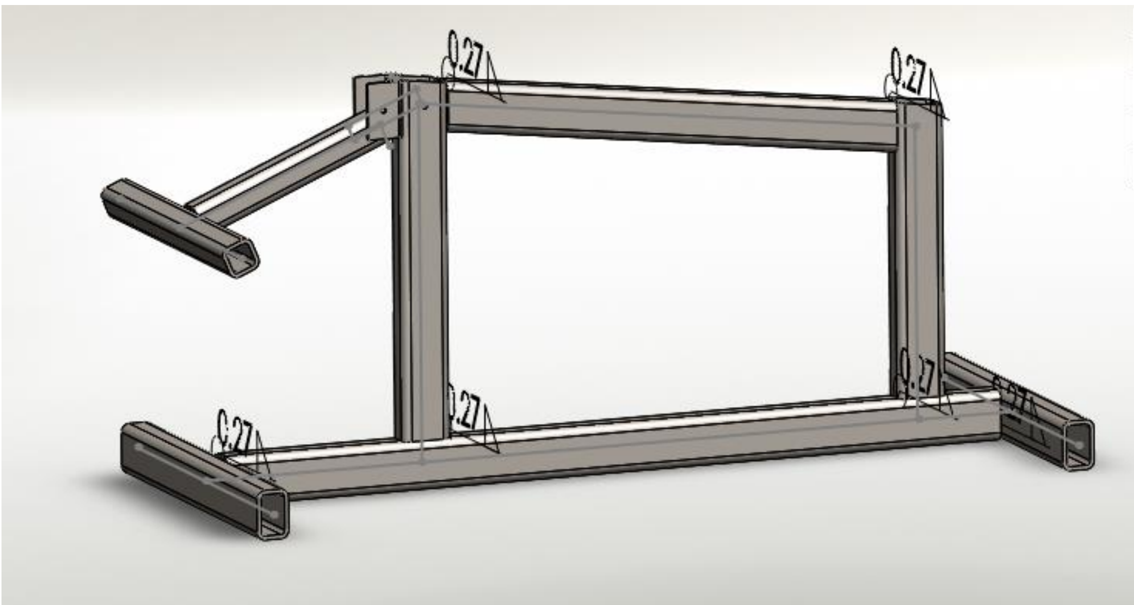

Figure 3.2: Frame body of the leg extension design

Before proceeding with fabrication of the design as in Figure 3.2, calculation for maximum stress and deflection for the frame design needed to be done for ensuring the ability of the design. These calculations shown below is the calculation made for the beam used in the design which illustrated in Figure 3.3.

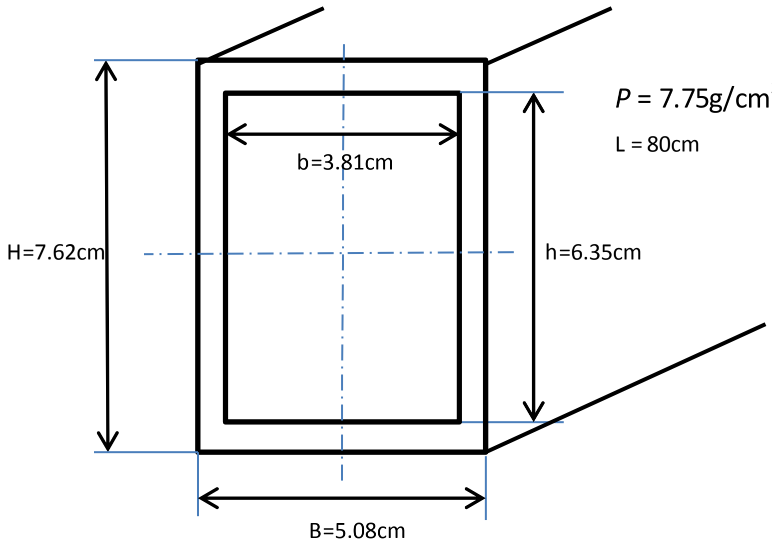

Figure 3.3: Cross section area of the beam

Cross section area, A

$$A = BH - bh = (5.08\ cm)(7.62\ cm) - (3.81\ cm)(6.35\ cm) = 14.5161\ cm^2 \quad (3.1)$$

Volume, V

$$V = AL = 14.5161\ cm^2 \times 80\ cm = 1161.288\ cm^3 \quad (3.2)$$

Mass, m

$$m = V\rho = 1161.288\ cm^3 \times 7.75\ g/cm^3 = 8999.982\ g = 9\ g \quad (3.3)$$

