DESIGN AND DEVELOPMENT OF A LOCKING MECHANISM FOR A GEAR-BASED PROSTHETIC KNEE JOINT

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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ABSTRAK

Tesis ini adalah berdasarkan projeck mereka bentuk mekanisme untuk mengunci prostesis berasaskan gear. Mekanisme ini direka untuk membekalkan kestabilan kepada pengguna semasa berdiri supaya mengelakkan mereka daripada jatuh secara tiba-tiba. Projek ini mula dengan kajian tentang kitaran pergerakan manusia semasa berjalan, prostesis anggota bawah dan reka bentuk prostesis berasaskan gear. Kemudian, projek ini diikuti dengan pembangunan konsep reka bentuk mekanisme mengunci, penghasilan prototaip dan ujian fungsian prototaip. Akhirnya, reka bentuk dipilih adalah mekanisme yang menggunakan elektromagnet dengan litar kawalan untuk mengunci lutut prostetik. Elektromagnet telah digunakan dan dikawal oleh mikrokontroler untuk mengunci atau membuka kunci lutut prostetik melalui pengesanan kedudukan oleh sensor gyro semasa pergerakan paha. Semasa penghasilan prototaip, lutut prostetik berasaskan gear yang diubahsuai bersama dengan mekanisme pengunci yang dicadangkan telah dibuat. Kemudian, eksperimen dijalankan untuk menguji fungsi mekanisme pengunci dan prestasi keseluruhan lutut protetik berasaskan gear. Hasilnya menunjukkan bahawa mekanisme mengunci tersebut yang dimasukkan ke dalam lutut prostetik berasaskan gear berfungsi dengan baik dengan program yang dimuatkan ke dalam mikrokontroler. Mekanisme mengunci berasaskan elektromagnet juga membolehkan lutut prostetik berasaskan gear mencipta kitaran gait yang lebih dekat dengan individu yang sihat. Walaupun ukuran prestasi kestabilan tidak dapat dijalankan disebabkan ketidakadaan kemudahan ujian, tetapi masih jelas bahawa mekanisme penguncian lutut prostetik tersebut akan meningkatkan prestasi dari segi kestabilan dan keselamatan prostesis yang berasaskan gear tersebut. Untuk pembangunan projek ini dan kerja-kerja masa depan, beberapa cadangan telah dibuat untuk memperbaiki produk tersebut. Cadangan-cadangan tersebut adalah untuk memastikan produk ini sesuai dan selamat untuk digunakan oleh semua amputees.

ABSTRACT

This thesis is based on the project about design and development of a locking mechanism for a gear-based knee joint prosthesis. The purpose to design and develop the locking mechanism is to provide stability when the user is standing upright to avoid sudden buckling or falling down. The project is started with the study of the human gait cycle movement, lower limb prostheses and design of gear-based knee joint prosthesis. Then, this project is followed by conceptual development of locking mechanism, prototype development and testing of the prototype. The final design being selected is an electromagnet based locking mechanism with a control circuit. The electromagnet is controlled by a microcontroller to lock or unlock the knee joint via the position detection by a gyro sensor during thigh movement. During prototype development, the modified gear-based knee joint prosthesis with the proposed locking mechanism are fabricated. Then, an experiment is conducted to test the functionality of the locking mechanism and overall performance of the gear-based knee joint prosthesis. The result shows that the proposed locking mechanism incorporated in the gear-based knee joint is working well with the program loaded to the microcontroller. The electromagnet based locking mechanism also enabled the gear based knee joint to recreate the lower-limb gait cycle closer to that of a healthy individual. Although the measure of the stability performance is not possible due to the unavailability of testing facility, it is obvious that the knee locking mechanism would enhance the stability performance and safety measure of that gear based knee joint prosthesis to some extent. For the development of this project and future works, some suggestions are made for refining the product. The suggestions are to ensure the product is suitable and safe to be used by all the amputees.

CHAPTER 1 INTRODUCTION

A Prosthesis is an artificial body part replacing the missing extremity. The transfemoral lower limb prosthesis is comprised of some primary and supporting components. Though supporting, the knee locking mechanism is one of the essential elements of lower limb prosthesis construction, and for its effective functioning.

1.1 Research background

The number of amputees rises from year to year due to dysvascularity, trauma, infections, as well as traffic accidents. There are about seven million transfemoral amputees around the world [1]. The increased number of amputees all around the world has led to the rapid development of various types of the prosthetic leg. A lower limb prosthesis is defined as a device that substitutes the function of a missing limb either due to amputation or a congenital defect [2]. It is able to mimic the real leg and provide the basic functions such as walking, standing as well as recover their outer look. The development of prosthetic leg has brought a big impact to the amputees because it can restore their walking ability so that they can carry out their daily routines as normal people.

Basically, a good functional prosthesis should have reliable stability during support phase and controllable flexion and extension movement during swing phase in order to approach the human normal swing of the lower limbs, and maintain body balance and natural gait. There is some functional demand of above-knee prosthesis, which are security, light-duty and miniaturization, low-power consumption, personification and functional compensation domain. Moreover, the prosthesis should be comfortable, easily manipulated, low cost, high reliability, simple and compact structure [3]. Even though there are so many types of knee joint prostheses available in the market, the research and design for a more efficient prosthesis are never stopped because each of the amputees is unique and customization of the prosthesis is needed. Fitting prostheses that are not suitable to the amputee’s dimension will cause an array of problems with their gait dynamics, which in turn leads to physical pain [1].

Prosthetic knee joint plays an important role in transfemoral lower limb prosthesis. A good artificial knee should mimic the behavior of biological knee by providing natural kinematics, high strength and stiffness required in the stance phase [4]. Prosthetic knees can be categorized as mechanical passive, variable damping or semi-active and active mechanism [5]. Generally, the passive mechanisms do not have any external power source and are less adaptive to ground level or gait speed [6]. Compare to passive knee prostheses, variable-damping knee prostheses have better knee stability, more adapted to the changing environment, and able to change ambulatory speed. It improves gait symmetry, which decreases energy consumption and may lead to a reduction in degenerative musculoskeletal changes for the amputee [5]. For the active prosthesis, it has a control system and variable settings that allows the prosthesis to adapt in response to different walking speeds and ground conditions. Different types of sensors are utilized to provide interaction between the prosthetic knee and the external environment [7]. However, active knee joint is more expensive than the passive knee joint and thus causes the active artificial limb is not easily accessible to amputees in lower-income countries [8].

A gear-based knee joint is a type of mechanical knee joint consisting of two spur gears, two bushing pins, two bracing plates, U-shape brace, bracket, waist belt which make the shank follow the residual limb movements without having an external power supply. Figure 1.1 shows the components of the gear-based knee joint, including the guiding arrangement. In this design, a set of stoppers is screwed to the faces of each gear to prevent further movement of the gears when the user is at stance phase [9]. The function of the stoppers is to prevent over-rotation of gears. In a prosthetic leg, the design of the knee joint is the most critical. During stance-phase of gait, a stabilizing torque at the prosthetic knee axis is required to keep the user upright and to prevent falling down. The torque is typically applied via dampers, locks or brakes [10]. Without this locking mechanism, the risk of falling down or buckling when accidentally hit by something or someone is higher.

