TRAJECTORY PLANNING OF HIP POWERED ORTHOTIC DEVICE USING CUBIC POLYNOMIAL EQUATION WITH VIA POINT

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A report submitted
in fulfillment of the requirements for the degree of
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2019

DECLARATION

I declare that this thesis entitled "TRAJECTORY PLANNING OF HIP POWERED ORTHOTIC DEVICE USING CUBIC POLYNOMIAL EQUATION WITH VIA POINT is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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I hereby declare that I have checked this report entitled "TRAJECTORY PLANNING OF HIP POWERED ORTHOTIC DEVICE USING CUBIC POLYNOMIAL EQUATION WITH VIA POINT" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother

SURIANI BINTI MOHD SAID

and father

MEOR AFFENDI BIN SHAARI

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ABSTRACT

Many robotic applications has been develop in this recent years and some of them encounters with human nature. Example of robotic application that associated with human nature is orthotic device, exoskeleton robots, humanoids, robotic arms and others. The development of orthotic device has the biggest impact among the lower extremity and disabilities patients. The purpose of this study was to develop a trajectory planning of human hips walking motion for the orthotic device in order to reduce the amount of jerk that occur during the walking motion. The objectives of this project is to design a trajectory planning using the cubic polynomial with via point and to evaluate the performance of motion in terms of angular position, velocity, acceleration and jerk in order to produce smooth motion. The scope of this project is to analyse the performance of jerk in human hips walking cycle based on the reference data of biomechanical human gaits with the method of cubic polynomial. In addition, the method used for developing the trajectory is cubic polynomial with via point. The via point is an intermediate point between the initial and final position path. This method is used to combine the initial and final position of the path to passing though the point in a smooth motion. The simulation of this project is based on the cubic polynomial with via point which generated by Matlab. Moreover, the evaluation of this experiment is based on the comparison graph by the experimental graph with the real-time human's hip walking motion graph. There are three type of profile generated in this project for 7-phase, 4 phase and 2 phase which is the angular position, velocity and acceleration. The results shows in implementing the cubic polynomial method is able to match the trajectory planning of a real-time human's hip walking motion for each profile. Other than that, in terms of error and accuracy show that position profile produce lower errors with 0.005028673 rad/s which provide higher accuracy in matching the reference graph of human hips motion. In addition, 7-phases provide a better performance in accuracy and error compares to 4-phase and 2-phases as shown in the result. Thus, by using the 7-phase profile is better in comparing the method of cubic polynomial with the reference human hips motion. Meanwhile, in terms of reducing the jerk to the smallest amount is not possible in this project due the amount of jerk that presented during terminal swing at 0.87s is higher with the value of 167.1771093 rad/s^3 .

ABSTRAK

Kebanyakan aplikasi robot telah berkembang untuk bertahun-tahun sejak kebelakangan ini dan kebanyakan robot aplikasi ini mempunyai kaitan dengan tubuh badan manusia. Contoh-contoh aplikasi robot yang mempunyai kaitan dengan sifat manusia adalah, peranti orthotic, robot exoskeleton, humanoids robot, robot yang berbentuk tangan dan lain-lain. Selain itu, perkembangan alat peranti orthotic ini mempunyai impak yang besar dan positif terhadap pesakit-pesakit kurang berupaya. Tujuan kajian ini adalah untuk membangunkan perancangan trajektori terhadap pergerakkan pinggul manusia semasa menggunakan peranti orthotic, supaya dapat menggurangkan jumlah pergerakan yang berlaku secara tiba-tiba atau dikenali sebagai "jerk" semasa pergerakkan berlaku. Objektif kajian ini adalah untuk mereka bentuk perancangan trajektori menggunakan polynomial kubik pada sebuah titik dan untuk menilai prestasi gerakan dari sudut sesuatu tempat, halaju, pecutan dan "jerk" yang terhasil supaya dapat menghasilkan gerakan yang lancar. Manakala, skop untuk projek ini adalah untuk menganalisis prestasi " jerk " terhadap pergerakan pinggul manusia berdasarkan rujukan data dari biomekanikal gaits manusia dengan kaedah yang digunakan. Di samping itu, kaedah yang digunakan untuk mencipta trajektori adalah dengan menggunakan polynomial kubik melalui sebuah titik. Titik yang dibincangkan di dalam projek ini merupakan sebuah titik diantara kedudukan laluan pertama dan terakhir. Kaedah ini digunakan untuk menggabungkan kedudukan awal, akhir dan kedudukan halalaju untuk memastikan pergerakkan tersebut adalah lancar. Simulasi yang digunakan untuk projek ini adalah berpandukan kaedah polynomial kubik dan dihasilkan menerusi perisian Matlab. Di samping itu, penilaian eksperimen ini adalah berpandukan graf melalui perbandingan diantara eksperimen graf dengan graf pergerakan pinggul manusia yang telah dikaji. Terdapat tiga jenis profil graf yang dinilai di dalam fasa 7, fasa 4 dan fasa 2 untuk projek ini iaitu graf kedudukan sudut, halaju dan pecutan. Keputusan menunjukkan dalam melaksanakan kaedahpolynomial kubik dapat mengikuti pergerakan asal trajektori pinggul manusia untuk setiap jenis profil. Selain itu, dari segi ketepatan dan ralat menunjukkan bahawa kedudukan profil menghasilkan ralat-ralat lebih rendah dengan 0.005028673 rad/s yang memberikan ketepatan yang lebih tinggi terhadap pergerakan asal pinggul manusia. Di samping itu, 7-fasa menyediakan prestasi yang lebih baik dalam ketepatan dan ralat berbanding fasa 4 dan fasa 2 seperti yang ditunjukkan dalam hasil keputusan. Oleh itu, dengan menggunakan profil fasa 7 adalah lebih baik dalam membandingkan kaedah polinomial kubik dengan rujukan asal pergerakan pinggul manusia. Sementara itu, dari segi mengurangkan " jerk " dengan jumlah yang paling kecil adalah mustahil dalam projek ini kerana jumlah " jerk " yang terhasil adalah tinggi pada 0.87 saat semasa fasa terminal swing dengan jumlah sebanyak 167.1771093 rad/s3.

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LIST OF SYMBOLS AND ABBREVIATIONS

SCI	-	Spinal Cord Injury
Rad		Radians
$\vec{\mathbf{j}}(\mathbf{t})$	-	Jerk
$\vec{a}$	-	Derivative of Acceleration
$\vec{r}$	-	Derivative of Position
$\vec{v}$	-	Derivative of Velocity
t	-	Time (s)
$\theta(t)$	-	Position Profile (s)
$\dot{\theta}(t)$	-	Velocity Profile (rad/s)
$\ddot{\theta}(t)$	-	Acceleration Profile (rad/s^2)
$\dddot{\theta}(t)$	-	Jerk Profile (rad/s^3)
t_0	-	Initial time (s)
t_f	-	Final time (s)
θ_0	-	Initial Angle (degree)
θ_f	-	Final Angle (degree)
v_0	-	Initial Velocity (degree/s)
v_f	-	Final Velocity (degree/s)
RMSE	-	Root Mean Square (rad)
AD	-	Average Difference (rad)
n	-	Number of Trial
T_{Ref}	-	Reference Trajectory
T_{Gen}	-	Generated Trajectory

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CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter gives a brief explanation about the research project on the trajectory planning in minimizing the amount of jerk that produce in orthotic device. The project consists of motivation, problem statement, objectives, thesis contribution and scope of work. Lastly, the description of the content for each chapter is presented.

1.2 Motivation

Many disease causes gait disorder or movement disorder which carries to imbalance walking pattern, falling, disability and others. For example, stroke, spinal injury, cardiac illness, cerebellar disease, accidents or others condition which can cause disabilities. A rehabilitation device is introduce in this modern world for people that have a walking disabilities. The orthotic device are known with their capability to support and help a lower limb extremities patient for their rehabilitation phase. In addition, the device is essential to move symmetrically to human walking cycle and able to duplicate the movement efficiently. The development of orthotic device also can help the lower extremities patient to regain their walking abilities again.

In Malaysia, based on the World Health statistics report by World Health Organization's (WHO) in 2013 stated that about 8% percent of Malaysian community are above 60 years old is in a good health condition. Meanwhile, in 2011 of annual report by the Malaysian Ministry of Health's reported that children aged between 0 to 18 years old are detected with physical and cerebral palsy disabilities are about 11% and 7.2% percent [1]. As the percentage above-mentioned, the gait disorder also can affects the range of age between those groups and it is not a common thing amongst them [1]. In this advance technology, the development of powered orthotics devices became a feasible solution to regain walking ability which could improve their walking capability during the rehabilitation phase and by planning a trajectory for the orthotic device are able to create a smooth motion towards the device.

1.3 Problem Statement

The orthotic device is an equipment that applied to the human body to support, correct deformities or improve the movement of joints or limbs on human bodies. Meanwhile, the movement of the device must be imitating the human walking cycle in real-life. Therefore, by implementing trajectory planning allows motion of the device to move in a stable phase from its starting configuration until the final configuration, in order to achieve the required goals. However, undesired motion or a sudden movement are known as the jerk is occur during the motion cycle of the device and may affect the stability of the device. A method or technique are needed to be defined for trajectory planning to minimize the amount of jerk occurs on the device for efficient walking gaits.

On top of that, the accuracy of stability during the walking motion with varies of speed also need to be considered that may be affected by the jerk .Thus, the parameter need to be study is the angular position, angular velocity, angular acceleration and jerk. The amount of rotation that required to change the orientation from one to another about a specified axis are expressed from the angular position of a body orientation with respect to a specified reference position. The changing on the angular position may influence the orientation of the device where the increases amount of orientation provide a smooth walking which proportional to the human walking gaits.

In planning a continuous path, the angular velocity of the joint is required when assigning a constraint on the path planning. The value of angular velocities is essential in order to connect between two consecutive points with the intermediate point. Therefore, when controlling the robot motion between two paths points it must be in continuous state for velocity and positions. Furthermore, the initial and final position of joint angles must matched with the given angles. Thus, the velocity values in planning a trajectory must not equal to zero in order to create a smooth trajectories. The purpose of velocity is useful in providing a continuity on the acceleration of the path point.

Therefore by implementing the method of cubic polynomial with via point able to solved the problem of reducing jerk because jerk can be limited by smooth acceleration and deceleration. A research question is developed to determine the technique or method of walking motion that can provide a higher stability and minimum jerk to the orthotic device with varies speed.

1.4 Objectives

The objective of the project is:

1. To design and develop a trajectory planning using the cubic polynomial with via point in order to reduce jerk motion.
2. To evaluate the performance of the motion in terms of angular position, angular velocity, angular acceleration and jerk towards the orthotic device.
3. To validate the accuracy of the proposed method in reducing a jerk motion by comparing the experimental data with the real-time data of normal human walking gaits.

1.5 Scope

The scope for this project is to design the trajectory planning of hips motion on the orthotic device and the method used for designing the trajectory is the cubic polynomial with via point. Moreover, the purpose of designing the trajectory planning on the orthotic device is to reduce the amount of jerk produce during the motion. A few variables need to be consider while planning the trajectory which is the angular position, angular velocity, angular acceleration and jerk during the motion. The tools used to examine this project is by using the MATLAB software in order to generate the graph for the result. This project is based on the comparison graph between the experimental methods with the real data of hips of human walking gaits. The real data is derive from the research of multi-task gait analysis which develop by Bovi G, Rabuffetti M, Mazzoleni P and Ferrarin M [23]. It contain a research of human walking cycle staring from the ankle, knee to hips. The main part of analysing the motion of human body is too focused only on the movement of the hips.

CHAPTER 2

LITERATURE REVIEW

2.1 Background Theory

Nowadays, robotics has the bigger impact on humanity where it can be implemented in the human or industrial environment. Therefore, a lot of effort are presented in robotics in order to help patients with lower extremity injuries for physical rehabilitation that caused by a different type of paresis such as the spinal cord injury (SCI), stroke and unilateral lower limb disorder [2]. In the area of robot-assisted rehabilitation, various exoskeleton, and orthotic device have been presented each year for the upper and lower extremities for people that have a permanent injury due to stroke or accidents in their therapy to regain walking ability. The existence of this robotic system is to solve problem of damage parts at the lower limb of a human's body, such as knee, hips or ankle. The exoskeleton device is an efficient device that can conduct a training rehabilitation and physical therapist for the lower extremity patients [3]. Thus, it is a good way to help these patients to recover and regain mobility.