Moments of inertia,

$$I_x = (HBL\rho)(H^2 + L^2)/12 - (hbl\rho)(h^2 + L^2)/12 \quad (3.4)$$

$$= (23999.952)(6458.0644)/12 - (14999.97)(6440.3225)/12$$

$$= 4865715.946\ g.cm^2$$

$$I_y = (HBL\rho)(B^2 + L^2)/12 - (hbL\rho)(b^2 + L^2)/12 \quad (3.5)$$

$$= (23999.952)(6425.8064)/12 - (hbL\rho)(b^2 + L^2)/12$$

$$= 4833458.011\ g.cm^2$$

Area Moments of Inertia,

$$I_{xx} = BH^3/12 - bh^3/12 \quad (3.6)$$

$$= (5.08)(7.62)^3/12 - (3.81)(6.35)^3/12$$

$$= 106.009\ cm^4$$

$$I_{yy} = HB^3/12 - hb^3/12 \quad (3.7)$$

$$= (7.62)(5.08)^3/12 - (6.35)(3.81)^3/12$$

$$= 53.974\ cm^4$$

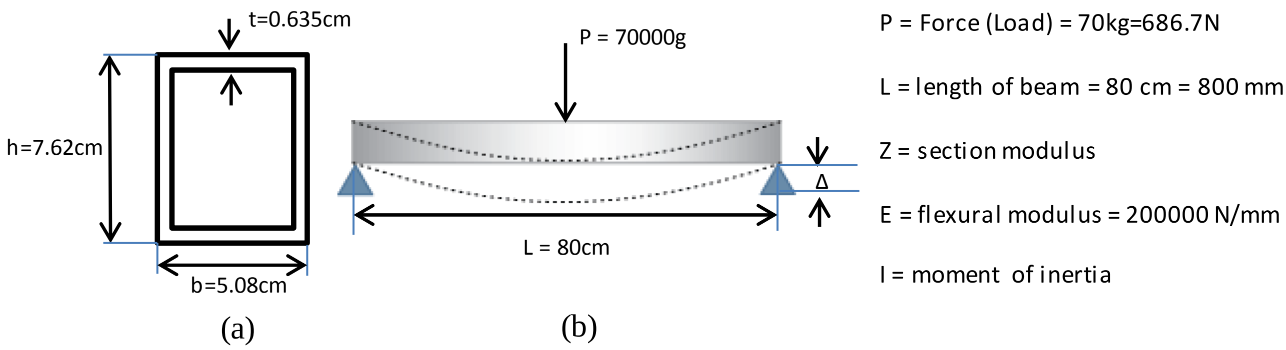

Figure 3.4: (a) Cross section view of the beam; (b) Side view of the beam when load is applied

The following calculations were based on Figure 3.4:

Moment of inertia about bending axis, I

$$I = \frac{bh^3 - (b-2t)(h-2t)^3}{12} \quad (3.8)$$

$$= \frac{(5.08)(7.62)^3 - (5.08-1.27)(7.62-1.27)^3}{12}$$

$$= 106\ cm^4$$

Section modulus,

$$Z = \frac{2I}{h} = 2 \times \frac{106}{7.62} = 27.82\ cm^3 \quad (3.9)$$

Max Stress, σ

$$\sigma = \frac{PL}{4Z} = \frac{(686.7)(800)}{4(27820)} \tag{3.10}$$

$$= 4.9367\ MPa$$

Max Deflection, Δ

$$\Delta = \frac{PL^3}{48EI} = \frac{(686.7)(800)^3}{48(200000)(1060000)} \tag{3.11}$$

$$= 0.03455\ mm$$

3.2.2 Simulation Using Solidworks

Finite Element Analysis (FEA) will be performed on the designed frame using the Solidworks software under the simulation studies feature in the software. Through FEA, visualizations on stress concentrations and deflections can be viewed in order for design consideration. Firstly for simulation analysis, static study was chosen as shown in Figure 3.5.

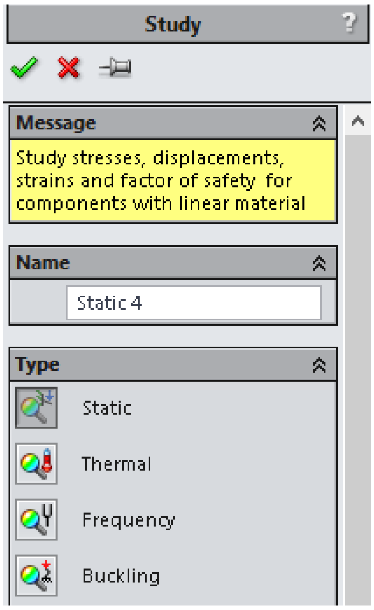

Figure 3.5: Static study in Solidworks simulation

After that, external load which is force was selected. It is set for 686.5N in this study as for aiming that the design could withstand a 70kg weight load which is assuming that it is the standard weight or maximum weight for person to use the exerciser.

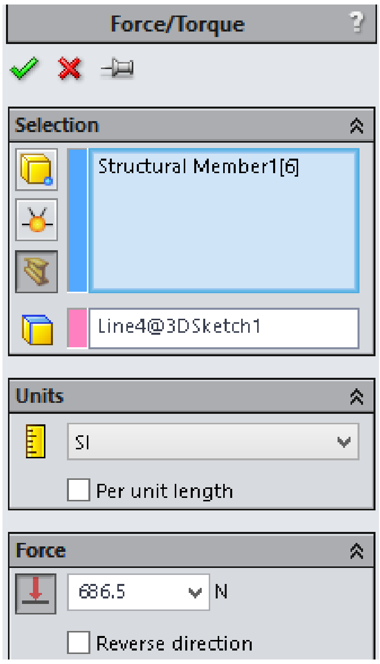

Figure 3.6: External load which is force is applied to the simulation

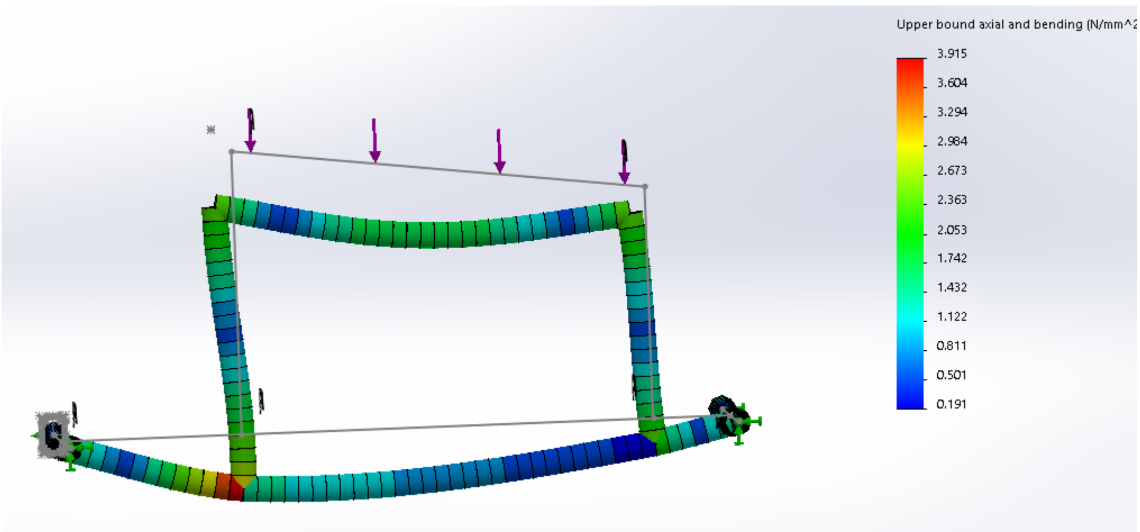

Figure 3.7: Deformation frame design simulation

3.2.3 Fabrication

Fabrication process is made once the design was completely done and had achieved satisfaction criteria. Main process involved in the fabrication of the hardware was the welding of the steels used as the frame accordingly.