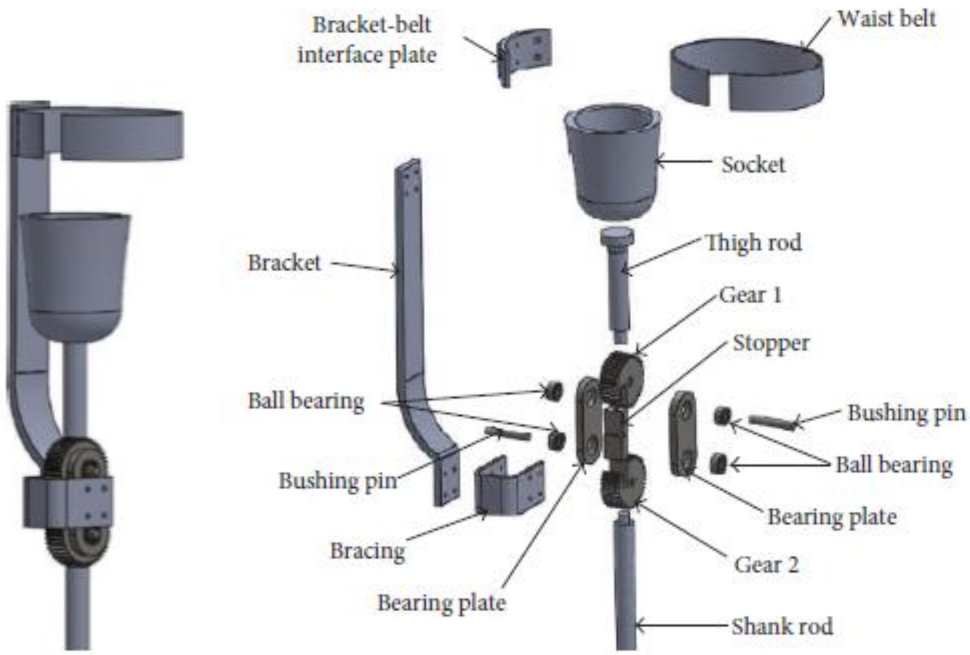


Figure 1.1: Gear-based knee joint components [9].

1.2 Problem statements

Previous researchers have been developed a gear-based knee joint prosthesis with a passive mechanism. However, the gear-based knee joint does not have an appropriate stance phase control or locking mechanism to support the user during stance phase to prevent unwanted jerking and sudden falling down. Since a good artificial knee joint should be able to support users during stance phase and provide flexibility during swing phase, thus a locking mechanism on the knee joint plays an important role to achieve this condition.

1.3 Objectives

The objective of this project is to design and develop an efficient locking mechanism for gear-based knee joint prosthesis to secure stance phase knee stability.

1.4 Scope of work

This research is focused on developing a locking mechanism for gear-based knee joint prosthesis to improve the stance phase control of the knee joint. The prototype of the gear-based knee joint prosthesis is developed in order to test the functionality of the locking mechanism to be introduced on it. The prototype is fabricated using the materials and equipment available in the School of Mechanical Engineering, Universiti Sains Malaysia. Besides, the function of the newly introduced locking mechanism in this research should be able to lock the knee joint during stance phase to support the amputee and unlock during swing phase when an amputee having normal walking on the ground level.

1.5 Thesis outline

Chapter 1 provides a concise background on knee joint prosthesis. The problem statement in this research and objective are presented. This chapter also contains the project scopes, project objective and outline of the report.

Chapter 2 of this thesis consists of literature reviews on lower limb prosthesis, types of knee joint prosthesis, human gait cycle. These literature reviews are made based on journals, review articles and conference papers as references.

Chapter 3 provides the methodology used in this research. This chapter will detail the methodologies used in each phase of this project from a preliminary study of gear-based knee joint until result analysis in order to achieve the objective.

Chapter 4 of this thesis will present the design of the locking mechanism with the modified gear-based knee joint and their fabrication process.

Chapter 5 of this thesis will discuss the result of data collected from the experiment and the performance of the proposed gear-based knee joint locking mechanism.

Chapter 6 consists of a conclusion of this project. Besides, some suggestions and recommendations are given for improvement in future research.

CHAPTER 2 LITERATURE REVIEW

The prosthetic lower limb is prescribed to the people who undergo amputation to recover their walking ability. A lower limb prosthesis consists of several components which the knee joint is the most important component among the others. A good prosthetic knee joint must able to assist the user to walk like normal people. In a prosthetic knee joint, the knee locking mechanism is an important feature to avoid buckling due to any unexpected incident which in turn protect the user from falling down. In the following sections, the literature regarding the human gait, lower limb prosthesis, types of prosthetic knee joint and knee locking mechanisms are undergo to provide background information prior to the design of knee locking mechanism of a gear-based knee joint prosthesis.

2.1 Gait cycle movement of human lower limb

Human gait consists of a synchronized and cyclic movement of each leg that helps a person to move forward. The knee and ankle joints are playing important roles in human locomotion because they are responsible for articulation, load-bearing, and the general dynamic control of an overall stable gait. However, limb amputation has interrupted this coordination [1]. The absence of function of the ankle and knee joints in transfemoral amputees commonly result in a number of deviations from normal gait and physiological deficits [11].

In biomechanical terms, the cyclic motion of walking is defined as the “gait cycle”. The gait cycle can be divided into two general phases which are stance phase and swing phase. The stance phase, also called the support phase, is defined as the time period of the cycle when the foot is in contact with the ground whereas swing phase is defined as the time when the foot is in the air [11]. Stance is divided into four phases which are heel strike to foot flat, foot flat through mid-stance, mid-stance through heel off and heel off to toe off whereas swing is divided into two phases: Acceleration to mid-swing and mid-swing to deceleration [12]. The normal human gait cycle is shown in Figure 2.1 whereas Figure 2.2 showing the phases of gait cycle for knee angle.

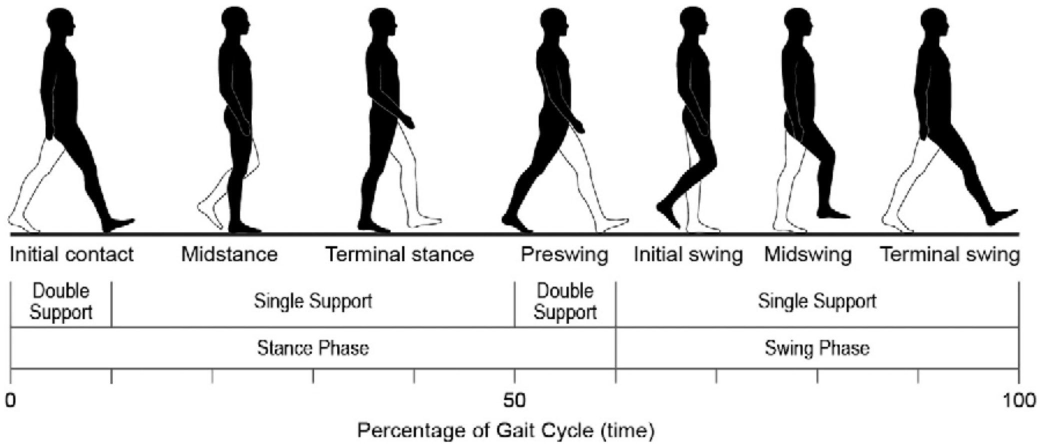


Figure 2.1: Normal human gait cycle [13].