A few years ago, rehabilitation therapy are widely used due to the increasing number of disability patients which made the medical centres enthusiastic to develop an efficient and reliable method to treat the patients rather than used a traditional methods [4]. The weakness of using the traditional method is the therapy treatment may require two or more therapist to assistance one patient in moving the effected part of the patient manually for example the leg. Moreover, the treatment are done at least twice a week and the cost charged for the treatment are much higher. Therefore, by using the robotic system device could reduce the amount of therapist in assisting on one patient [5][6][7]. The understanding of human walking gaits is an easy task but implementing the gaits on the machine are more complex and challengeable [8]. The movement of the device must be imitating the walking pattern of a human limb, therefore, the device must be lifelike with a minimum jerk so the machine could adapt the walking gaits efficiently. Jerk is known as the rate of change of acceleration with respected with time or in other word it is an abruptly motion that occur during the movement. In the studies of robotics, to produce a motion that matched to real-life human and less jerk are by planning a trajectory on the device. The next subchapter will describe more on the topics that encounter in this project.

2.2 Overview of human walking cycle in robotics application

For the past years, many researcher has been paid more attention to studying human walking. There are an increasing enthusiasm among the researcher to research the human walking cycle due to predictive abilities and potential applications in the areas of clinical biomechanics, rehabilitations engineering, neurosciences and robotics [8][9]. The importance of human walking cycle in robotic application is the stabilities and efficiency of the device. Thus, in normal walking gaits, the motion must depend on continual interchange between mobility and stability [8].

The understanding of human walking cycle is desired in any application of robotics that associated with human like characteristic. Nowadays, many invention of application in robotics has already associated with human physique. An example of robotic applications that associate with human characteristic is the exoskeleton device, orthotic device, humanoid robots, robotics arm and others. The human walking cycle is a repeated pattern of a human movement which involve steps and strides. A steps describe as a single step, while a complete gait cycle is called as a stride. The step time is define as time period between a heel strike on one leg and the contra-lateral legs [10]. The human walking gaits are well described in the research of biomechanics.

Humans walking motion generally tend to move their body in forward position towards a desired location and speed for moving forward. Then, in the walking principle, by using a least amount of energy it is possible to achieve the initial goals and humans body tend to move in a straight line while moving in forward position. Besides that, the most efficient energy of movement is when the body figure moves up and down with a small energy used. In addition, our brain usually generates information to the feet to act as a shock absorber while implement a less pressure in walking for excluding the force that exert on the body as it landed. Meanwhile, the feet of the body must form a rigid lever towards the end phase when the foot touches the ground for providing a motion to propel the body to move forward.

2.3 Types of Motion

Trajectory planning of a lower limbs can be generate based on a different phases. The phases of one gait cycle can be categorized into three types which is the two phases or known as the stance and swing phase, four phases (Double stance, Single stance and Swing) and seven phases (Heel strike, full foot, Mid-stance, Heel off, posterior swing, Mid-swing and Anterior swing) as illustrated in Figure 2.1 [11][12]

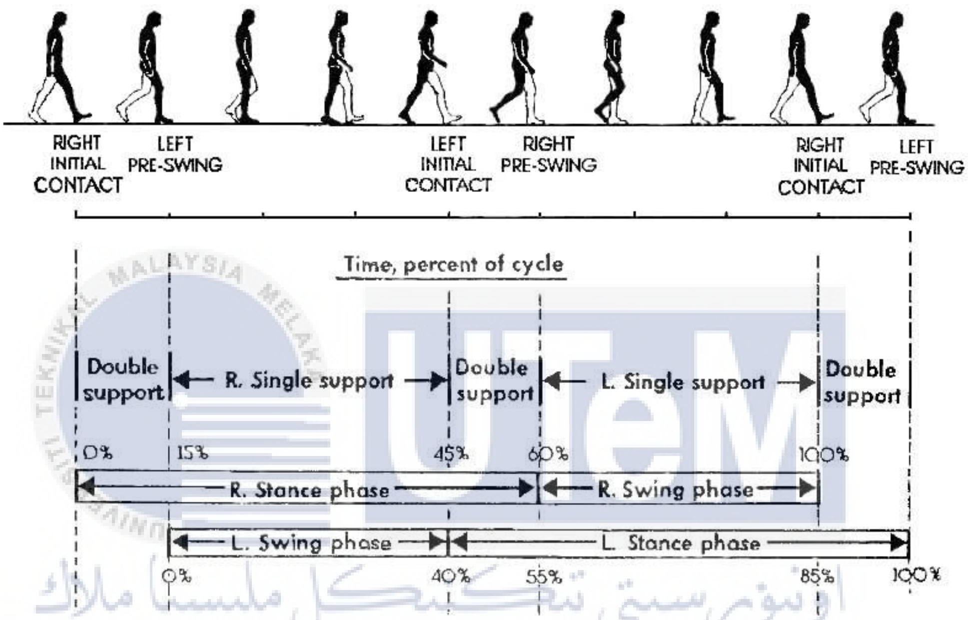


Figure 2.1: Walking Gait Cycle based on different Phases [13]

The figure shown above contains all three categories of walking gaits which develop from the reference of biomechanical analysis in human gait motion. In addition, the sequence of motion is initiate from the initial contact of heel on the ground however the toe are not yet touch and the motion is continuous with interchange from both leg until it reach the final contact or position. The advantages of using the phases of gait motion is to facilitate the planning of trajectory while avoiding the error that occur during the implementation of trajectory. It is due to the requirement of sequence of motion for hip, knee and ankle joint [12]. In this project, the implementation hips motion of seven phases profile will used as a reference data for developing the trajectory planning in the experimental part.

2.3.1 2 Phase (swing and stance phases)

There are two phases of a human walking process which is the stance phase and swing phase in human cycle. Stance is describe as the period of gait cycle during the interaction of foot with the ground while swing is the vice versa from the stance. The stance phase engage the gait cycle about 60% percent while the swing phase initiate only about 40% percent of human walking gaits and the motion involve is a combination of open and close chain activities [14]. The motion of swing phases produce shortest time period about 40% in full trajectory compared to the stance phases [12]. Based on the Figure 2.2 a single support position is occur along the whole trajectory of swing phases. Stance phase is the phase where the initial contact of the motion is occur, when the heel begin to touch the ground but except the toes [14]. Then, the walking motion continues until the mid-stance phase before changing to other phases.

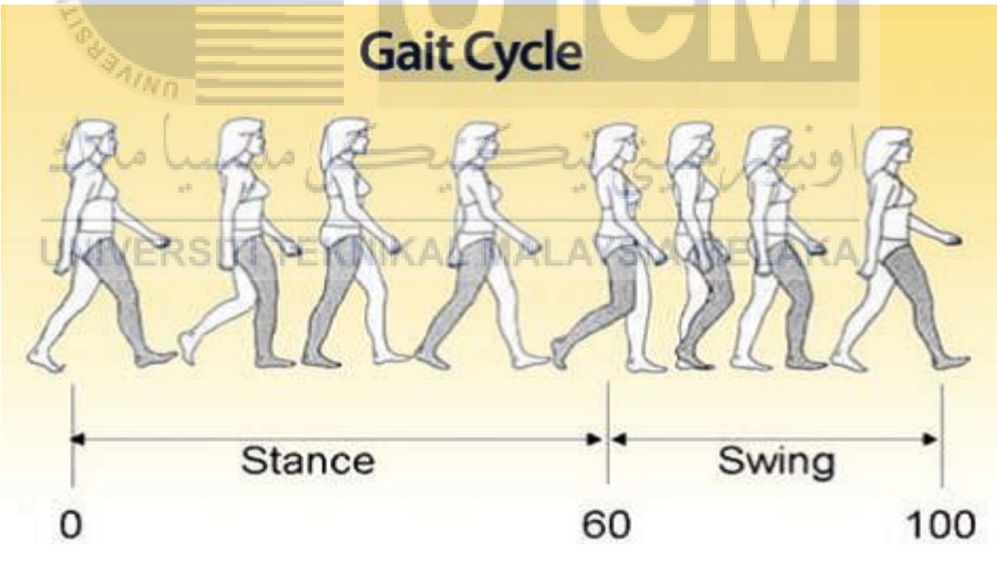


Figure 2.2: The phases of stance and swing cycle

2.3.2 4 Phase (Single and Double Support Phase)

Double support phase contain the gait cycles about 30 % percent of the human walking gaits that occur only on the stance phases. The double support phase is initiate when both feet is contacted with the ground. It is occur when one limb is at the finale stance phases and the contralateral limb is begin at the stance phase. In addition, if the gaits move in a faster state, the double support time will be lessen and it is vice versa with a slower gait motion. Meanwhile, in single support phase contains about 12 % to 50 % percent of the gait cycle. The motion are begins when only one of the foot is contacted with the ground. In other terms, it begins with opposite toe off and ends with an opposite foot strike. There are two period which associate with the single support phase which is the right stance and the left stance.

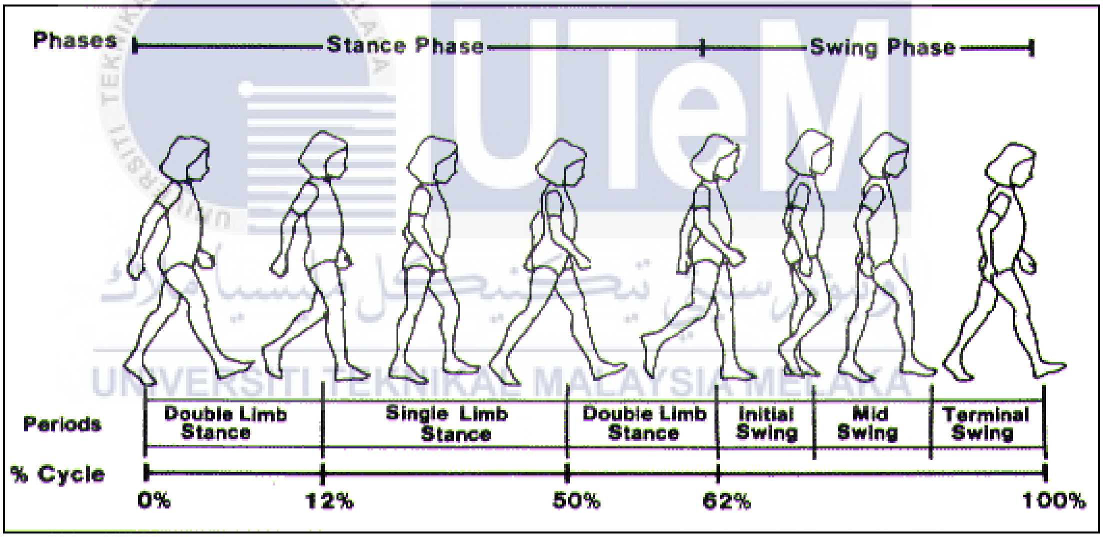


Figure 2.3: The single and double support phase during the stance phase

2.3.3 7 Sub Phases

From the two phases of human gait in Figure 2.2, the gait is separated by eight types of human walking motion which is the initial contact, loading response, mid-stance, terminal stance, pre-swing, initial swing, mid-swing and finally the terminal swing as shown in the Figure 2.3 [11]. The heel strike or known as an initial contact of foot to hit the ground. Initial contact is a phase for shock absorbing, provide limb stability and contain forward progression. The second phase is describe as the loading response which act as a shock absorber from the ground reaction during the knee flexion phase. Mid-stance phase is initiate after the process of second phases. Mid stance starts during the opposite reference foot is raised from the floor and end with a vertical position of contralateral tibia. Moreover, the purpose of terminal stance is to initiate the body in order to passing through the supporting foot. The fifth phase of human gaits is the pre-swing phase. The goal in this gaits is to position the limb for a swing motion or in other words is the weight release. The beginning of initial swing is when the ipsilateral foot is raised from the ground and ends during the swinging foot is opposite to stance foot. Meanwhile, mid swing phase produce once the swing foot crosses the stance foot and ends when the tibia of swing limb achieve at vertical position. The last phase of the human cycle is the terminal swing. The purpose of the last phase is to complete the motion of the limb movement and to prepare for the next phase. Figure 2.4 shows the flow of human walking motion in one gait cycle.