Figure 3.8: Frame body of the exerciser

Once the frame design was completed, few additional features for the exerciser design were made. Seat was added to the frame for comfort and ergonomic factor. Wooden block has been used as the seat for the exerciser. As for the weight load, bumper plates were not fabricated from scratch but instead they were bought from the market.

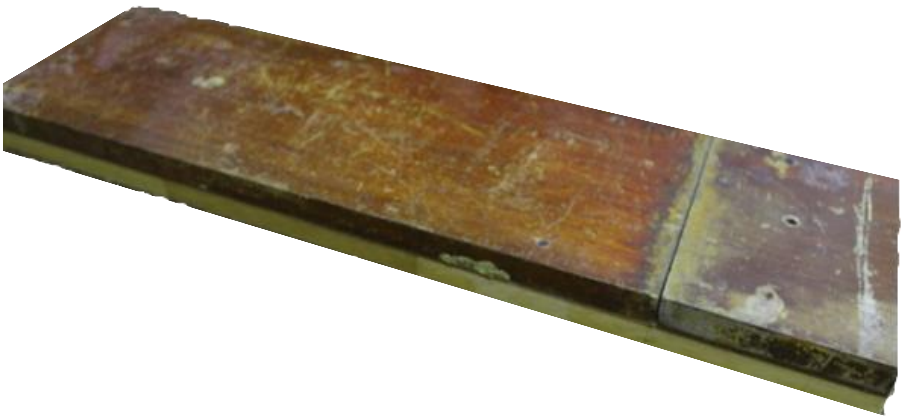

Figure 3.9: Wooden block used for the seat

Figure 3.10: Bumper plates used for the training

Total mass of plates is 5kg with 2 plates of 0.5kg, a pair of 0.75kg and a pair of 1.25kg plates. All of these plates has the same hole diameter which is 2.5cm and has almost the same thickness which is around 1.9cm ± 0.1cm. The diameters of the plates are as follows:

Table 3.1: Diameter of each plate

Plate mass (kg)	**Diameter (cm)**
0.50	9
0.75	11.2
1.25	13

3.2.4 Sensor

This study requires the determination of angular position, angular velocity and angular acceleration of the leg as it swings performing the leg extension exercise. In order to measure those parameters, IMU sensor is necessary. For this study, MPU6050 was used as the sensor. This sensor contains a MEMS accelerometer and a MEMS gyro in a single chip. In the study, this sensor was placed on the exerciser which acted as a test rig for this study. It was strapped at the link of the exerciser for the swinging action of the leg. Since the leg and the exercise of that link part are moving or swinging simultaneously, it can be considered as one same movement. Hence the parameters of the knee extension can indirectly be obtained.

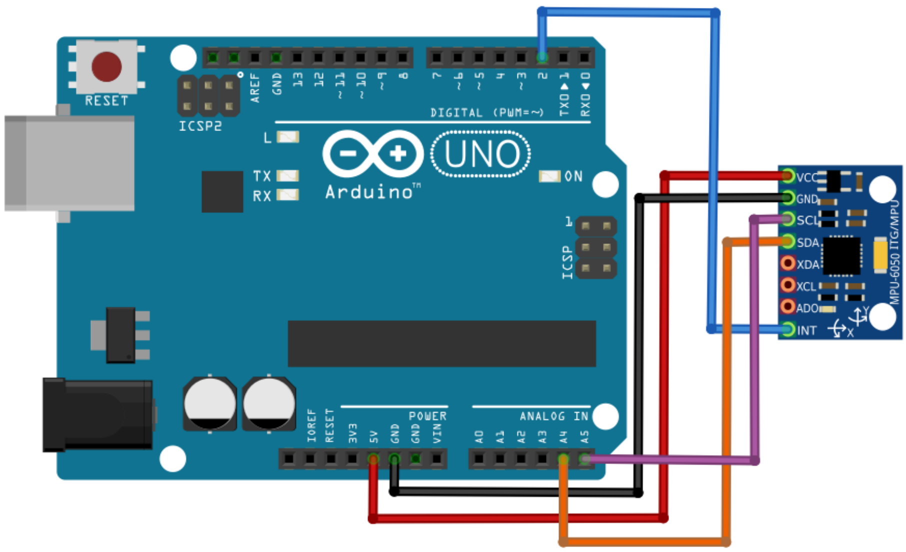

Figure 3.11: The connection of the circuit of MPU6050 and Arduino board

The MPU6050 communicates with the Arduino through the I2C protocol. The MPU 6050 is connected to Arduino as shown in the above diagram. 5V pin of MPU6050 module is connected to the 5V pin of arduino while GND of arduino is connected to the GND of the MPU6050. Since the program will take advantage of arduino's interrupt pin, arduino's digital pin 2 (interrupt pin 0) is connected to the pin labelled as INT on the MPU 6050. Next, the I2C lines needed to set up where the pin labelled as SDA on the MPU 6050 is connected to the arduino's analog pin 4 (SDA) for this and the pin labelled as SCL on the MPU 6050 is connected to the arduino's analog pin 5 (SCL).