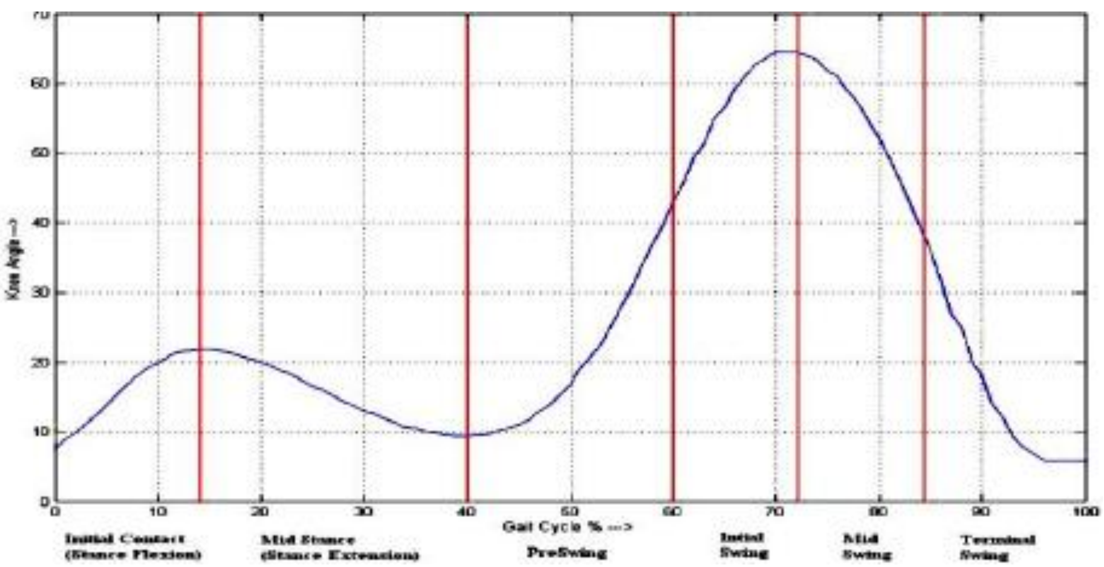


Figure 2.2: Phases of the gait cycle for knee angle [14].

2.2 Lower limb prosthesis

Above knee amputation, also known as transfemoral amputation, is a type of leg amputation that occurs between the knee and hip [5]. The lower limb amputees can be classified into a range of K-levels by providing a score (K0, K1, K2, K3, K4). Higher K-level (e.g. K4) indicates transfemoral amputees (TFA) with greater ambulation skills and exhibits performance of higher impact stress activities [15]. Usually, rehabilitation after amputation involves the use of a prosthetic limb as a substitute for the lost extremity and to restore much of the functional ability lost [16]. After an amputation, victims might face a lot of physical long-term such as phantom limb pain and psychological effects such as depression, anxiety and social discomfort [17]. Therefore, prosthesis plays an important role in helping the victims to restore their mobility and comfort their feelings as well as regain their self-esteem.

A lower limb prosthesis typically consists of a socket, knee joint and foot [16]. The sockets are usually custom fitted according to the anatomical shape in order to protect the residual limb and allow users to transmit the load to the rest of the prosthesis. The prosthetic knee joint is crucial to mimic the function of the normal knee whereas the foot is to provide a stable weight-bearing platform while offering mobility function by changing position and responding to ground reaction force vector (GRFV) during gait on different walking surfaces [11].

2.3 Types of prosthetic knee

Generally, the prosthesis knee joint can be classified according to their actuator schemes as passive, semi-active or variable damping and active devices [18]. Passive or variable damping knee prostheses are based on a mechanical hinge with speed and ease of swing controlled by the following mechanisms: free swing, manual lock, constant friction, weight-activated friction, geometric locking and hydraulics [6]. Passive prosthetic knees do not require a power supply to operate and they are designed mainly to provide stability during the stance phase of the gait cycle [5, 18]. Since they are not able to provide external power during the gait cycle, thus they cannot replicate the generative phases of the natural knee and also led to a challenge of stance control [19]. For active prosthetic leg, energy is being transferred from a power source to generate an active torque at the knee joint to allow prolonged use in a harsh environment [20]. Active prosthetic knees are based on programmable sensors that detect the angular position of the knee throughout the gait cycle and send an input signal to the prosthetic knee. In addition, the prosthesis also able to adapt in response to different walking speeds and ground conditions to prevent amputee from falling down due to the capability of the control system to deliver active response [6, 7].

There are 5 kinds of passive knee mechanisms, which are manual, single axis, poly-centric, knee with exterior hinges and weight-activated knee [1]. The single axis prosthesis works as a hinge, allowing flexion and extension by means of rotation about one axis [21]. Poly-centric knees are generally made of 4, 5 and 6 bar mechanism where the instantaneous center of the mechanism shifts during the gait cycle and locks based on the position of the shank with respect to the thigh in the gait cycle. Knee with an exterior hinge type mechanism was used earlier in the development of prosthetic knees and they assembled an orthotic device. Weight-activated knee mechanisms are often coupled with single axis knees to provide better locking [22].

Semi-active prosthetics for lower limbs are mainly controlled by microprocessors to assist the amputee during both the swing and the stance phase of the gait cycle. These prostheses are controlled by means of a variety of sensorial data such as inertial, force, angular or electromyographic. These common signals are used on the control systems to improve stability while modulating joint stiffness for different gait speed and terrain. However, these types of prostheses are limited to modulate joint stiffness during the stance phase of the gait cycle in order to improve walking stability and to transfer positive mechanical work to the joints [18]. Actuators for semi-active prosthesis have evolved from pneumatic to hydraulic and rheological devices. Pneumatic swing controls often have been recommended for slow to moderate cadence walkers whereas hydraulic swing controls allow amputees to walk at any speed if they are properly aligned and adjusted [23]. Some of the semi-active prostheses are Intelligent Prosthesis (IP), Ottobock C-Leg and Rheo knee (RK) [18]. The Blatchford Intelligent Prosthesis (IP) knee was the first commercially available prosthetic knee which incorporates microprocessor control of the swing phase of gait [16]. For Ottobock C-Leg, it can detects knee position, ankle force and torque, and provides adjustable damping for flexion and extension in swing, and additionally offers damping control throughout stance [24]. The Rheo knee is a microprocessor controlled prosthetic knee which is adaptable to different ground conditions using a magneto-rheological actuator. This actuator was developed at the Massachusetts Institute of Technology (MIT) to act as a brake dissipating energy during stance phase [18].

The working principle of an active mechanism is externally powered and controlled through embedded sensors to assist the amputee on activities of daily living. Some active prosthetic legs are Waseda Leg, Power Knee (PK), MIT Prosthesis, ANGELAA and CYBERLEGs [18]. The commercially available Power Knee by Össur uses an echo-type control approach based on the sensing of the sound side leg. Depending on the phase of the gait cycle and the posture of the limb, the microprocessor determines the required position of the knee and sends this information to the actuator, which moves the joint to the defined position [19]. The new second generation Power Knee delivers significant improvements in terms of weight, height and noise reduction as well as in power autonomy and ease of use [12].

2.4 Knee locking mechanism

Stance phase control is referred to as the resisting of knee flexion during weight bearing to achieve stance phase knee stability [25]. It is a very crucial feature that prevents the knee from buckling in the event of an accident or an unexpected change during gait control [7]. During the support, a stabilizing torque at the prosthetic knee axis is required to keep the user upright and to prevent falling. The torque is typically applied via dampers, locks or brakes. Effective knee joint control enables transfemoral amputees to walk in a functional, safe and efficient way [10].

For instance, single axis knee, which utilizes a simple pivot mechanism does not have stance control function and users often use a manual lock and available friction to prevent the leg from over-speeding during the forward swing when moving into the next step [7, 26]. Besides, single axis locking knee joints such as ICRC knee use a mechanical latch engaged by the user to provide extra stability. The LCKnee which developed by Andrysek et al., uses single-axis architecture with an automatic stance locking mechanism to lock the knee during early stance and unlocks it during late stance to enable late-stance flexion for the transition into the swing. A similar automatic stance locking mechanism was earlier developed by Farber and Jacobson [26]. For the weight-activated prosthetic knee, body weight is applied to it and friction lock will be activated to enable stance phase control [1].