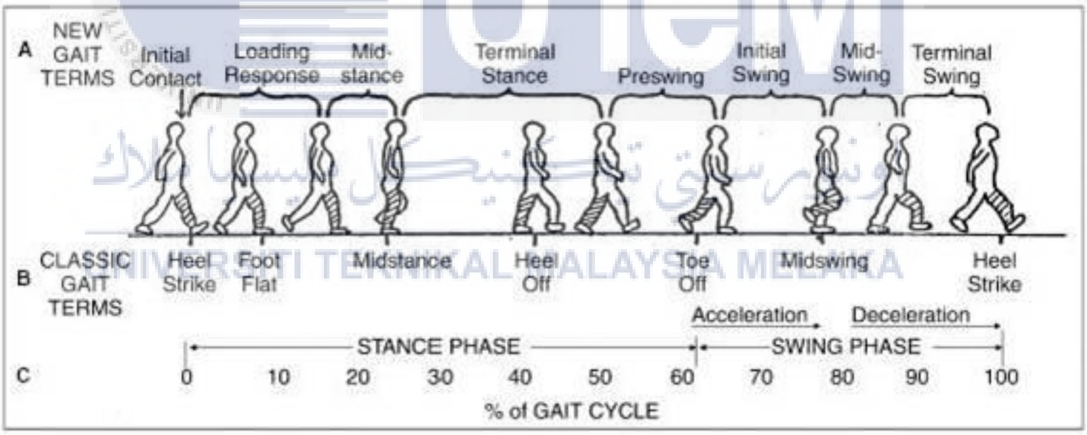


Figure 2.4: Seven sub-phases of one stride length

2.4 Trajectory Planning

Trajectory planning is a motion planning for the movement of the robot to travel from the starting position to the desired position. The purpose of planning a trajectory is to generate the reference input of the control system for the manipulator, in order to execute the motion [12]. The input is describe as the geometric path, dynamic and kinematic constraint while the trajectory joint or the end effector is known as the output. Basic of executing any trajectory planning algorithm is the same in motion law [12].Moreover, trajectory planning is one of the important role in robotics world which used to design a path for manipulator or electrical motor in order to move to its desired point [13]. The development on the trajectory must be in the area of space joint, after the inversion of kinematic of the given geometric path as stated by other researcher in their studies [14][15]. Meanwhile trajectory is also refer as a time history of position, acceleration and velocity for each degree of freedom. One of the most important part in robotics is the reduction of jerk on the manipulators for creating a smooth motion without any vibrational phenomena. It is a fundamental issue in robotics application that are widely used in the modern applications.

The benefits of generating on the trajectory profile in joint space is it would not require a calculation of inverse kinematic compares to Cartesian space and able to exclude the problems that arise in kinematic singularities and manipulator redundancy [12][16]. Major advantages of trajectory planning in the joint space area, especially for the control system to act on the manipulator rather than on the end effector. It is easier to alter the trajectories according to their design requirement if it's employed in the joint space area.

Based on the previous studies, most of basic development on trajectory planning is due to a problem such as minimum execution time, minimum energy on the actuator, minimum jerk or some other parameters [13]. Minimum time algorithm is the primarily trajectory planning technique that proposed in the research world which associate with the industrial sector in order to increase productivity. A few technique has been proposed in solving the problem, however the outcomes produce is a non-continuous torques which lead the motion on the joint to be delayed from the reference trajectory with a tracking errors that increase from the disturbance or modelling errors [12]. Therefore to overcome the problem the method of spline function is use to generate a smooth trajectories. The second problem that encountered with the basic of trajectory planning is the minimum energy. Minimum energy are not required for all robotic applications, only for a certain manipulators that have a limited capacity of energy source such as submarine exploration robots or spatial robot. Besides that, the robot trajectory can be planning with an energetic criteria able to reduce stresses of the actuator to the manipulator easily which lead to smooth trajectories [12] [13].

In generating a smooth trajectory, other than focusing on the problem of connecting the final and initial condition it is essential to satisfy the number of trajectory order. Trajectory order is the order of the robot dynamic model, where the time derivatives reflect state and control constraint of the robot system [14]. Therefore, in selecting a trajectory it must be accurate for preventing the joint controller reach its saturation which cause a tracking error. It is essential when coordinating a motion of several joint is desired. Minimizing a jerk in trajectory are one of the most research problem that associate with robotic application. A research conducted by vanni zanotto and alessamdro gasparetto state that in generating a smooth trajectory, the essential condition is to limit the vibration of the manipulator during a fast movement with short execution time. It can be achieve by controlling the weight of both function [15].

2.4.1 Jerk

The fundamental issue in robotics application in designing a trajectory is to overcome the occurrence of jerk in the manipulator. Jerk is known as quick or a sudden movement which occur during a motion. In the term of physics, jerk can be known as the rate of change of acceleration which is the derivative of acceleration, velocity and position with respect to time. It can be defined by the following expressions below:

$$\vec{j}(t) = \frac{d\vec{a}(t)}{dt} = \dot{\vec{a}}(t) = \frac{d^2\vec{v}(t)}{dt^2} = \ddot{\vec{v}}(t) = \frac{d^3\vec{r}(t)}{dt^3} = \dddot{\vec{r}}(t) \quad (1)$$

$Where$

$\vec{a}$ $is\ acceleration$;

$\vec{r}$ $is\ position$;

$\vec{v}$ $is\ velocity$;

t $is\ time$;

The expression shows that jerk occurs from the first derivation of acceleration through the second derivation of velocities and the third derivation of position with respect to time or it can be known as the third derivative of position. Thus, the occurance of jerk are based from the rate of change of acceleration and by emphasizing the continuity of acceleration in the manipulator may reduce the amount of jerk. Reducing jerk are importance to any robotic application or industry platform because highest amount of jerk values can impair the structure of a robots and its resonance frequencies [12]. Furthermore, an excessive jerk might leads to a resonant vibrations on the actuators in the robot's structure which difficult for a controller to track accurately [16] compared to a low jerk. Besides that, minimizing a jerk provide many benefits for the manipulator which is the tracking error of the trajectory is reduce, stresses of manipulator acutator and structure are reduce, limitation of robot manipulator due to resonance frequencies is limited and coordination of natural robot motion is produced [10].

Meanwhile, some of research has been conducted in reducing a jerk and most of the technique can be found in the scientific literature, The method described in this project is to define the kinematic constraint of a robotic motion such as velocity, acceleration, position and jerk, so the real manipulator can be applied when planning the trajectory. There are several different method used by the recent research in generating a smooth trajectories with less jerk. One of the research used a polynomial to approximate the desired trajectories when optimizing a parametric curve in order to achieve near optimal result [18][21][22]. Based on the research in [18] they optimize a cubic spline to minimize jerk for a specific motion time while [19] presented an algorithm that produces a third order trajectory which created by isolating the trajectory into seven segments. This approach allows them to reduce the problem by identifying the best form and then solve the equation from that form in order to calculate the exact trajectory. A similar approach as [19] is conducted in this project, however as in [19] they extend this approach to produce multi-axis trajectories by synchronizing several single-axis but in this project, the analysis of different categories of biochemical analysis for human gait motion which is called 2-phase, 4-phase and 7-phase. Other than that, research in [20] also produce fourth order trajectory which the basic concept is dividing the trajectory into several segment where the highest derivatives has one of three constant values. A fourth order trajectory, trajectory, requires more segment than third order trajectory and it is much complex. To solve this problem by limiting themselves to deal with rest to rest motion and assume a single specific trajectory form. This form produce eight segment with a non-zero snap (fourth derivative of position) and all of these segment have the exact time length.

2.4.2 Via Point

Via point are known as an intermediate point between the initial and final poses for a path to passing through where the acceleration and joint rates are not in zero state. It is suitable for avoiding an obstacle of a manipulator [17]. P_1 is defined as the intermediate point where the final velocity of P_0 and the initial value of P_2 is equal with the value of intermediate point, P_1 in order to generate a smooth, motion path. Therefore the initial and final velocities value of P_0 and P_1 are not equal to zero. Moreover, in the view of industrial robotic, the via point method can be used in finding a suitable point for a smooth path way which can avoid any obstacles surround the manipulator. In trajectory planning, via point is essential in generating a smooth motion where we it can be generate by following the assigned point until it reach the final position of the end-effector.

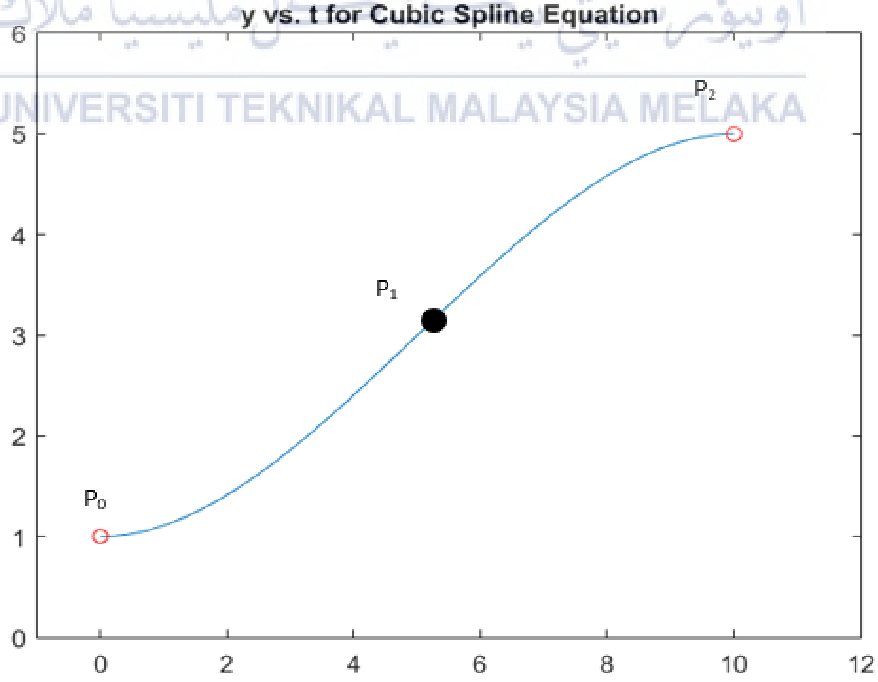


Figure 2.5: The illustration of via point flow.