By using the sensor, angular position (angle) of the knee extension can be obtained. However, the value for the angular velocity and acceleration cannot be obtained directly. To get those values, differentiation method has to be applied.

In order to get the value for angular velocity, differentiation of angular displacement has to be made which is as follows:

$$\text{Angular velocity}, \dot{\theta} = \frac{\theta_{new} - \theta_{prev}}{dt} \tag{3.12}$$

From the calculated value of angular velocity, the value of angular acceleration can also be calculated as well by using the following formula:

$$\text{Angular acceleration}, \ddot{\theta} = \frac{\dot{\theta}_{new} - \dot{\theta}_{prev}}{dt} \tag{3.13}$$

Finally, torque values will be determined based on the following equation which derived from equation in literature review:

$$\text{Torque}, \tau = m_{leg}ar - m_{load}gr\cos\theta \tag{3.14}$$

Where m_{leg} is the mass of the leg, a is the acceleration, r is the radius or length of the link and g is the gravitational force.

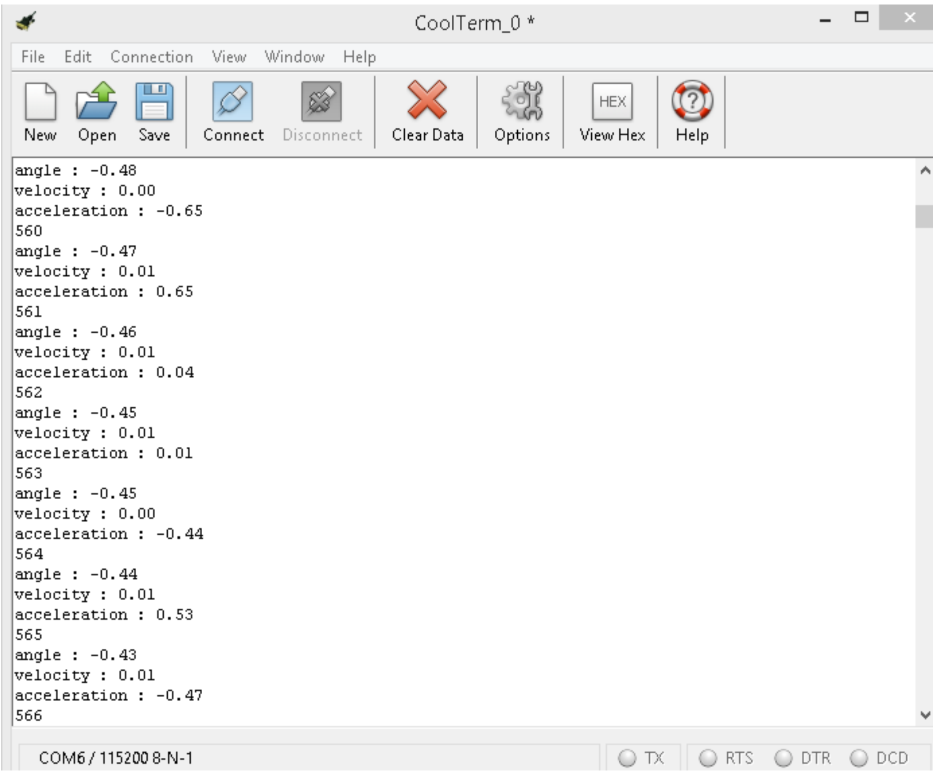

Figure 3.12: Using CoolTerm software to save and export the data

Since the Arduino IDE software only has the ability to read the data through serial monitor but does not have the ability to save, let alone exporting the data to excel, other software has to be used in order to achieve that. Therefore, CoolTerm software has been used to serve that purpose.

3.3 SYSTEM ASSEMBLY

Following the completion of the hardware parts, both the hardware of the exerciser and the electronic part containing the sensor are required to be assembled together as one system. As mentioned previously, the sensor needed to be placed on the movable link of the exerciser. To do so, the circuit containing both arduino board and IMU board is placed in a box. The placement inside the box is secured with the usage of silicon to glue the boards. This is vital so that the sensor will not be moving around inside the box as the knee extension is performed. The arduino will then need to be connected with PC or laptop using USB cable. A longer cable length is better to be used here as a short cable will limit and might disturbs the movement of the exercise since the computer has to be within a very short distance from the exerciser. First and important thing that needed to be done once the connection has been established is to calibrate the IMU sensor. In order to calibrate, the link bar needed to be adjusted parallel to the angle of the sitting bar. Once calibration is done, proceed with the evaluation method.

(a) (b)

Figure 3.13: Arduino and IMU circuit placement in a box when (a) box is opened (b) box is closed