Apart from that, the knee locking mechanism also implemented on a dynamically walking robot. Similar to lower limb prostheses, all dynamically walking robots with knees suffer from the problem of needing a knee locking mechanism. There are some locking mechanisms used on dynamically walking robots, which are mechanical latch and a solenoid used by 2D biped Mike by Wisse for unlocking, electromagnetic release system for a movable latch used on 3D walker by Collins for locking, and electromagnet with iron disk used on first version of bipedal walking robot Dribbel which developed at Control Engineering group of University of Twente for knee locking purpose [27].

2.5 Limitations of existing prosthesis

Single axis constant friction knee prosthesis stable only when the net ground reaction force passes anterior to the knee centre and only swing properly at one fixed cadence. This prosthesis with mechanical swing phase control is optimal only for those individuals who are not capable of varying their cadence. Manually locked knee prostheses normally are reserved for only the most feeble or unsteady amputee, because the stiff-legged gait that results is not only abnormal but also requires extra effort from the patient. Some mechanical knee prostheses also offer a simplified stance control knee prostheses based on weight-activated friction brake. However, such mechanical stance control knee prostheses are best suited for very limited ambulators who walk rather slowly [23]. Another disadvantage of the weight-activated knee is that it requires full removal of weight from the prosthesis for knee flexion to occur which in turn causes unnatural and delay initiation of swing phase [25]. Polycentric knee prostheses with friction swing phase control also suitable for those individuals who walk at one speed only. Compare to single axis knees, polycentric knees offer greater toe clearance at mid-swing [23]. Recently, a gear-based knee joint is designed to improve the performance of mechanical-type above knee prostheses due to the existing passive knee prostheses are unable to follow the real-time movement of the residual limb. It has been designed and developed to enable the shank of a lower-limb prosthesis to follow the movement of the thigh of a transfemoral amputee [9]. However, the lack of an appropriate locking mechanism has led to a challenge of stance phase control.

On the other hand, active knees are more expensive compared to passive knees [22]. Prosthetic knee joints in the United States and Europe cost several thousand dollars to manufacture and distribute. Furthermore, even the passive knee joints in developed countries are too expensive to meet the requirements of amputees in the developing world [26]. Besides, additional training is required to properly fit and fine-tune active knees, which hinders the widespread adoption of active knees [1]. For example, the system of Otto Bock C-leg is not user-adaptive because knee damping levels needed to be programmed to the amputee until the prosthesis is comfortable, moves naturally and is safe. Knee damping may not be set to ideal values which resulting in undesirable gait movement [24].

CHAPTER 3 METHODOLOGY

A preliminary study is conducted to understand the design of the gear-based knee joint prosthesis before proceeding to design a locking mechanism for it. The previous design of gear-based knee joint prosthesis consists of two important features, which are the set of stoppers screwed to the faces of each gear to prevent further rotation of gears and the bracket-bracing arrangement attached to the waist of amputees for supporting and balancing purpose. The overall design is able to allow the shank to follow residual limb movement [9]. Besides, various aspects which are relevant to the knee-joint prostheses have been reviewed, such as human gait, mechanism of different prosthetic knees and design of stance phase control in order to have a better understanding on the relationship between the gait of the user and design and functions of a prosthetic leg. Then, this project is started with conceptual design, followed by prototype development, testing on the proposed design of locking mechanism and result analysis on its performance. Figure 3.1 shows the flow of this project.

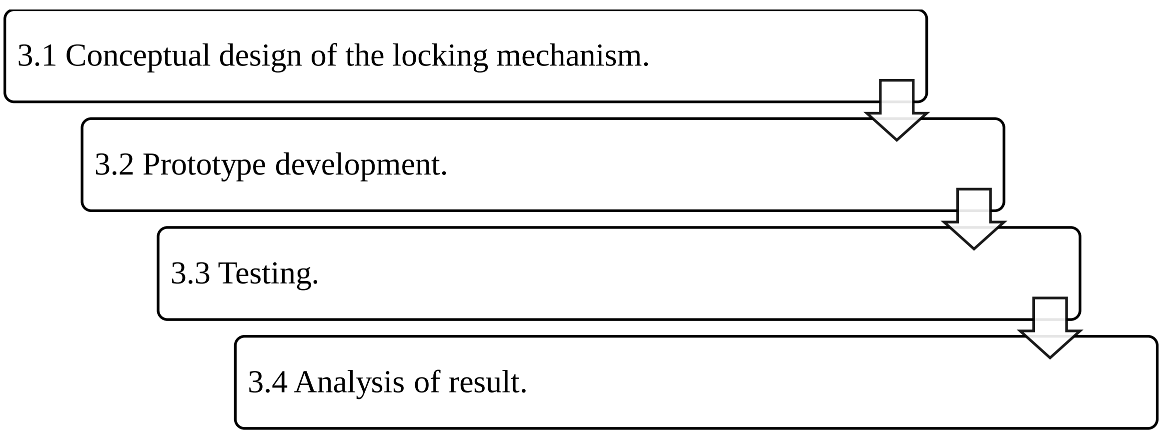


Figure 3.1: Flow chart of design and development of the knee joint locking mechanism.

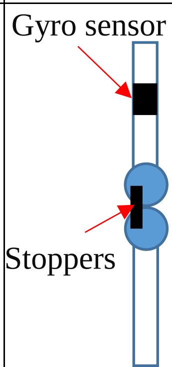
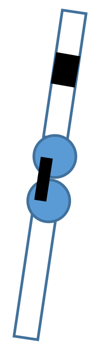
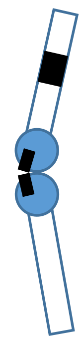
3.1 Conceptual design of locking mechanism

Brainstorming technique is used to generate ideas on the design of locking mechanism for gear-based knee joint. There are two designs being come out after brainstorming and only one is selected. The alternative being eliminated is due to its more complex design and less responsive compared to the other alternative. In the following section, only the design alternative being selected is discussed in the aspect of its overall design concept and working principle.

3.1.1 Overall concept of the locking mechanism

A control system is introduced to control the locking mechanism. In this design, a gyro sensor will be used to detect the angular movement of the thigh. Once the thigh is moved with a certain angle, the sensor will trigger a signal to unlock the knee joint. When the user is standing stationary, the knee joint will be locked to secure the user. This locking mechanism will be controlled by a microcontroller. The overall concept of the locking mechanism is illustrated in Table 3.1.

Table 3.1: Illustration of the locking mechanism.

Angular Displacement	0°	1°	2°
Knee Flexion			
Description	The knee is locked at this moment.	When the thigh starts to move, the knee joint will start to unlock.	At this moment, the knee joint is unlocked. The knee joint can be flexed.

3.1.2 Locking mechanism working principle

An electromagnet is used to lock the knee joint during stance phase. It is a product made by placing a metal core inside a coil of wire that is carrying an electrical current. When the electricity going through the wire, the magnetic field is produced. While the electric current is flowing, the core acts as a strong magnet. In order to ensure the electromagnet able to attract the shank rod for locking purpose, the electromagnetic force generated by the electromagnet and magnetic properties of the material being attracted are important.