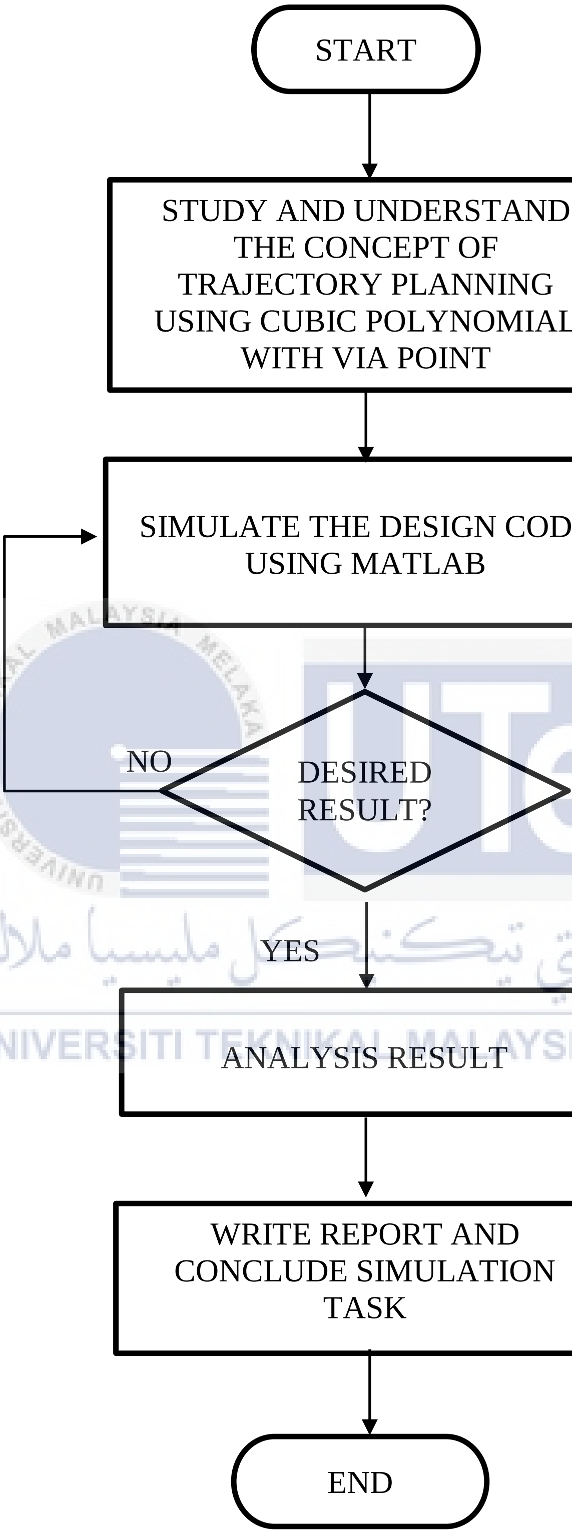
CHAPTER 3

METHODOLOGY

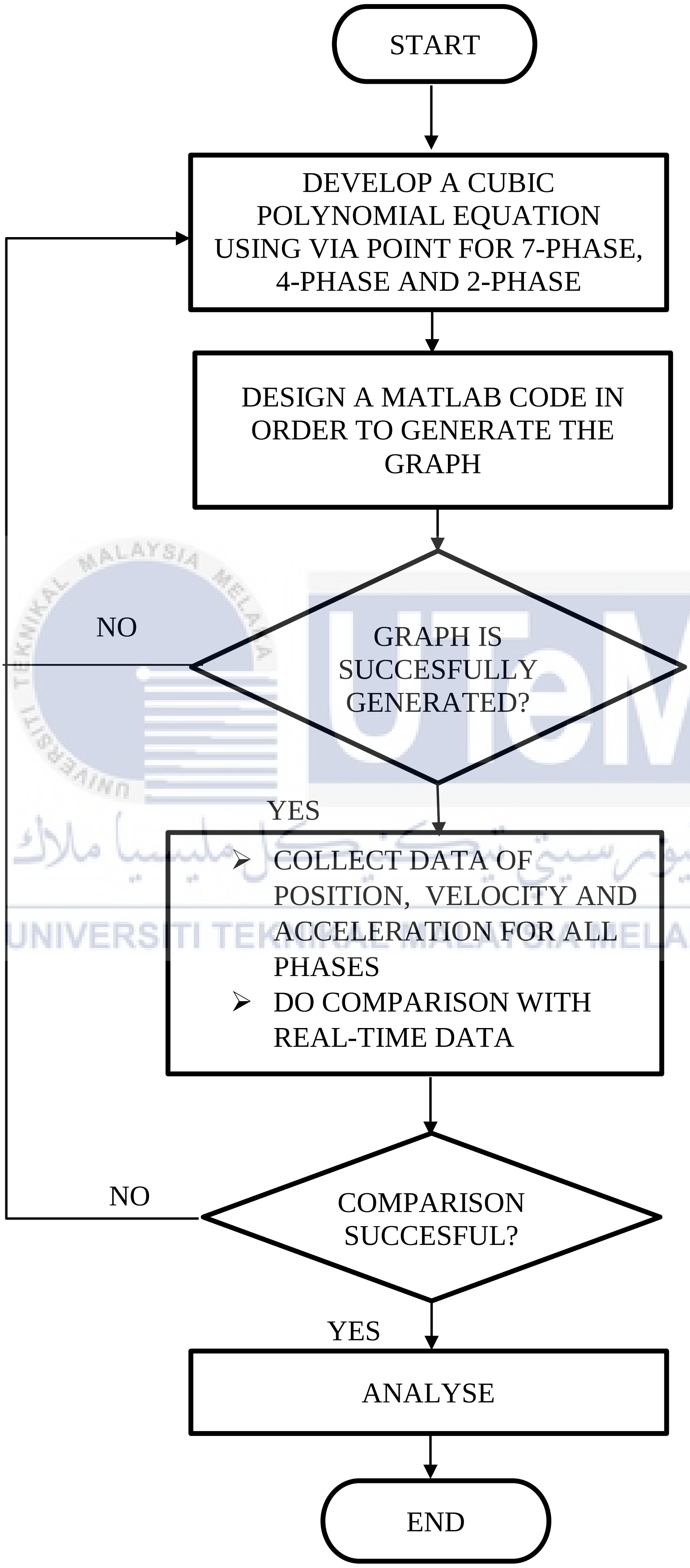
3.1 Overview

This chapter will elaborates the methodology of this project. Moreover, this chapter will explain more on the procedure and how the project is conducted. To achieve the study objectives, Matlab are mostly used tool for this project. Other than that, the method or technique used for this project will be illustrate in this chapter. Thus, this chapter shows the guideline on how the project is begun and ended. The following Flowcharts will summarize the whole chapter for this project.

3.2 Project Flow Chart



3.3 Simulation Flow Chart



3.4 Proposed Method

The method that has been proposed for this project is the cubic polynomial with via point in order to analyse the motion of human walking cycle. Therefore, by using this method the trajectory planning of the orthotic device are able to generate the motion which closer to the real-time data of human walking cycle.

3.5 Designing a trajectory planning using cubic polynomial with via point for walking motion

In cubic polynomial, we know that the motion path is described by a desired duration and final goal point but in implementing the method using the Via point we have a different type of working principle. Generally, we allow the path to be specified which include the intermediate point and if the manipulators is come to rest at any of the point, the cubic solution in (7) can be used to calculate the rest points. To able via point to pass through the cubic without stopping, we need to generalize the way where we can fit the via point into the constraint path.

For the first section, cubic polynomials of a third order can be expressed as shown in Equation (2).

$$\theta(t) = \sum_{0 \leq k \leq 3} a_k \, t^k \tag{2}$$

The position equation of hips motion for k + 0, 1,2,3 is shown in (3)

Position: *(3)*

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

The velocity profile of hips motion shown in (4) can be obtained by derivation equation in (3)

Velocitty:

$$\dot{\theta}(t) = a_1 + 2a_2t + 3a_3t^2 \tag{4}$$

Then, for acceleration the profile is the second derivation equation of (4) as shown in (5)

Acceleration:

$$\ddot{\theta}(t) = 2a_2 + 6a_3t \tag{5}$$

Lastly, jerk equation can be obtained by deriving the equation in (5) or known as third derivative of position profile as shown in (6).

Jerk:

$$\dddot{\theta}(t) = 6a_3 \tag{6}$$

In order to generate smooth trajectories of cubic polynomial, the joint angle of position and velocity must be in a continuous state. Therefore, the angles of initial and final joint must be equal to initial and final joint rates. The time instant for both joint must be zero for the angle to start and stop at rest. In this project, the initial time will be defined as, $t_0 = 0$ and the final time is $t = t_f$ while the initial and final angle is θ_0 *and* θ_f respectively.

To achieve a smooth motion, four constraint of cubic polynomial is proposed. Two of the constraint comes from initial and final value of velocity which equivalent to zero as shown in equation (7).

$$\theta(t_0) = \theta_0$$

$$\theta(t_f) = \theta_f \tag{7}$$

$$\dot{\theta}(t_0) = v_0 = 0$$

$$\dot{\theta}(t_f) = v_f = 0$$

For equation (8), we can determine the four unknown parameters constraints of a0, a1, a2 and a3 by applying the equation in (3), (4), (5) and (7).

$$a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{3(\theta_f - \theta_0)}{{t_f}^2} \qquad (8)$$

$$a_3 = \frac{-2(\theta_f - \theta_0)}{{t_f}^3}$$

In order to create via point, the desired velocities of the joint must be known and the velocities constraint at each end point are not equal to zero. Thus, the velocities of end point are known the angle equation in (3) will be generate as shown in equation (9)

$$\dot{\theta}(0) = \dot{\theta}_0$$

$$\dot{\theta}_{(t_f)} = \dot{\theta}_f \qquad (9)$$

The derivative of via point for equation (2), (3) and (4) will be defined in equation (10)

$$\theta_0 = a_0$$

$$\theta_0 = a_0 + a_1 t_f + a_2 {t^2}_f + a_3 {t^3}_f$$

$$\dot{\theta}_0 = a_1 \qquad (10)$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t^2{}_f$$

By solving the equation of a_i , the result is

$$a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{3(\theta_f - \theta_0)}{{t_f}^2} - \frac{2}{t_f}\dot{\theta}_0 - \frac{1}{t_f}\dot{\theta}_f \qquad (11)$$

$$a_3 = \frac{-2(\theta_f - \theta_0)}{{t_f}^3} + \frac{1}{{t_f}^2}(\dot{\theta}_f + \dot{\theta}_0)$$

Therefore by using the equation in (11), we can calculate the via point which connects with any initial and final position including the initial and final velocities.

3.6 Equipment Used

SIMULATION

There are many tools that has been develop nowadays for simulation process. Therefore, in this project we are using the Matlab software to simulate a graph using the selected method. MATLAB software is a platform of high performance language or programming for technical computing which suitable on high productivity research, development and analysis. It can be used for visualization, computation, and programming where the solution and problem can be stated in mathematical notation. The Matlab system is an array system that do not need dimension. Thus, it is able to solve several of technical computing problem and main problems that associated with vector and matrix formulations. It is also consists tools for developing, managing, debugging and profiling using the M-files application. The given set of tools facilitate the user works much easier in developing a programs. In addition, the software provide a various type of mathematical function for computational algorithms starting from the basic function such as sum, sine, cosine, complex arithmetic, matrix eigenvalues, inverse matrix, Fourier transform and others. It is much easier and faster to solve a complex mathematical operation using the Matlab software rather than manual calculation.

3.7 Research Parameters

In planning a trajectory, few essential parameters need to be consider during the motion. In these project, we are focusing on the angular position (radian), angular velocity (rad/s), acceleration (rad/ s^2), jerk (radian/s^3) ,error (rad/s) and accuracy(rad/s) that occur on the motion. Every motion that produce during the movement with respected to time will affect the parameters value. To produce a smooth motion we must ensure the position profile and velocity profile are continuous with the time variable especially when shifting from one phase gait to another. By using the equation in (1), we can generate the parameters graph for position, velocity, acceleration and jerk respectively at each phase. Moreover, the coefficient value for equation (1) are generated by using the equation in (11).

3.8 Simulation Experiments

In this project, there are two experiment will be conducted during the simulation process which is:

3.8.1 Experiment 1: Designing a trajectory planning using a cubic polynomial with via point based on the 7 phases human gait motion.

Objective:

The objective of this experiment is:

i) To create the experimental graph for angular position, velocity and acceleration.

ii) To generate the constraint parameters of a0, a1, a2 and a3 of the cubic polynomial equation.

iii) To identify the error and jerk produce from the comparison of reference graph and the experimental graph.

iv) To evaluate the performance of jerk with the error and accuracy.

3.8.2 Experiment 2: Designing a trajectory planning by using cubic polynomial based on 3 type human gaits motion.

Objective:

The objective of this experiment is:

i) To create the experimental graph for angular position, velocity and acceleration based on 2 phases, 4 phases and 7 phases motion.

ii) To evaluate the accuracy of the technique in matching the human walking gaits from the comparison of each phase.

iii) To evaluate the performance of the accuracy of each phase based on the calculation of average difference, root mean square (RMS) error.

3.9 Data collected

The implementation of collecting the data are done by using the Matlab coding and the type of data collected for the results is in terms of graphical geometry calculation. In addition, the plotted graph for 7-phase, 4-phase and 2-phase are drawn based on the coefficient data of each gait cycle for both experiment. Moreover, there are 3 main graph are plotted from the reference and experimental data:

1. Angular Position , θ versus Time (second)

2. Angular Velocity,$\dot{\theta}$ versus Time (radian per second)

3. Angular Acceleration,$\ddot{\theta}$ versus Time (radian per second2)

The initial time of each plotted graph are form from the 0 second until it reached to 1 second which according to each phase gaits. The time instant for the initial contact is produce at 0 seconds and start to initiate from 0 s to 0.1 s for loading response phase are occur during the initial double support stance period. The mid stance phase generates after the motion of loading response stage about 0.3 second and it continues from mid stance to terminal stance until it reached 0.5 second. A progression of the initial half of a single phase support that are involve with the centre body of mass while the terminal stance is known as the second half of the single support phase. The motion continues for pre swing and initial swing at 0.6 s to 0.73 s respectively where the pre swing is related more to the swing phase with following the preceding stance phase event. Meanwhile, mid swing is defined when the terbia is in the vertical position as the time of swing foot is opposite to stance limb. Then, the last contact phase contact ends at 1s after the movement of mid swing which is 0.87 second due to the position of terbia is in vertical state at the initial contact. Figure 3.1 shows the time contact for each phase.

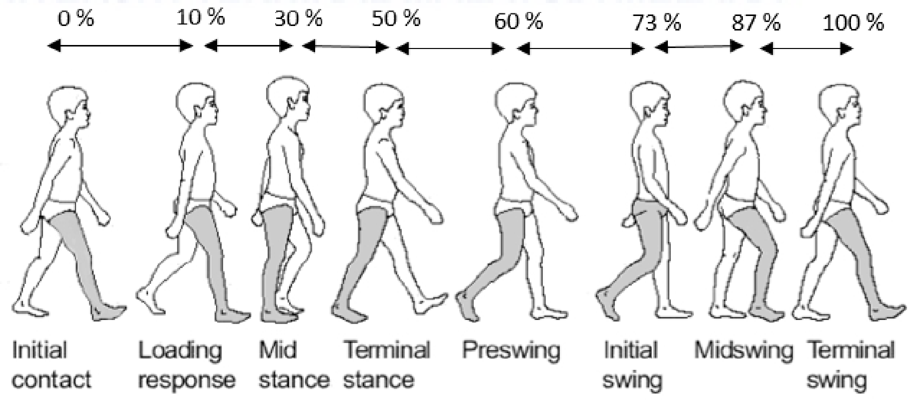


Figure 3.1: Time contact at each phase.