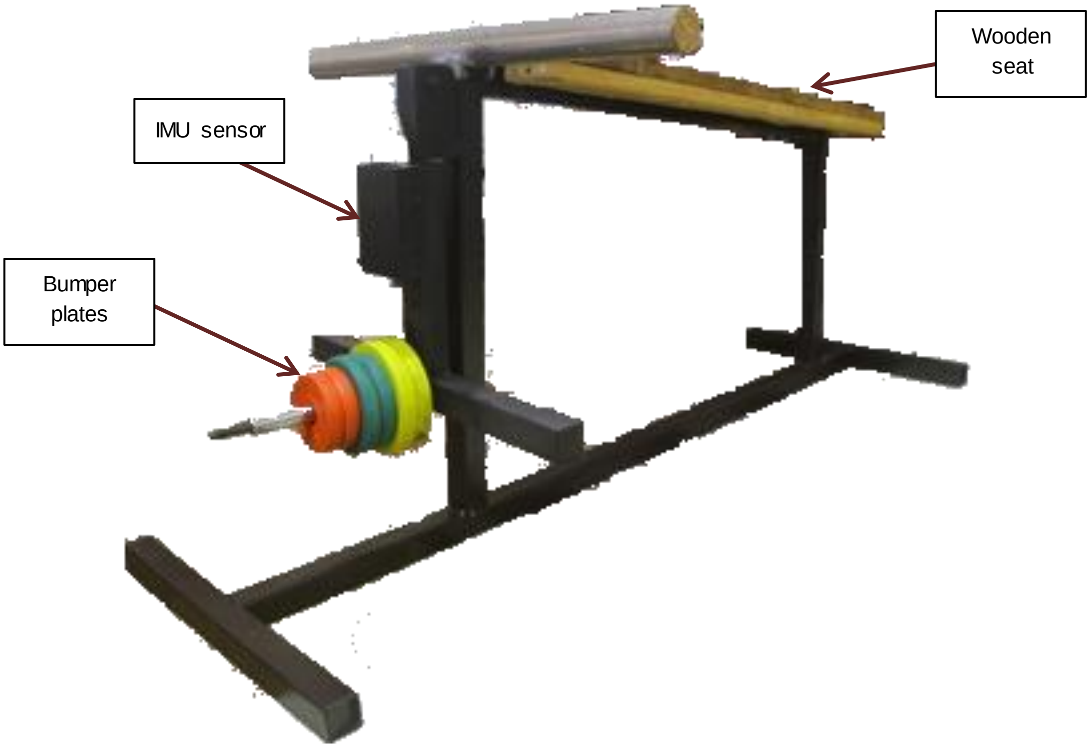

Figure 3.14: The complete assembly of the system

3.4 SYSTEM EVALUATION

Ultimately, the system designed needed to be tested. A strength training analysis will be performed using the system to measure and monitor the performance. Expected results from this analysis will be:

1. Angular position vs time
2. Angular velocity vs time
3. Angular acceleration vs time
4. Torque vs time

Training was conducted with a test subjects with the parameters as shown in the following table.

Table 3.2: Test subjects profile data.

Characteristics	Subject A	Subject B
Age	24	23
Height (cm)	158	161
Weight (kg)	56	60
Leg Length (cm)	33	37.2

Figure 3.15: Apparatus setup for strength training analysis

Figure 3.15 shows the angle measurement used in this study. The system was calibrated with zero degree angle when the link is parallel to the seat plane hence causing the angle to increase as the knee flexing while decrease as the knee extend. Each subjects needed to perform knee extension exercise as part of the strength training analysis. Both subjects perform the exercise with the load of 5kg bumper plates and 10 repetitions of knee flexion and extension. The data for the activity were recorded and tabulated in Excel.

CHAPTER 4

RESULT AND ANALYSIS

4.1 INTRODUCTION

This chapter will discuss the findings obtained from the experimental conducted for strength training activity. The data obtained from the experiment using the system developed will be analysed and presented in this chapter.

4.2 EXPERIMENTAL RESULT

The experiment that was conducted for the purpose of this study is for finding the position, velocity and acceleration of the leg while it swings performing knee extension activity. The values of these parameters were measured using IMU sensor, MPU6050 as the subject performing leg extension exercise. Using the parameters obtained, torque will then be calculated. From the data collected, it was exported and tabulated in Excel, and later graphs were made based on those data so that clear view and understanding of the results can be obtained. Even though each subjects performed the knee flexion and extension with 10 times repetition, the result shown in all of the following graphs are only shown up to 5 repetitions only. This is because of too much data values for 10 repetitions to be included in the graph.

4.2.1 Angular Displacement Analysis

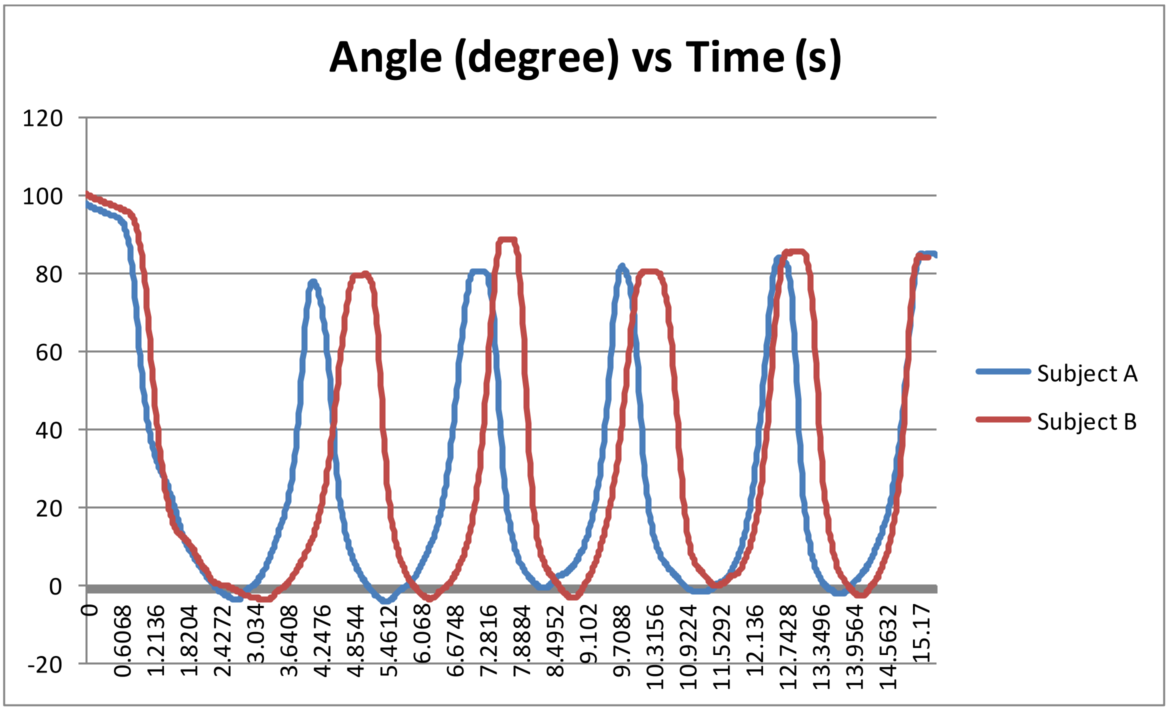

Figure 4.1: Angular displacement profile from strength training analysis

Based on figure 4.1, the downhill slope of the graph indicates knee extension while the increasing value of angle indicates the movement of knee flexion. As shown in the graph above, subject A tends to flex and extent less rather than subject B who always have higher value of angle when in flexion as well as extension. Subject A completed 5 repetition with 15.5 seconds while subject B finished with 15.36 seconds which seems to be faster than subject A. The maximum angle achieved by subject A during flexion was 81.69° while subject B was 88.71°.