The magnetic property of materials is referred to the magnetic permeability of a material, where it is the characteristic of a material which represent the establishment of an induced internal magnetic field by an external magnetic field. Permeability of material is defined as,

$\mu = \mu_0\mu_r$

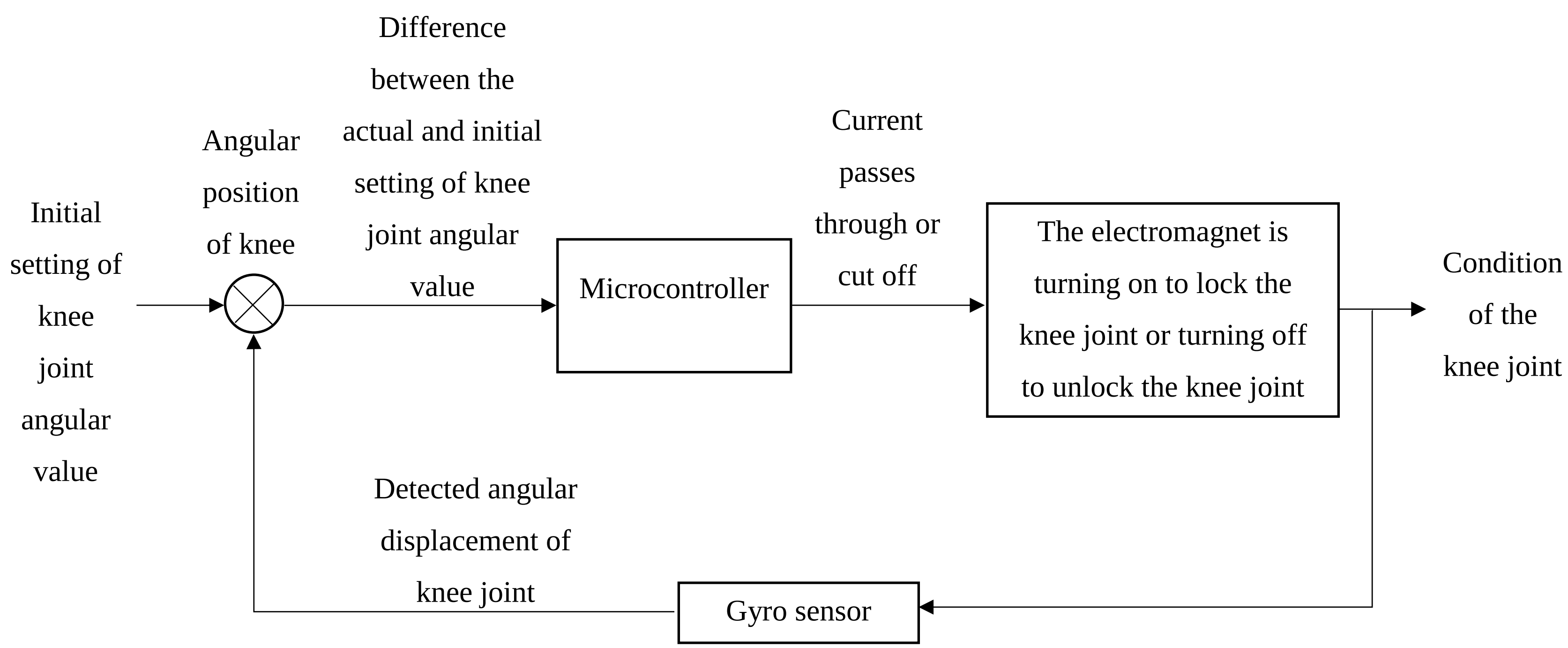
where

μ_0 is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ Henry/meter)

μ_r is the relative permeability of material ($\mu_r = 1$ for air or vacuum) [28].

Permeability of materials also used to indicate how easily the magnetic flux is build up in a material. It is also known as the magnetic susceptibility of material. Generally, the materials can be classified as diamagnetic, paramagnetic and ferromagnetic material. The diamagnetic material is weakly repelled by a magnet, paramagnetic material is weakly attracted by a magnet whereas ferromagnetic material is strongly attracted by a magnet. Paramagnetic materials, such as Aluminium, have relative magnetic permeability close to 1 while ferromagnetic materials, such as iron, can have relative permeability higher than 1×10^6 [29]. Thus, ferromagnetic material should be selected so that it can be strongly attracted to the electromagnet.

With the combination of microcontroller and electromagnet, the overall working flow of the locking mechanism is shown in Figure 3.2.



Figur e 3.2: Block diagram of the locking mechanism.

3.2 Prototype development

Before developing the prototype, the computer model of the knee joint prosthesis is constructed using SolidWorks. This allows the translation of the conceptual design into a visual representation. The model built includes the modification of the design of existing gear-based knee joint and also the fitting of the locking mechanism on the knee joint. The drawings are then used as a reference for the next process which is the fabrication process. At the same time, a circuit diagram is developed by using an online circuit design app, circuito.io to show the connections of all the electronic and electrical components. Then, a prototype of the gear-based knee joint with the integration of the locking mechanism is developed. The process of developing the prototype is shown in Figure 3.3. The fabrication is done in the workshop of School of Mechanical Engineering, Universiti Sains Malaysia. The new design of the gear-based knee joint and its fabrication will detail in Chapter 4.

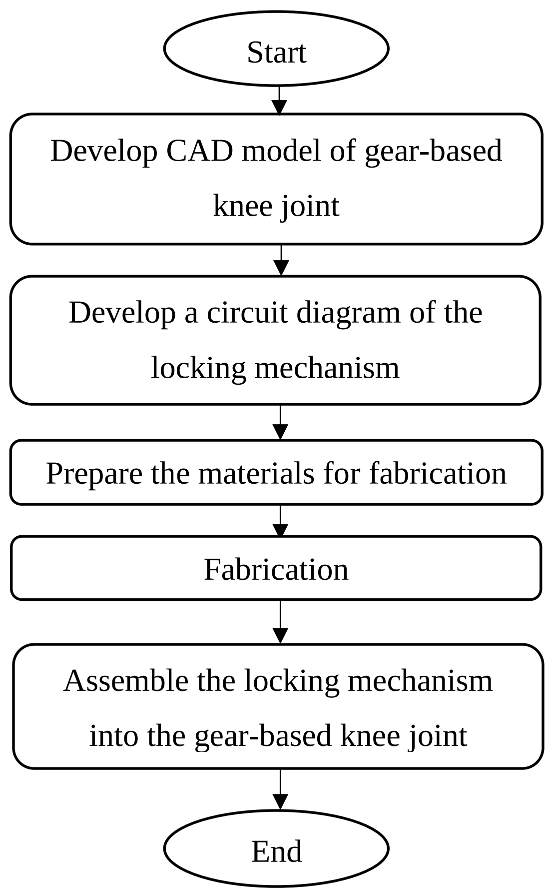


Figure 3.3: Process of prototype development.

3.3 Set-up of experiment for testing

The Arduino R3 UNO microcontroller board with the connection of all other circuit components is connected to the laptop via USB. The experiment is set-up as shown in Figure 3.4.