The result of the data, is analysed by creating a comparison graph between the reference graph and the experimental graph. The reference graph is created based on the biomechanical analysis motion [13] as shown in Table 3.1 while the experimental graph is created based on the coefficient value from equation (11) as shown in Table 3.2. Each experimental graph of position, velocity and acceleration are compared by the reference graph as shown in Figure 3.2, Figure 3.3 and Figure 3.4 for evaluating. The observation of the graph for experiment 1 are based on the root mean square (RMS) error which produce between the reference and experimental graph in order to identify the accuracy of the orthotic device. Meanwhile in experiment 2, the observation will be based on the root mean square (RMS) error and average difference between experimental graph and the reference graph.

Table 3.2, shows the coefficient value of a0, a1, a2 and a3 for each time period by using the method of cubic polynomial (9)(10)(11). Each phases produce a different amount of time period in order to complete a full phase. For seven phases consist of eight time period starting from loading response (0 - 10%), mid-stance (10 - 30%), terminal stance (30 - 50%), pre-swing (50 - 60%), initial swing (60 - 73%), mid-swing (73 - 87%) and terminal swing(87 - 100%). Meanwhile, for two and four phases started with double support (0 - 10%), Single support (10-50%), Double support (50-60%), Single support (60-100%) and stance phase (0 - 60%), swing phase (60 – 1%) respectively.

Table 3.1: The reference data of human hips walking cycle [13]

Time (s)	Position (angle)	Velocity (angle/s)	Acceleration (angle/s/s)	Jerk (rad/s^3)
0	0.507613778	0	0	0
0.1	6.04294014	5.35326362	53.5326362	9.34320759
0.3	4.55888319	55.42028475	250.3351056	17.17425534
0.5	2.309390545	-7.24746323	-313.3387399	-49.18982256
0.6	-4.297005653	-9.06396198	-18.1649875	51.51753845
0.73	-2.484782696	-90.9401766	-629.8170355	-82.11801627
0.87	0.122700118	8.62487724	711.178956	167.1771093
1	4.289575458	15.17135058	50.35748722	-88.71931076

Table 3.2: The coefficient value for 7 phase, 4 phase and 2 phase (degree/s)

Phase	Time Period	Gait sub phase	a0	a1	a2	a3
7 phase	0 - 10%	loading response	6.04294014	5.35326362	-526.0094046	3506.729364
	10 -30%	Mid stance	4.55888319	55.42028475	-8.9769244	19.94872089
	30 - 50%	Terminal stance	2.309390545	-7.24746323	23.76221896	-31.68295861
	50 - 60%	Pre swing	-4.297005653	-9.06396198	71.55484259	-79.50538066
	60 - 73%	Initial swing	-2.484782696	-90.9401766	38.13675073	-34.82808285
	73 - 87%	mid swing	0.122700118	8.62487724	16.51555822	-12.65560017
	87 - 100%	Terminal swing	4.289575458	15.17135058	0	0
4 phase	0-10%	Double support	6.04294014	5.35326362	-526.0094046	3506.729364
	10-50%	Single support	5.509390545	5.24746323	-365.9445261	2439.630174
	50-60%	Double support	2.309390545	-11.24746323	-21.65805003	24.06450003
	60-100%	Single support	55.28957546	10.17135058	-425.0000000	472.2222222
2 phase	0-60%	stance phase	6.04294014	5.35326362	-14.61137235	16.23485817
	60-100%	swing phase	-2.484782696	-90.9401766	20.32307446	-13.54871631

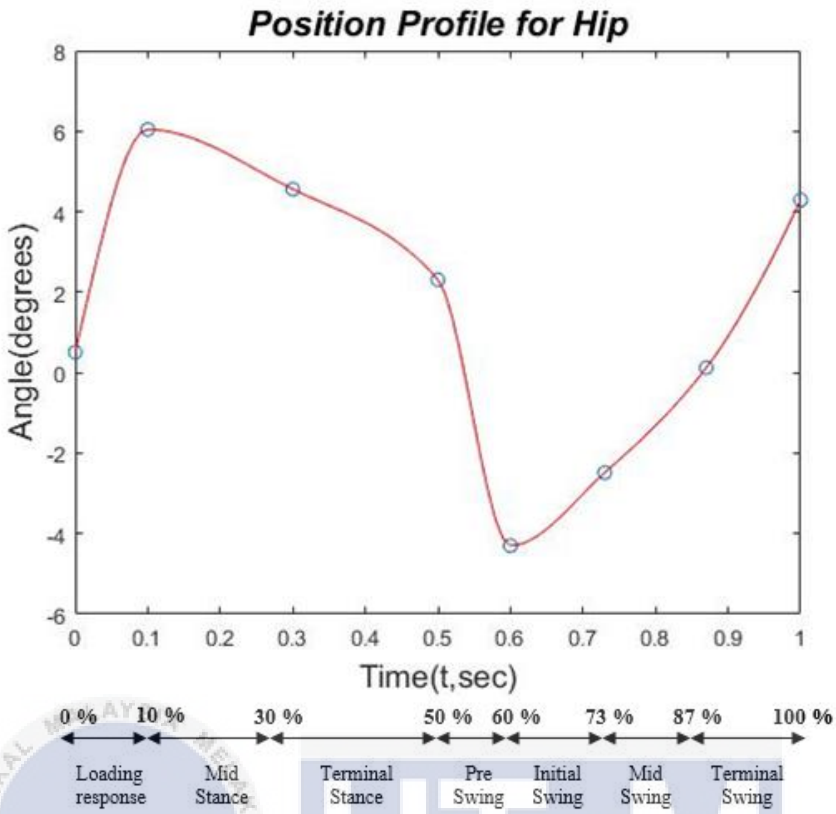


Figure 3.2: The reference graph in terms of Position [13]

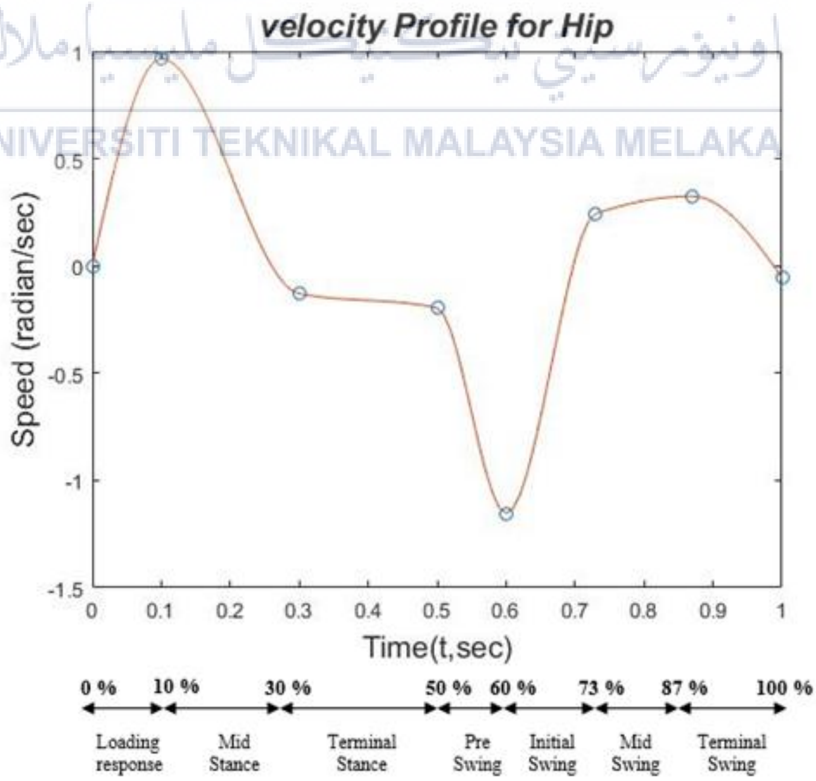


Figure 3.3: The reference graph in terms of Velocity [13]

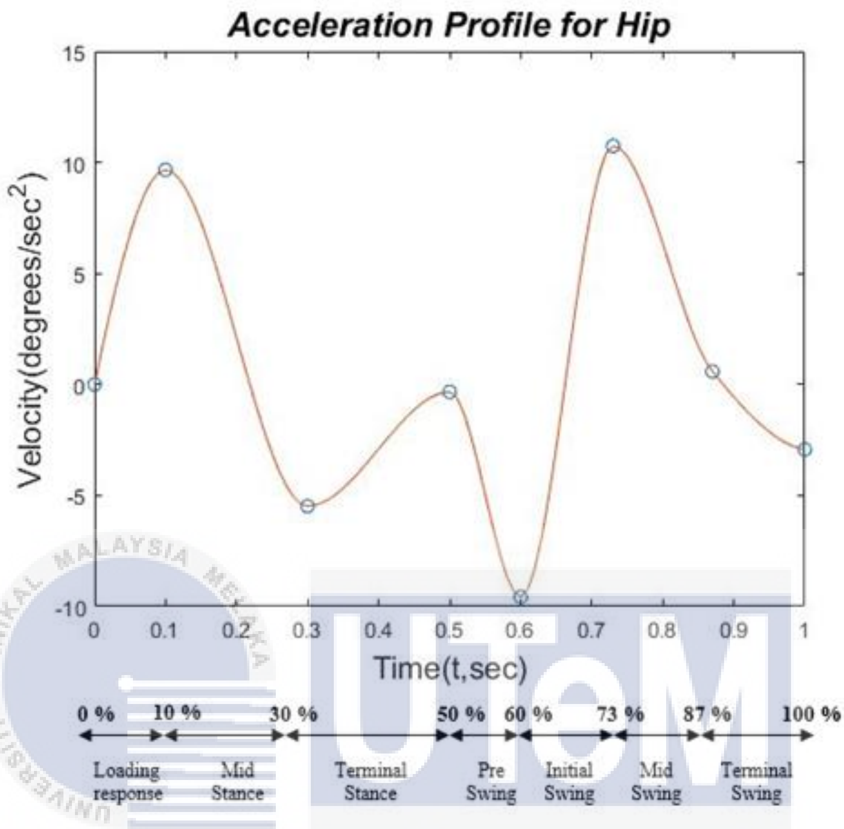


Figure 3.4 The reference graph in terms of Acceleration [13]

CHAPTER 4

RESULT AND DISCUSSION

4.1 Overview

In this chapter, the result for this project will be discussed and analysed by referring on the reference data of human hips walking gait cycle. This analysis are based on jerk occur in the comparison graph between reference graph of human hips walking and cubic polynomial graph. There are three type of phases were conducted in this chapter which is 7-phases, 4-phases (Single and Double support phase) and 2-phases (Swing and stance phases). The graph will be separated by 3 section which is position, velocity and acceleration for both experiment as stated in methodology. For both experiment 1 and 2, the reference graph is based on the Figure 3.2, 3.3 and 3.4 while the trajectory generation profile of position,velocity and acceleration for all phases is generated based on the value of coefficient in Table 3.2. All the result is presented in this chapter.

4.2 Scope of Analysis

This analysis was conducted by using the method of cubic polynomial in order to evaluate the performance of jerk that occurs on the orthotic device. The performance are evaluated by referring a comparison graph between the reference of human hips walking cycle and the method of cubic polynomial. There are two technique that have been simulated to analysed the accuracy and error between the reference and experimental graph which is the average difference (AD) and root mean square error (RMSE) as illustrated in equation (12) and (13).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_{Gen} - T_{Ref})^2}{n}} \qquad (12)$$

$$Average\ Difference = \frac{\sum_{i=1}^{n}(T_{Gen} - T_{Ref})}{n} \tag{13}$$

Where the T_{Ref} is the hips trajectory reference, T_{Gen} is the generated tajectory using the cubic polynomial method and n is the number of trial.

4.3 Experiment 1: Designing a trajectory planning using a cubic polynomial with via point based on the 7 phases human gait motion.

Figure 4.1 shows the position profile of hip joint with the comparison of reference graph and the cubic polynomial method. Furthermore, figure 4.2 shows the velocity profile with the comparison of reference data where it is produced by derivation of position equation (3) of cubic polynomial with the same value of the coefficient constant of (t) variable and with same method for figure 4.3 shows the acceleration profile with the comparison of reference data that produced by derivation of velocity equation (4) of cubic polynomial with the same value of coefficient constant of (t) variables.