4.2.2 Angular Velocity Analysis

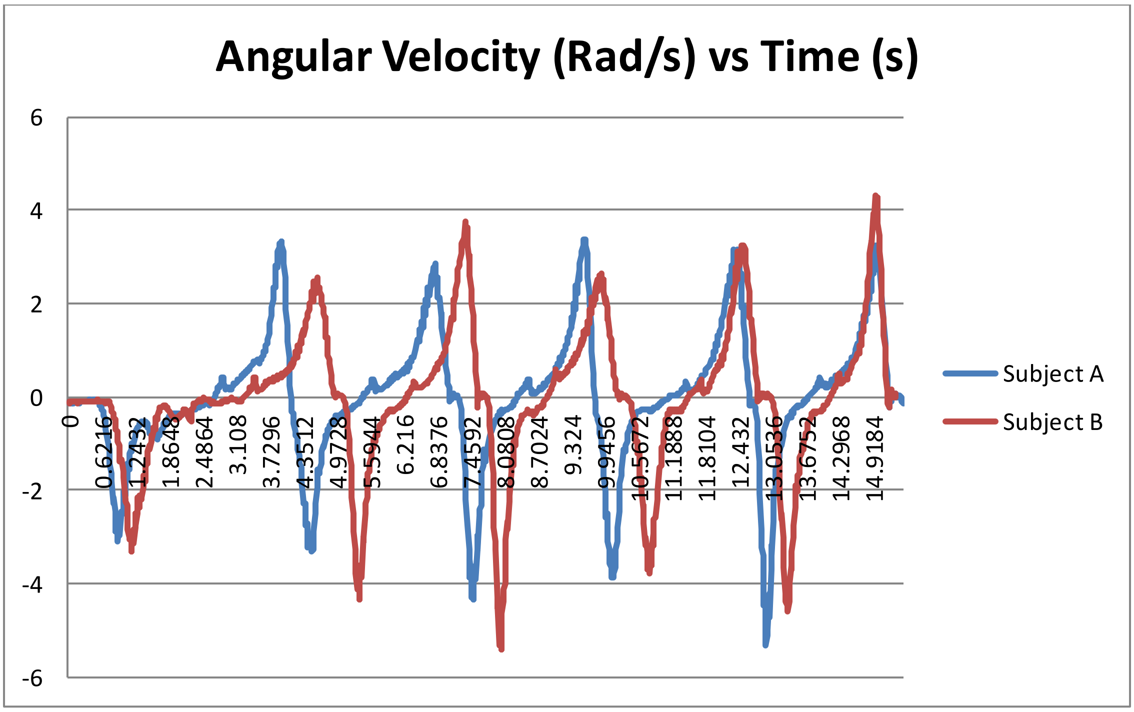

Figure 4.2: Angular velocity profile from strength training analysis

Based on figure 4.2, both subjects A and B had achieved their maximum angular velocity during the fifth repetition where the peak values for subject A is 3.36 rad/s while subject B is 4.3 rad/s. The negative value of the velocity indicating the knee extension movement while positive value is for knee flexion movement.