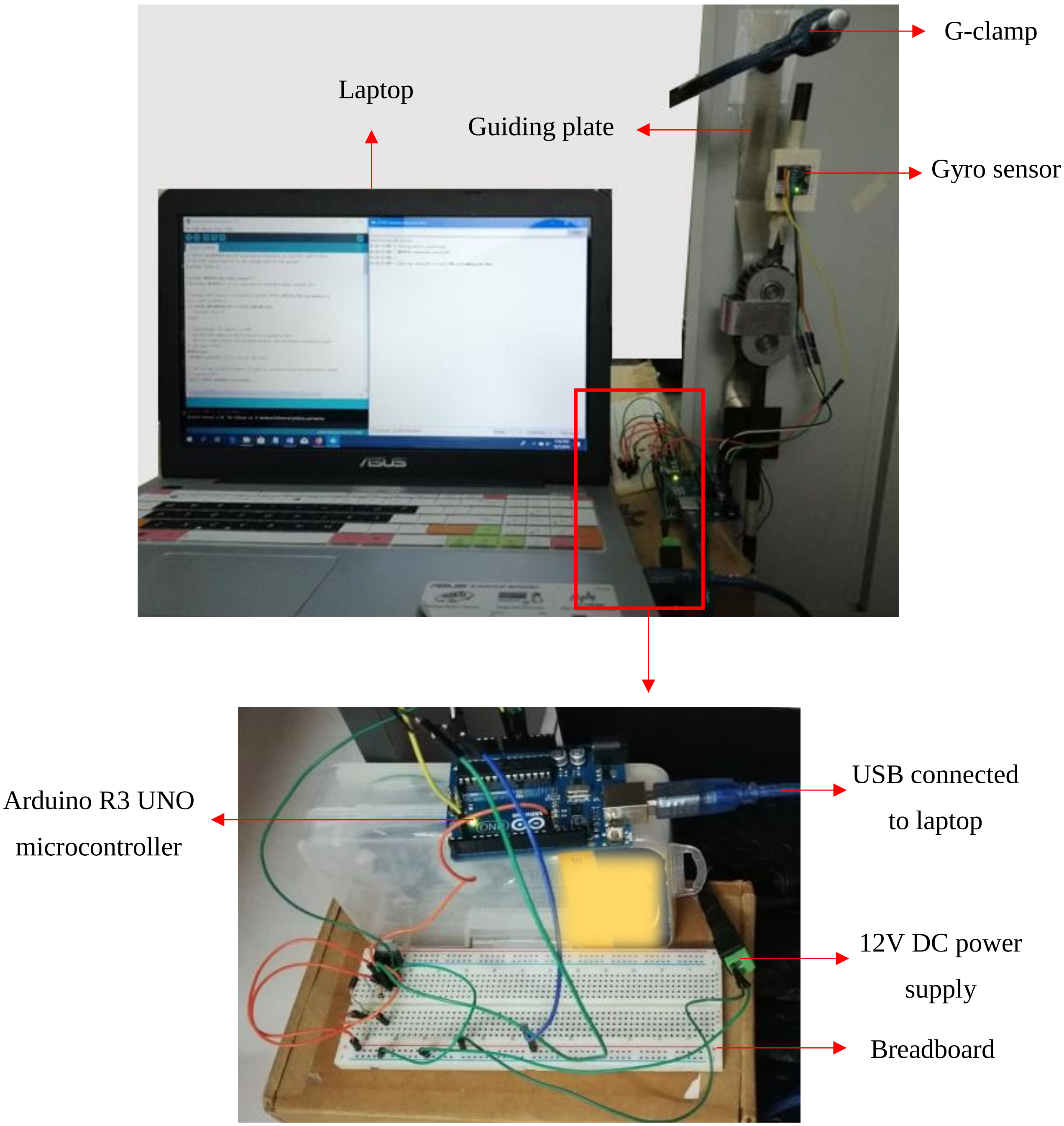


Figure 3.4: Set-up of the experiment.

Then, the experiment is carried out by following the procedure which is shown in Figure 3.5.

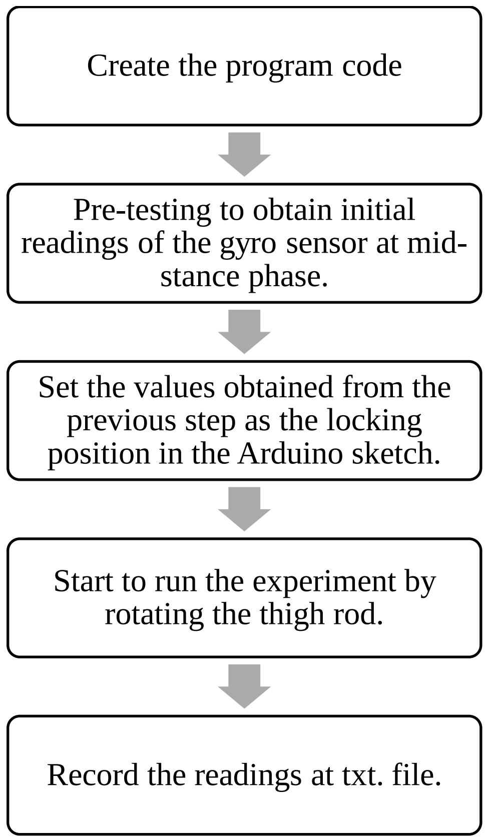


Figure 3.5: Procedure of experiment.

3.3.1 Program code development

Before starting to test the prototype, the coding to control the locking mechanism needs to be created. Arduino program is written in the Arduino Integrated Development Environment (IDE) and the programming language is similar to C language. After the sketch is written, it is uploaded on the Arduino board for execution. The algorithm of the program is shown in Figure 3.6 and the full program code can refer to APPENDIX B.

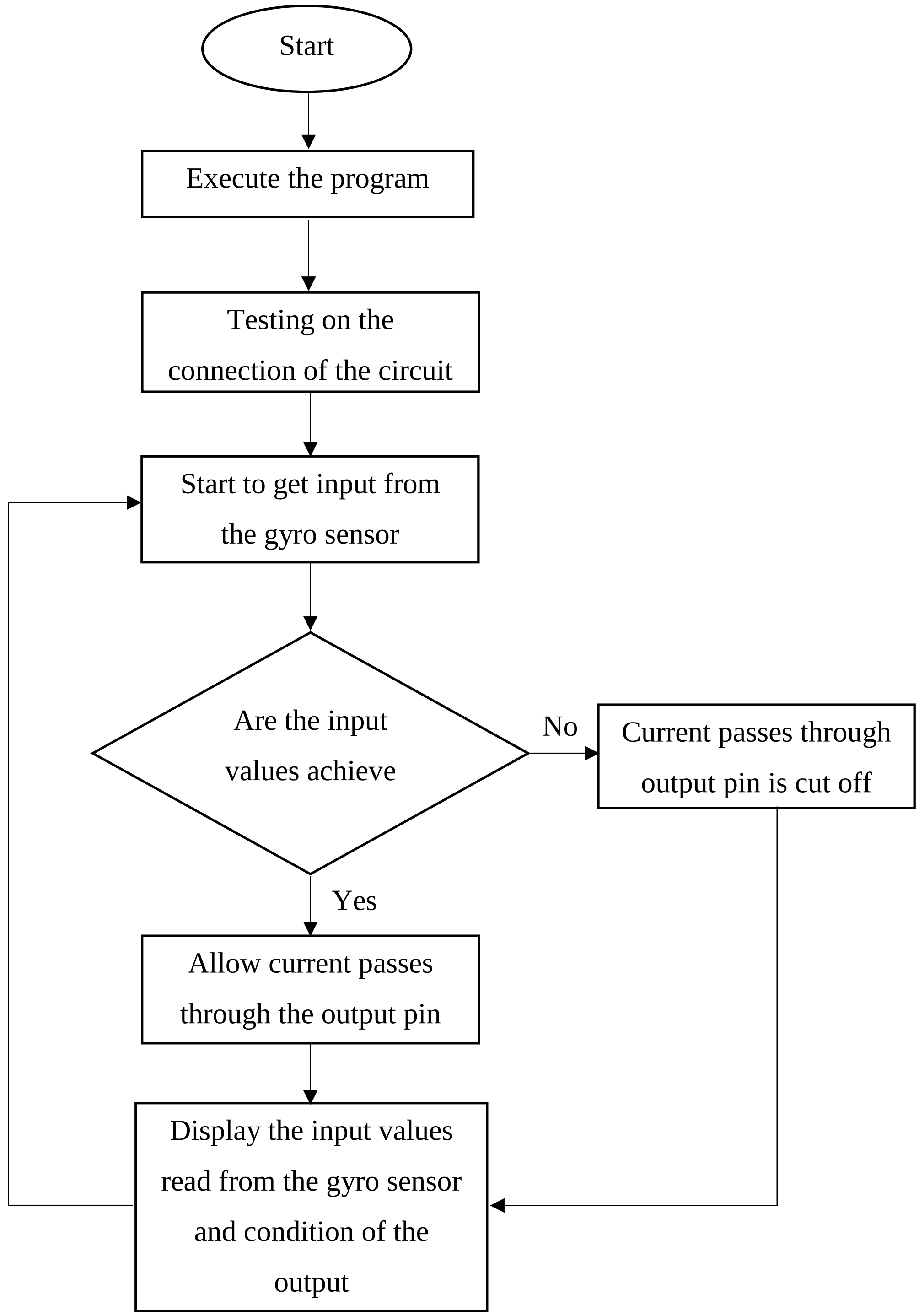


Figure 3.6: Algorithm of the program code.