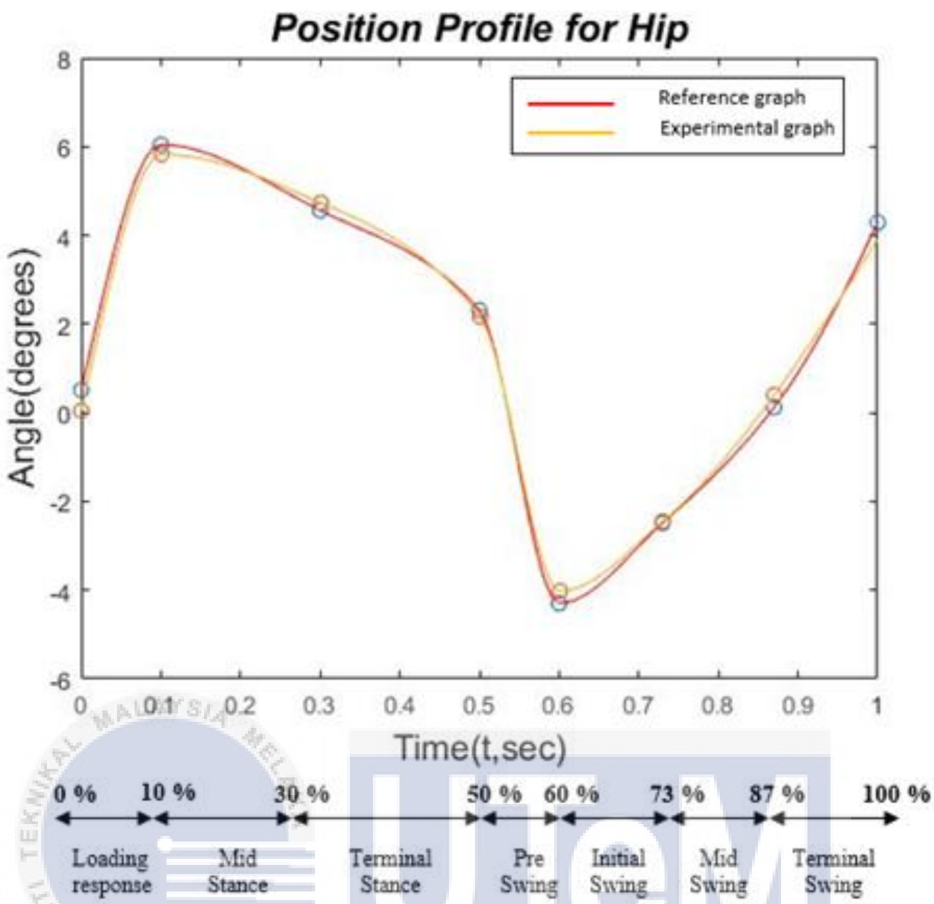


Figure 4.1: Comparison between the reference hip motion and cubic polynomial method in term of Position

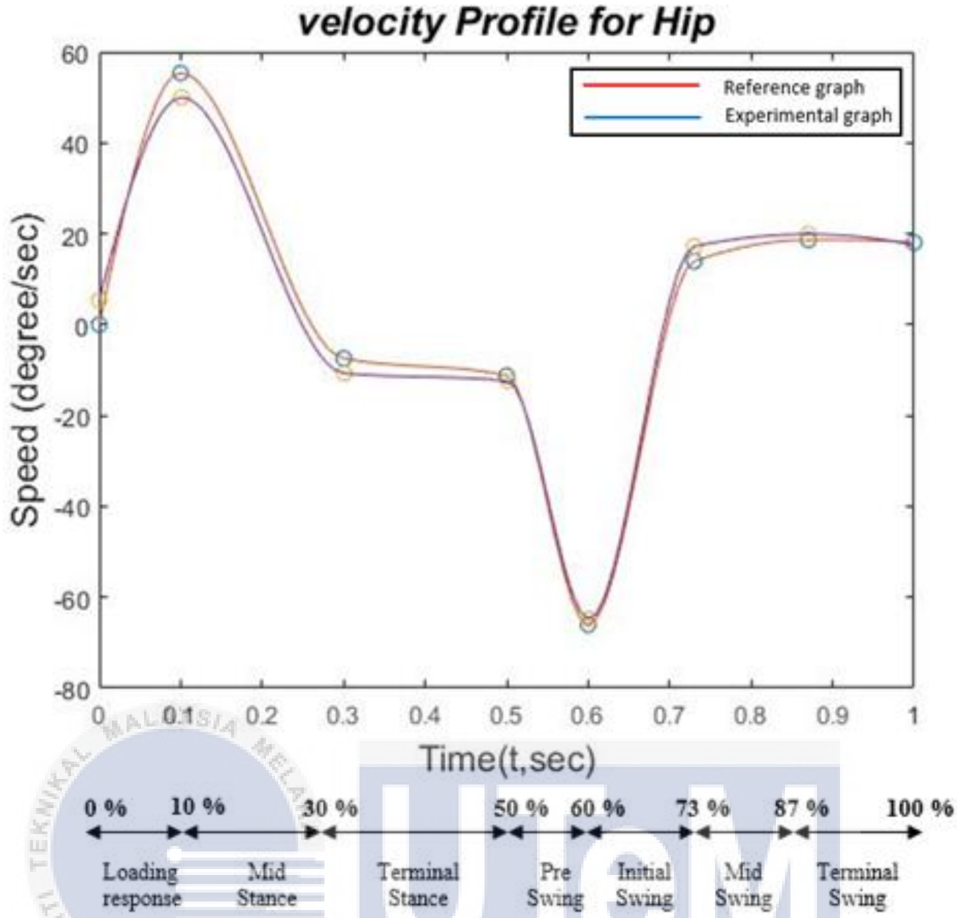


Figure 4.2: Comparison between the reference hip motion and cubic polynomial method in term of Velocity

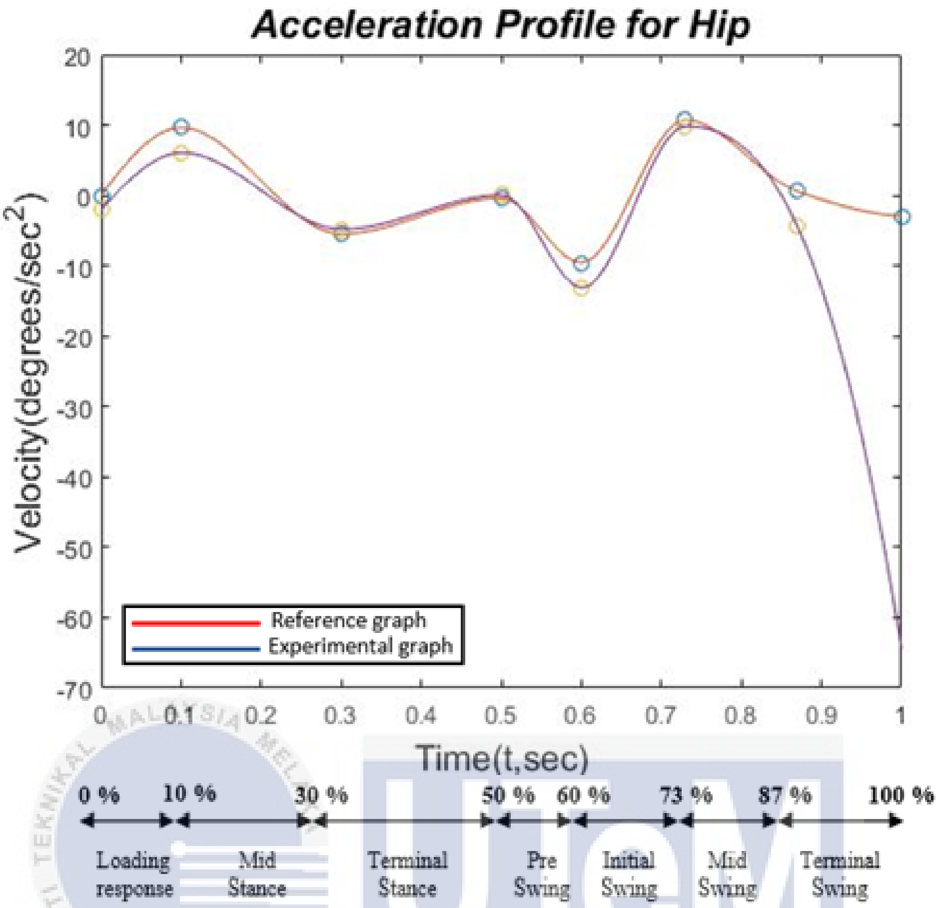


Figure 4.3: Comparison between the reference hip motion and cubic polynomial method in term of Acceleration

A. Analysis of accuracy and error produce.

In terms of position:

Figure 4.1 shows the comparison between human hips trajectory data and the trajectory that are generated by cubic polynomial method. Based on the data in Table 3.1 and 3.2, both graphs have been formed in terms of position profile. The graph are formed based on the data of eight phases which started at 0 second and end at 1 second. We can observedf from the Table 4.1 that during the loading response (0 - 10%) phase it produce higher error compares to the reference graph which is 0.00653308 rad. In addition, the error during the terminal stance (30 - 50%) and initial swing (60 - 73%) has a slightly decrease about (0.001485814 and 0.002101138 rad) respectively compares to terminal swing (87 - 100%) which is 0.007200463 rad the most higher than other phases. Therefore, we can stated that the cubic trajectory in terms of position are able to trail the movement of human hip walking cycle.

Moreover, in terms of accuracy loading response (0 - 10%) and terminal swing (87 - 100%) produce highest error compares to terminal stance (30 - 50%) with 0.001485814 rad. This indicate that terminal stance produce higher accuracy in trajectory the reference motion of hips cycle.

Table 4.1: RMS error between cubic polynomial and reference data of human hips walking cycle in term of Position

Gait sub phase	Time period	RMSE error (rad)
loading response	0 - 10%	0.00653308
Mid stance	10 - 30%	0.003209259
Terminal stance	30 - 50%	0.001485814
Pre swing	50 - 60%	0.001797124
Initial swing	60 - 73%	0.002101138
mid swing	73 - 87%	0.002003806
Terminal swing	87 - 100%	0.007200463

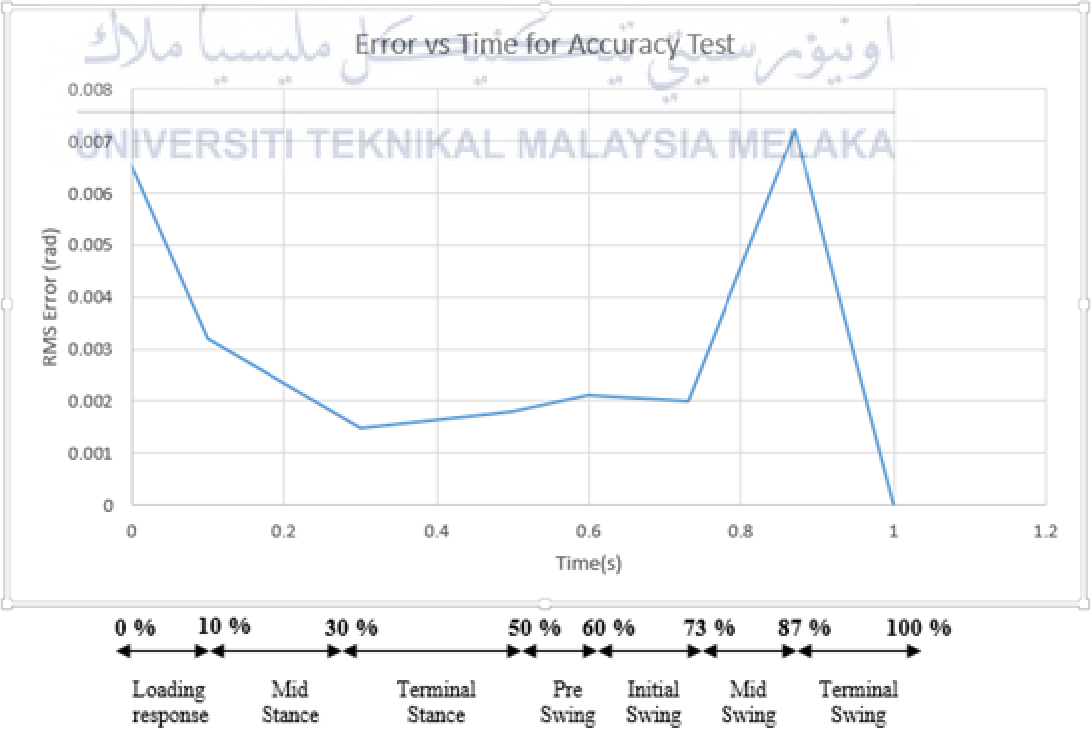


Figure 4.4: Graph of error versus time for each interval phase in terms of position.