4.2.3 Angular Acceleration Analysis

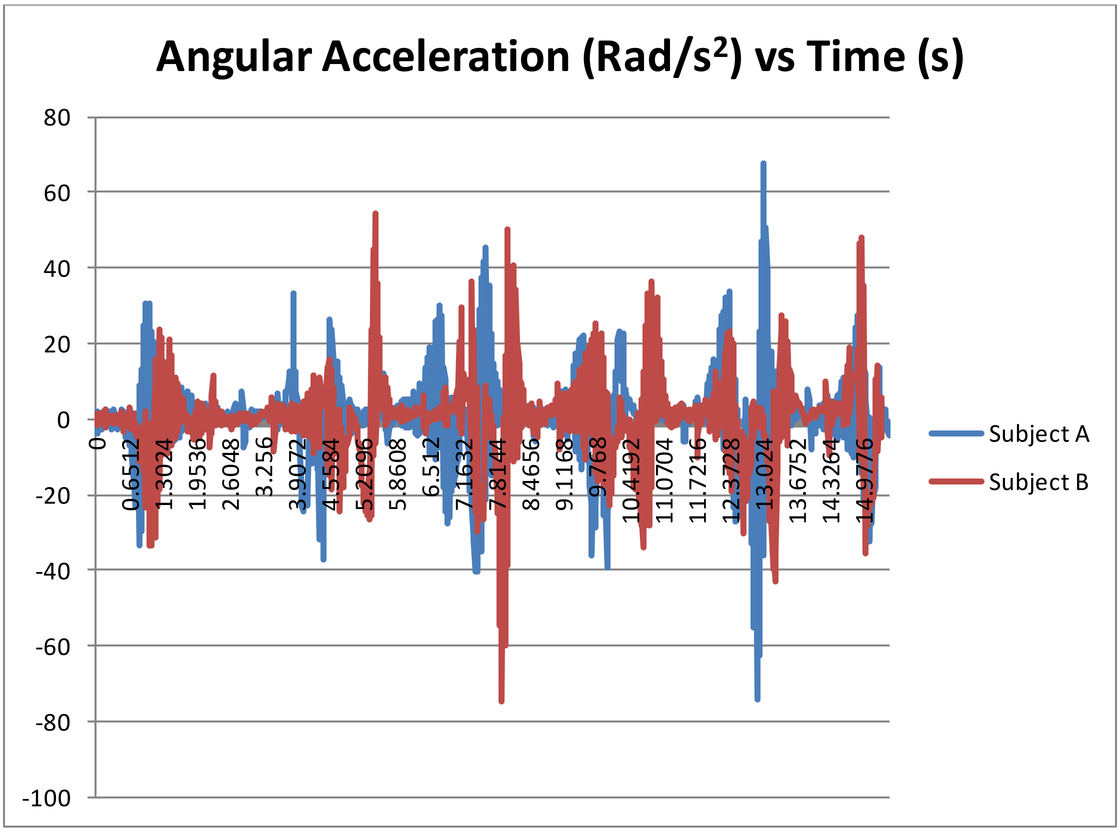

Figure 4.3: Angular acceleration profile from strength training analysis

Angular acceleration was determined via differentiation of angular velocity. Based on figure 4.3, the maximum value for subject A is 67.37 rad/s^2 while the minimum value is -62.53 rad/s^2. As for subject B, the maximum value is 54.4 rad/s^2 and the minimum value is -74.96 rad/s^2. The positive values of the data indicate increasing of acceleration while the negative value is when the movement is decelerating.

4.2.4 Torque Analysis

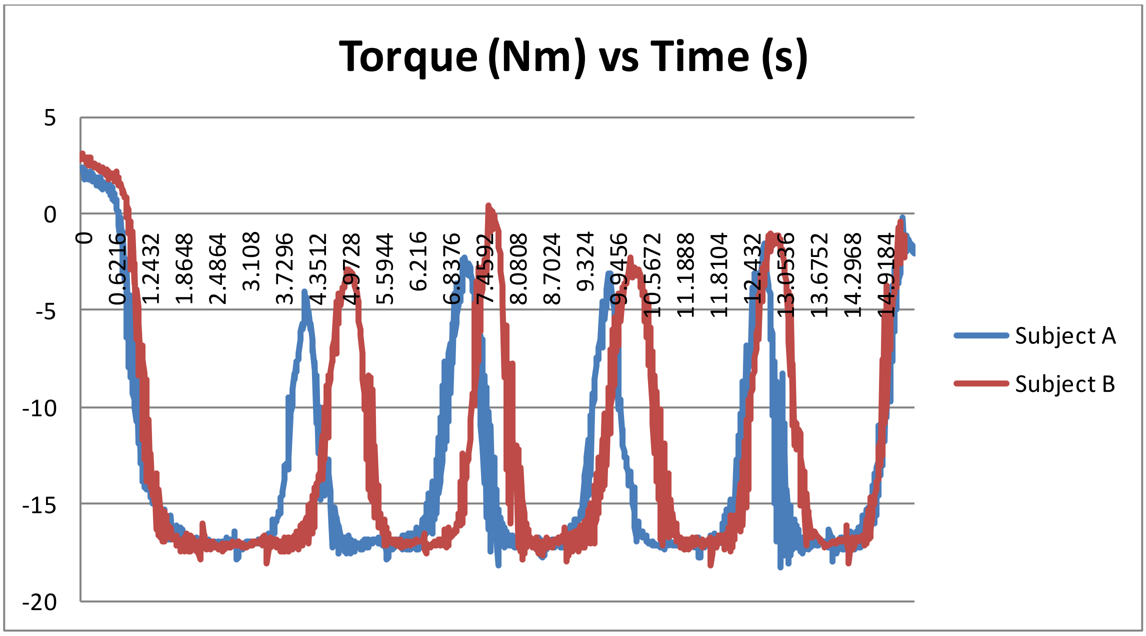

Figure 4.4: Torque (Nm) vs Time (s)

Based on figure 4.4, both subjects perform quite the same pattern except for the values that differ from each other. Overall, subject B has higher torque compared to subject A. The maximum torque for subject A is 2.37 Nm and the minimum is -18.28 Nm while subject B has the maximum value of 3.06 Nm and the minimum of -18.17 Nm.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter summarizes the whole project by coming up with conclusions that are made based on the research of this project. This chapter also includes conclusion and recommendations that can be implemented future suppose that this project would be continued in the future.

5.2 Conclusion

In conclusion, the project has fulfilled all of the objectives stated. The design and fabrication of the exerciser for assisting the study was made. The system to measure and monitor the performance of strength training was also been built. Through the developed system, parameters which include displacement angle, angular velocity, angular acceleration and torque were obtained as the subjects perform strength training using the system.

Based on the results obtained from this study, both subjects have different values for all parameters. Subject B had shown higher capability in all aspect of parameters. This is due to the more involvement in sports related activity by subject B compared to subject A. However, based on the studies conducted by others, it was proven that strength performance could be improved by individual by doing more training.

Comparing the results obtained by this study from the literature reviews made, it can be concluded that the study is valid. The graph of angular position, angular velocity and angular acceleration obtained in this study has similar pattern to the result that can be seen in the literature review section despite the different values since in this study, subjects needed to perform the action of extension and flexion of the knee while in the graph shown in the literature review was the graph for gait analysis. Nevertheless, considering the angle differences with gait analysis and the swinging action of leg in training in this study, the graph for angular displacement can be reasonably accepted for representing the angular position of legs when performing the exercise in the training. Likewise for angular velocity and angular acceleration, the values differ from literature review as results obtained from this study were from the differentiation of angular displacement and angular velocity respectively and could also be accepted as long as the pattern for its graph is in a similar way as the literature review. However, since hip torque was not calculated for this study, it cannot be plotted against knee torque as it was shown in the literature review. Since the graph for torque in this study is not compared for literature review and thus, it cannot be verified correctly.