3.3.2 Pre-testing

Before starting to collect the data, the initial values read by the gyro sensor need to be obtained. The program code, which also known as sketch is run on Arduino software and the readings of yaw (y), pitch (p) and roll (r) are generated in the serial monitor which are as shown in Figure 3.7.

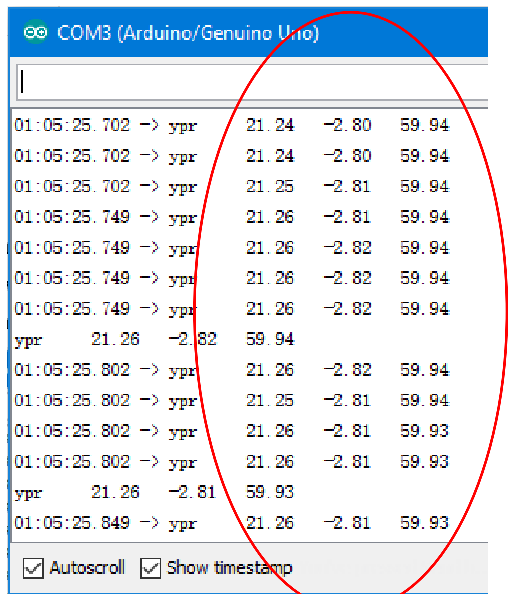


Figure 3.7: Angles detected by the gyro sensor are shown in the serial monitor of Arduino software.

Then, the values of p and r are put into the program to serve as the conditions to turn on or off the electromagnet. Figure 3.8 shows the main part of the program to control the output.

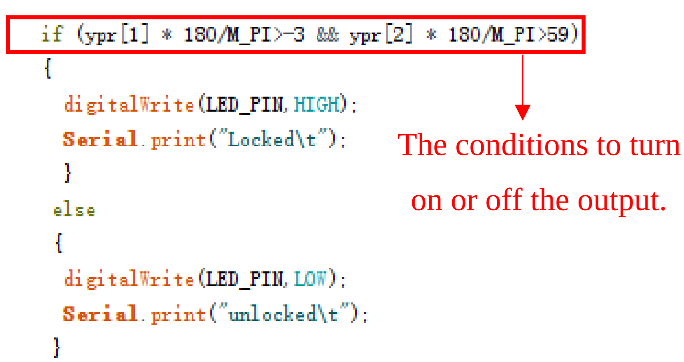


Figure 3.8: Main part of the program to control the output.

3.3.3 Data collection

After the values obtained in the previous step is put into the program code, the program is executed and at the same time start to rotate the thigh rod. The input values get from the gyro sensor and output status are shown in the serial monitor of Arduino software. Figure 3.8 shows the illustration of running the experiment whereas Figure 3.9 shows the illustration of the data collection.

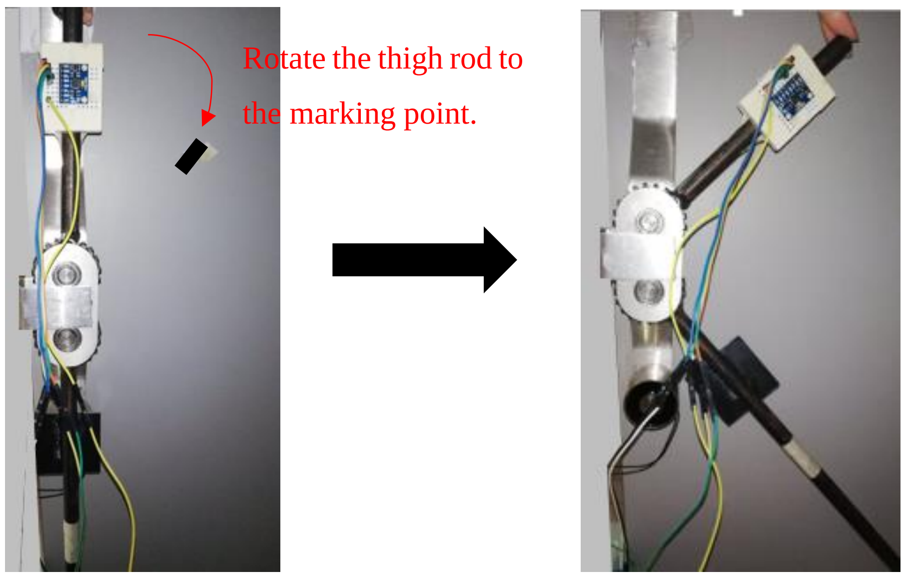


Figure 3.9: Illustration of the running experiment.

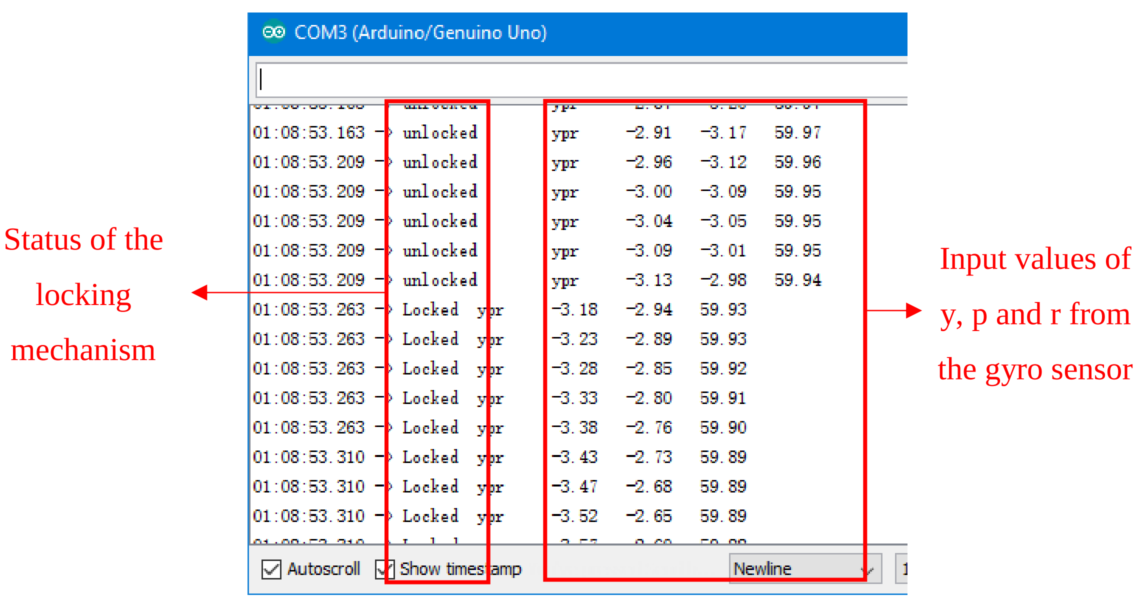


Figure 3.10: Illustration of data collection in the Arduino serial monitor.

3.4 Data analysis

The raw data from the serial monitor while running the experiment is saved in txt. file and then transferred to the Microsoft Excel. The performance of the locking mechanism is evaluated by calculating the standard deviation of the data collected when the output is on and off. Standard deviation is one of the measures of dispersion. It is a measure of by how much the values in the data set are likely to differ from the mean. The formula of standard deviation is given by

$$s = \sqrt{\frac{\sum (X - \overline{X})^2}{n-1}}$$

where

s = standard deviation

n = number of sample

X = each value of dataset

$\bar{X}$ = sample mean [30].