In terms of velocity:

The figure 4.2 shows the result of velocity profile using the cubic polynomial method with the comparison graph of reference human hips cycle and the same concept as position profile is applied to the velocity profile. Therefore, we can observed that during the loading response phase (0 - 10%) which is 0.067537177 rad, the error is increased until the terminal stance (30 - 50%) (0.038196276 rad) and started to decrease during the pre-swing (50 - 60%) and initial swing (60 - 73%) about 0.207266742 and 0.207792621 rad respectively. However, an error are also occur during the mid-swing (73 - 87%) and terminal swing (87 - 100%) which is 0.04616515 and 0.22683694 rad respectively. Based on table 4.2, shows that the terminal swing (87 - 100%) with 0.22683694 radian produce higher root mean square error (RMSE) compares to other phases. Thus, the method of cubic polynomial in terms of velocity has the ability to generate the movement of hips cycle which closer to the reference gait cycle.

In terms of accuracy, we can observe that the lowest accuracy will be occur at pre swing (50 - 60%), initial swing (60 - 73%) and terminal swing (87 - 100%) which is 0.207266742, 0.207792621 and 0.22683694 rad respectively. Meanwhile, for higher accuracy is constantly occur at mid stance (10 - 30%) and terminal stance (30 - 50%) with 0.039484958 and 0.038196276 radians.

Table 4.2: RMS error between cubic polynomial and reference data of human hips walking cycle in term of Velocity

Gait sub phase	Time period	RMSE error (rad)
loading response	0 - 10%	0.067537177
Mid stance	10 - 30%	0.039484958
Terminal stance	30 - 50%	0.038196276
Pre swing	50 - 60%	0.207266742
Initial swing	60 - 73%	0.207792621
mid swing	73 - 87%	0.04616515
Terminal swing	87 - 100%	0.22683694

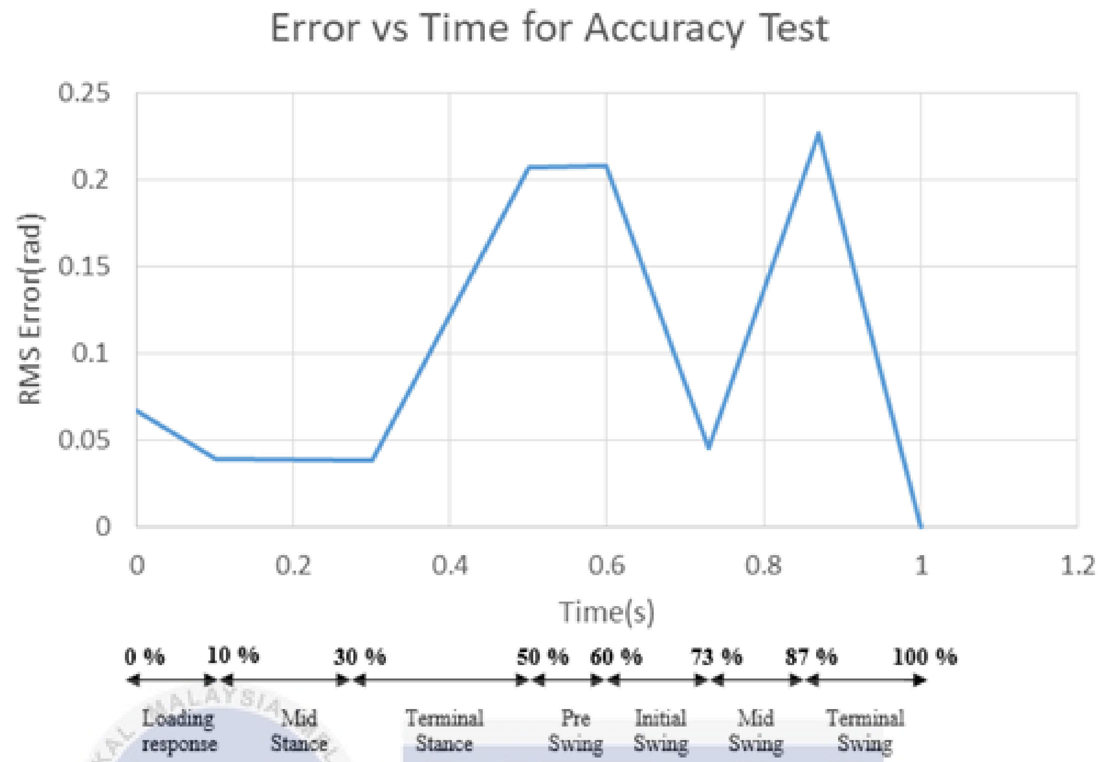


Figure 4.5: Graph of error versus time for each interval phase in terms of velocity

In terms of acceleration:

In figure 4.3 shows the acceleration profile with the comparison graph of reference hip cycle with the cubic polynomial. For acceleration, we can observe that during the loading response (0 - 10%)(0.050614115 rad) and mid-stance (10 - 30%)(0.04484718 rad) the error occurs are slightly higher than the pre swing phase (50 - 60%) and initial swing (60 - 73%) with 0.044375285 and 0.045403492 rad respectively. However, the highest error among the others phases is occur at the terminal swing (87 - 100%) which is 0.07176676 rad as shown in Table 4.3. Thus, for acceleration profile it also has the ability to trail the reference motion of human hips walking cycle.

In accuracy perspectives, starting from mid-stance (10 - 30%) the error is gradually increase until the terminal stance (87 - 100%) before it is dramatically declined to 0 radian. For acceleration we can observe that, the accuracy of acceleration in trajectory the reference hips motion is lower due to the increasing amount of error.

Table 4.3: RMS error between cubic polynomial and reference data of human hips walking cycle in term of Acceleration

Gait sub phase	Time period	RMSE error (rad)
loading response	0 - 10%	0.050614115
Mid stance	10 - 30%	0.04484718
Terminal stance	30 - 50%	0.00983402
Pre swing	50 - 60%	0.044375285
Initial swing	60 - 73%	0.045403492
mid swing	73 - 87%	0.062968438
Terminal swing	87 - 100%	0.07176676

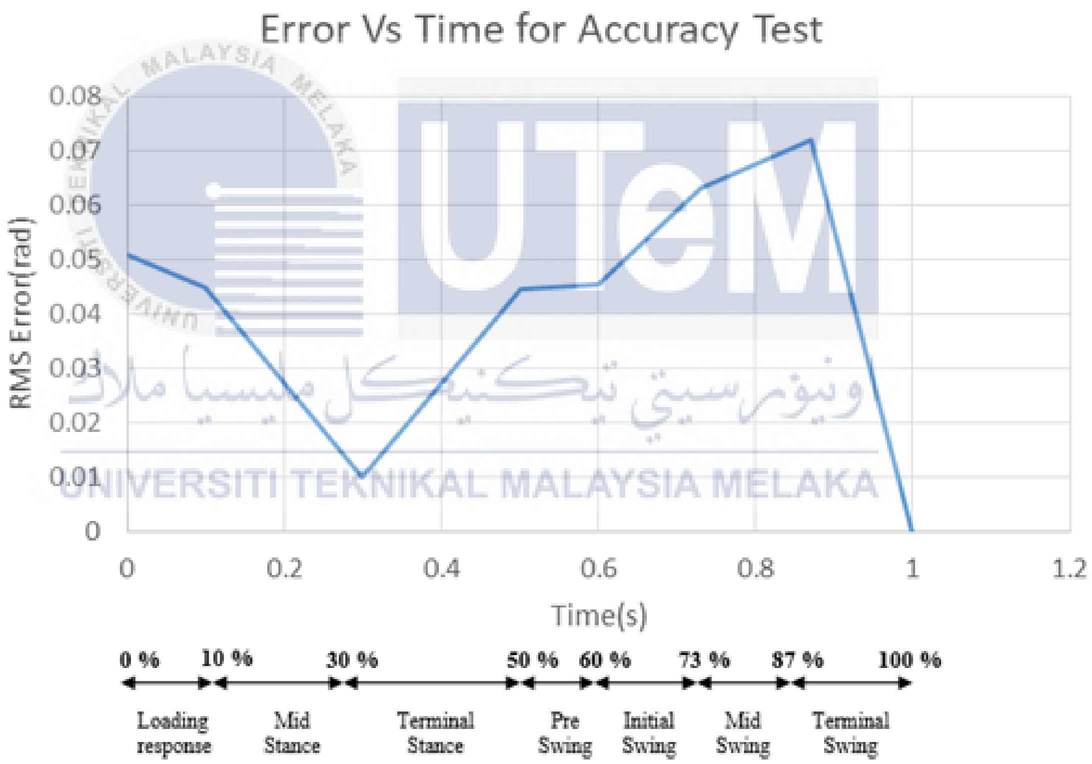


Figure 4.6: Graph of error versus time for each interval phase in terms of acceleration

In terms of position, velocity and acceleration profile:

According to the Table 4.4 below, shows the RMS error between the reference data of human hips gait with the cubic polynomial method for each profile, thus for position is 0.005028673 rad and the velocity is 0.158629282 rad while the acceleration is 0.049675048 rad. From the observation, we can state that the highest error among other profile is the velocity with the value of 0.158629282 rad. It is indicate that higher jerk is produce on the orthotic device during the velocity phase compares to the other phases. Based on the observation from the table 4.4, we notice that velocity profile produce lower accuracy compares to position profile due to the higher amount of error. Thus, accuracy of velocity profile in trailing the reference hips motion are lower compares to others.

Table 4.4: RMS error between cubic polynomial and reference data of human hips walking cycle for each profile

Profile	RMSE (radian)
Position	0.005028673
Velocity	0.158629282
Acceleration	0.049675048

B. Analysis performance of jerk

Based on the figure 4.7 below, shows a jerk profile that occurs on the orthotic device during the performance of position, velocity and acceleration on the device. Whereas, the performance is occur in every phases starting from the loading response, mid- stance, terminal stance, pre-swing, initial swing, mid- swing and ends at the terminal swing. It is begin at 0 s and end at 1 s in order to complete one full cycle. We can identified that the highest jerk produced is at 0.87 s which is in the phase of terminal swing with the value of 167.1771093 rad/s^3. Meanwhile the lowest jerk occurs at 0.1 s about 9.34320759 rad/s^3 which encounter at the loading response.

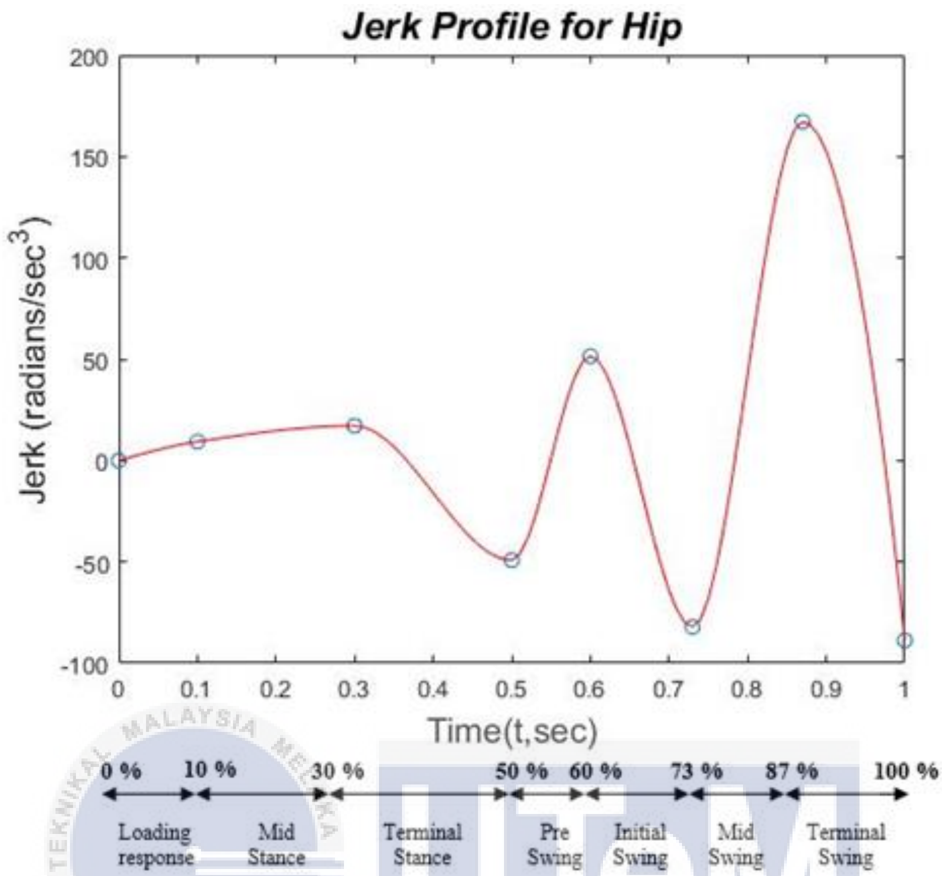


Figure 4.7: Jerk profile of comparison graph between the reference hips walking motion and cubic polynomial method.