5.3 Recommendations

In order to improve the outcome of this research in the future, several recommendations can be implemented. Among the suggestions for future work are:

1. Conduct testing for maximum weight of the design could withstand

   As for this thesis, the design only simulated to withstand a weight of 70kg. Accurate maximum weight that the design could withstand was never determined. Since there are still many people weighing more than 70kg, therefore the design should be tested for the maximum weight it could possibly withstand and the maximum load should be more than 70kg should this project is carried out in the future.

2. Development of graphical user interface

   By developing graphical user interface GUI, it will make the system becomes much easier to be used by user. User can predetermine the data that needed to be keyed-in by them such as the mass and length of leg.

3. Using two IMU

   Two IMU can be used for this study where one can be placed on the head of the knee while the other can be placed on the shank. This is similar to the method performed in one of the literature review provided in chapter 2. However, only one IMU sensor was used in this study due to fund and low expertise in programming for more than one sensor.

4. Using EMG

   Alternatively, strength performance could also be monitored using the reading of EMG signal. Through this method, muscle activity signal could be determined which is preferred for study of muscle strength.

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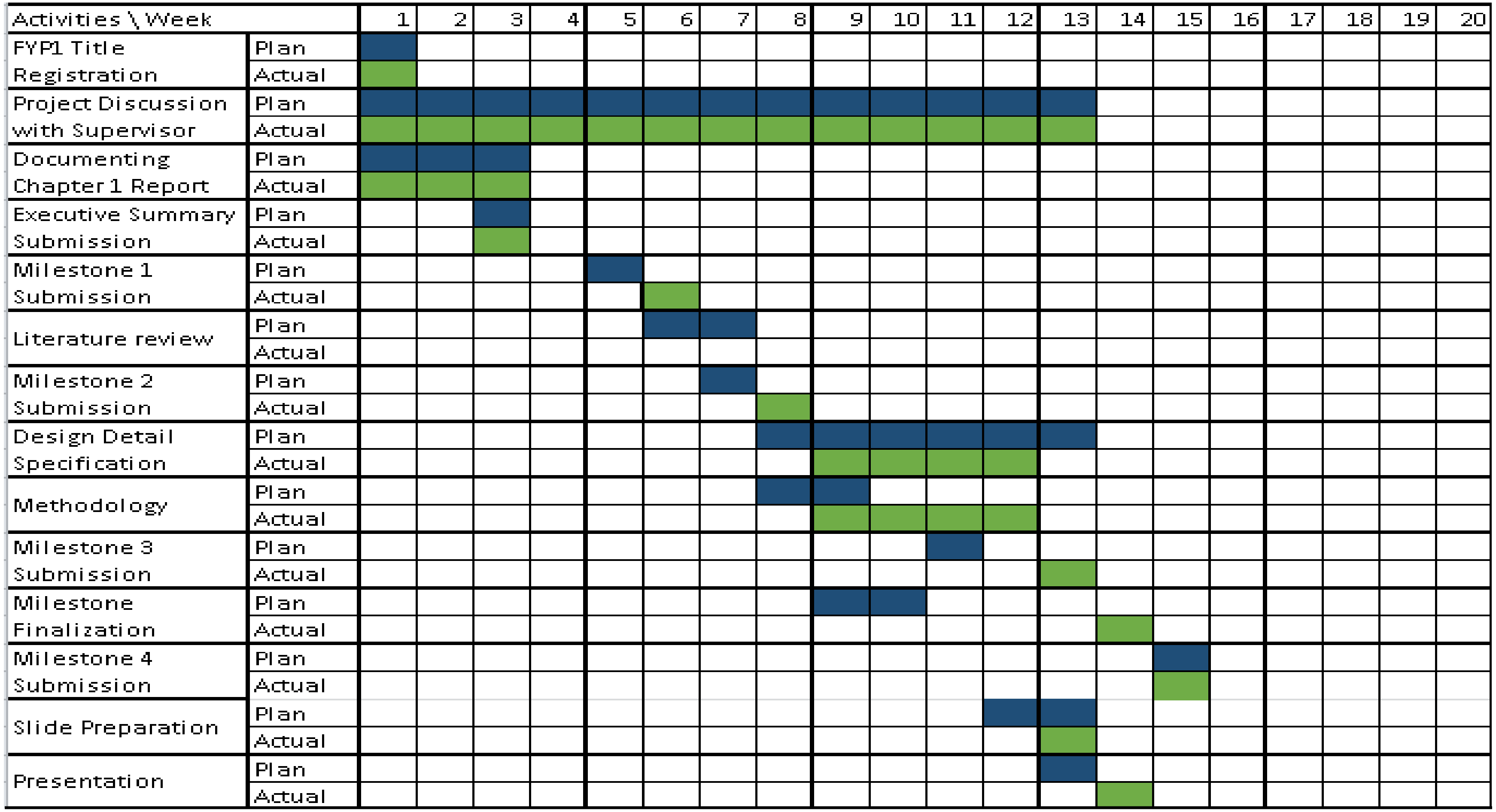
APPENDIX A

GANTT CHART FOR FINAL YEAR PROJECT 1



APPENDIX B

GANTT CHART FOR FINAL YEAR PROJECT 2

Activities \ Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Purchasing components	Plan																
	Actual																
Prepare material	Plan																
	Actual																
Finalize design	Plan																
	Actual																
Fabricating	Plan																
	Actual																
Circuit & programming	Plan																
	Actual																
Testing	Plan																
	Actual																
Data analysis	Plan																
	Actual																
Writing Chapter 4	Plan																
	Actual																
Correction chapter 4	Plan																
	Actual																
Writing Chapter 5	Plan																
	Actual																
Correction chapter 5	Plan																
	Actual																
Presentation	Plan																
	Actual																
Finalize thesis	Plan																
	Actual																
Thesis submission	Plan																
	Actual																