In this project, the mean value is the condition value set to lock and unlock the knee joint which gets after running the pre-test. The data obtained during locking and unlocking will be used to calculate how much it differs from the values set in the program.

Since the raw data obtained is the angle measured from vertical axis to the direction of rotation, the data is multiplied by -2 to get the knee joint angles due to the ratio of gear movement is 1:1. Figure 3.11 shows the illustration of the angle values obtained and knee joint angle.

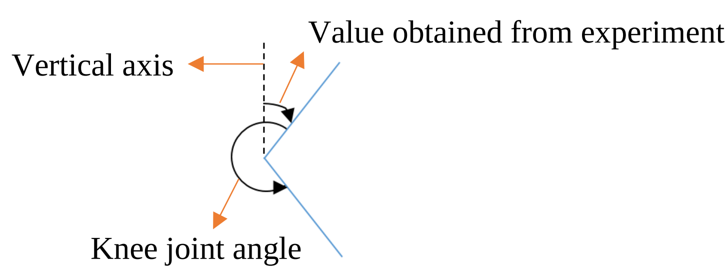


Figure 3.11: Illustration of the value obtained from experiment and knee joint angle.

Besides, three sets of data are obtained and the graphs of the knee joint angle against time interval are plotted by using the data obtained. Then, the graph is being compared with the normal human gait cycle for analyzing.

CHAPTER 4 DESIGN AND FABRICATION

An electromagnet based locking mechanism is designed for the gear-based knee joint prosthesis. To fit the proposed locking mechanism into the gear-based knee joint, some components of the existing design need to be modified. After finalization of the overall design, a prototype is fabricated. The fabrication of the prototype involves the knee joint prosthesis as well as the electromagnet based locking mechanism with the control system.

4.1 Design of locking mechanism

The final design of the gear-based knee joint with the integration of the locking mechanism is shown in Figure 4.1. The electromagnet is screwed to the guiding plate and a shank ring is placed opposite the electromagnet which screwed on the shank rod.

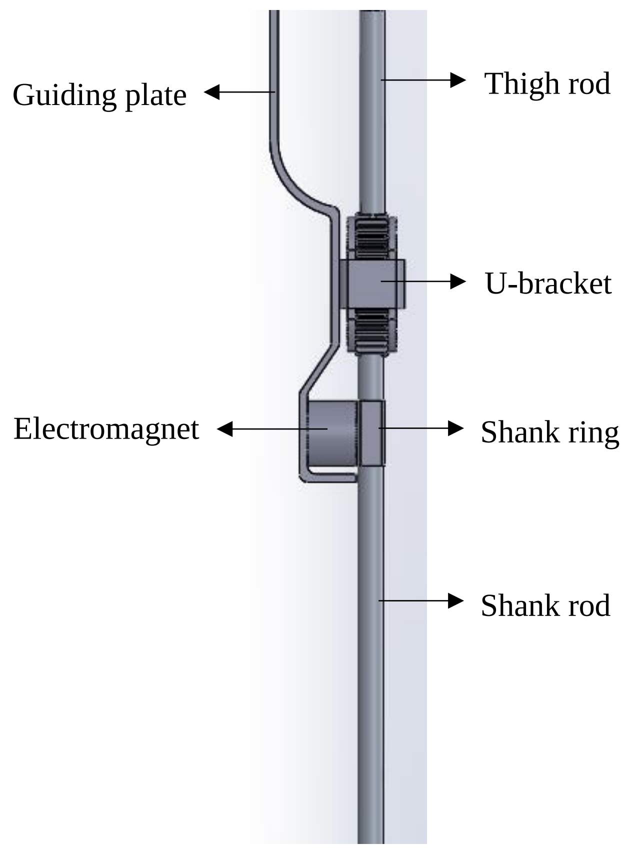


Figure 4.1: Final design of gear-based knee joint prosthesis with the integration of locking mechanism.

Compare to the original design, one component has been modified and one component is added in the new proposed design, which is guiding plate and shank ring respectively. These two components are shown in Figure 4.2 and Figure 4.3 respectively. For detail drawings of the components, can refer to APPENDIX A.

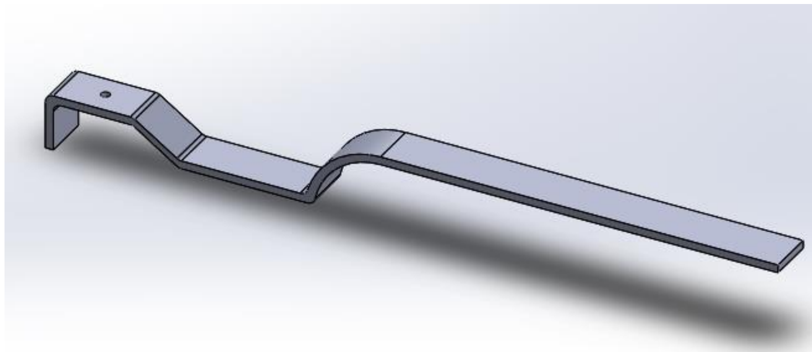


Figure 4.2: Design of guiding plate after modification.

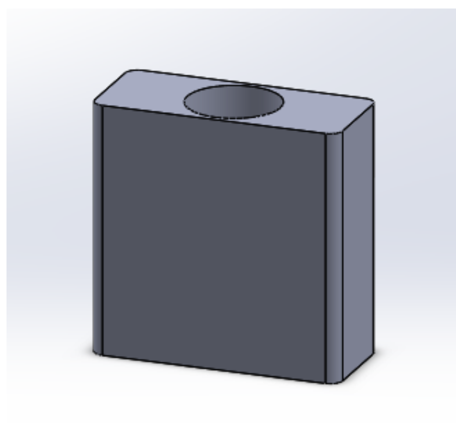


Figure 4.3: Design of shank ring.

In the previous design, the material of Aluminium alloy 1060-H16 is used for the shank rod [9]. However, the relative permeability of Aluminium alloy 1060-H16 is just slightly more than 1 which is considered very low and not able to be strongly attracted by an electromagnet to lock the knee joint. Therefore, a shank ring is being introduced in the design to solve this problem and ferromagnetic material, which is stainless steel (ferrite) is selected to make the shank ring.

4.2 Fabrication of locking mechanism

By referring to the engineering drawings created previously, the main components of the gear-based knee joint are fabricated. The prototype development is divided into two parts, which are the fabrication of gear-based knee joint and development of the control circuit to control the electromagnet. Then, the locking mechanism will be assembled with the gear-based knee joint.

4.2.1 Gear-based knee joint structure fabrication

A prototype of the gear-based knee joint is developed by using the available materials and facilities in the School of Mechanical Engineering, Universiti Sains Malaysia. The prototype is made up of thigh rod, shank rod, a pair of gears, U-bracket, guiding plate and shank ring. Table 4.1 shows the materials used to make each component of the prototype.

Table 4.1: Material used on each component of the prototype.

No.	Component	Material Used
1	Thigh rod	Mild steel
2	Shank rod	Mild steel
3	Gear	Mild steel
4	U-bracket	Aluminium alloy
5	Bushing pin	Mild steel
6	Guiding plate	Aluminium alloy
7	Shank ring	Mild steel

Due to time constraint and limitation on the facility in the workshop of School of Mechanical Engineering, Universiti Sains Malaysia, the prototype developed is more concerned on its functionality and not aesthetics aspect. The prototype developed is fitted with the locking mechanism and it is shown in Figure 4.4.