4.4 Experiment 2: Designing a trajectory planning by using cubic polynomial based on 3 type human gaits motion.

For this experiment, a comparison graph of 7, 4 and 2 phase profile between the real human hips profile is generate in order to observe the accuracy of the phases in matching the real human hips cycle. The development of this graph is starting from 0s and end at 1s.

In terms of position:

Figure 4.8 shows the comparison graph for 7, 4 and 2 phase using the cubic polynomial method with the reference hips motion in terms of position. The figure below illustrate that only 7 phase are able to match the real data of human hips motion rather than 2 or 4 phase. However, for 4 phase the trajectory able to track the real data of human hips only starting at 0 s until 0.5 s. Based on table 4.5, shows the numerical analysis based on RMS error and average difference for all techniques are obtained for the comparison part. RMS error for 2-phases, 4-phases and 7-phases are 0.090185891, 0.576178748 and 0.005028673 radians/s respectively. The highest and lowest RMSE error will be at 4 phase which is 0.576178748 and 7 phases with 0.005028673 rad/s. Meanwhile, for average difference for 2-phases, 4-phases and 7-phases are 0.046038973, 0.310083014 and -0.001610045 rad/s respectively.

Table 4.5: RMSE Error, Average Difference and Error Difference in terms of Position.

Phase	RMSE Error(rad)	Average difference(rad)
2	0.090185891	0.046038973
4	0.576178748	0.310083014
7	0.005028673	-0.001610045

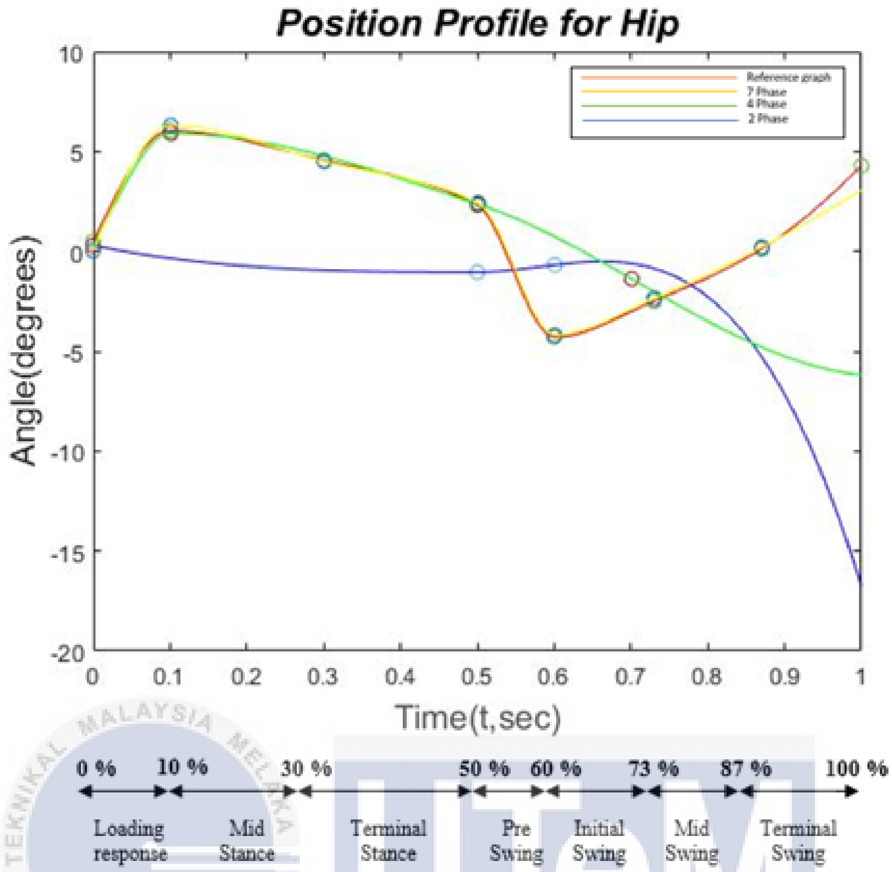


Figure 4.8: Comparison between the reference hip motion with 7, 4 and 2 phase of cubic polynomial method in term of Position

In terms of velocity:

Figure 4.9 show comparison graph for 7, 4 and 2 phase using the cubic polynomial method with the reference hips motion in terms of velocity. It is indicate that the velocity profile for 7-phases has the ability to track the real data of human hips trajectory while for 2-phases and 4-phases produce low accuracy in matching the reference trajectory. Moreover, RMSE error for all phases which obtained in the comparison part is 73.96388671, 0.983685735 and 0.158629282 rad/s for 2-phase, 4-phase and 7-phase respectively. The highest RMSE error with 73.96388671 rad/s is occur during the swing and stance phases (2-phase) while the lowest RMSE error is initiate at 7-phase with 0.158629282 rad/s. Thus, we can observed that 7-phases provide higher accuracy in matching the trajectory of human hips reference compares to 2-phase or 4-phases. In addition, for average difference for all phases from 2-phases to 7-phases is -0.911918406, 0.086261545 and 0.069192376 rad/s respectively.

Table 4.6: RMSE Error, Average Difference and Error Difference in terms of Velocity

Phase	RMSE Error(rad)	Average difference(rad)
2	73.96388671	-0.911918406
4	0.983685735	0.086261545
7	0.158629282	0.069192376

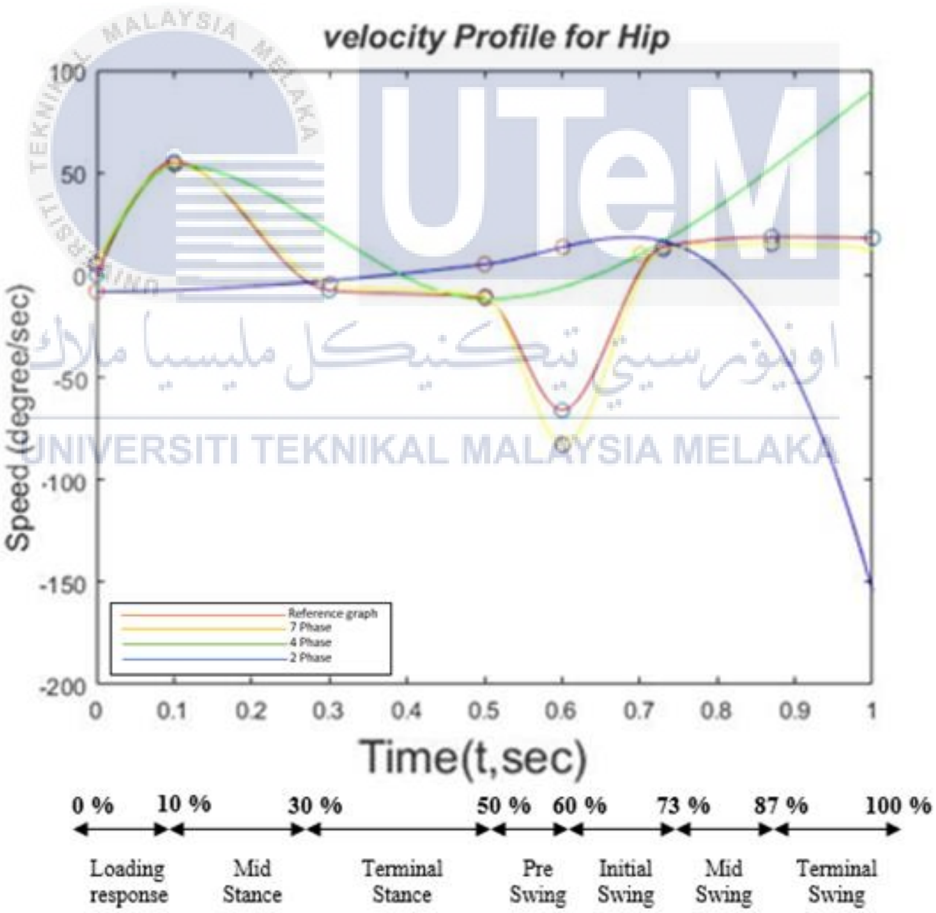


Figure 4.9: Comparison between the reference hip motion with 7, 4 and 2 phase of cubic polynomial method in term of velocity.

In terms of acceleration:

Besides that, figure 4.10 shows the comparison graph for 7, 4 and 2 phase using the cubic polynomial method with the reference hips motion in terms of acceleration. Comparison graph below illustrate the accuracy of cubic polynomial in matching the trajectory of human hips cycle. As we can see, that 7-phases in terms of acceleration profile has the ability in matching the reference profile compares to 4-phases or 2-phases. Table 4.7 shows the numerical analysis based on the RMS error and average difference error. The RMS error value for 2-phases, 4-phases and 7-phases is 7.486197111, 20.97233218 and 0.049675048 rad/s respectively. For this profile, it is indicates that higher accuracy with the lowest error is occur during the cycle motion of 7-phase which is 0.049675048 rad/s. Then, the highest error with a lower accuracy generates during the cycle motion is 4-phases. Meanwhile, for average difference which generates at 2-phase, 4-phase and 7-phases is -4.481758396, -12.81952887 and 0.024099058 rad/s respectively.

Table 4.7: RMSE Error, Average Difference and Error Difference in terms of Acceleration

Phase	RMSE Error(rad)	Average difference(rad)
2	7.486197111	-4.481758396
4	20.97233218	-12.81952887
7	0.049675048	0.024099058

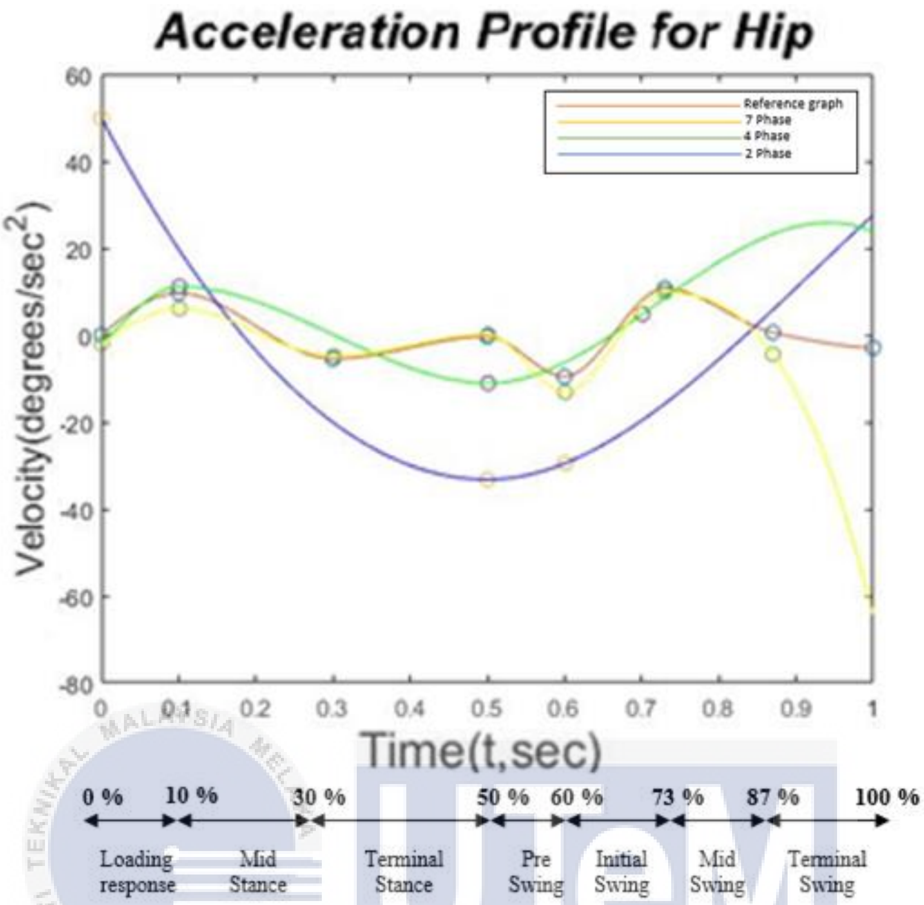


Figure 4.10: Comparison between the reference hip motion with 7, 4 and 2 phase of cubic polynomial method in term of acceleration

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In this project, the focus is on the performance of jerk that occurs on the orthotic device. Experiment 1 shows the capability of cubic polynomial method in matching the biomechanical human hips motion [13]. Meanwhile, experiment 2 shows the trajectory planning for three phases which is 7-phase, 4-phase and 2-phase in tracing the motion of biomechanical identically. In addition, both experiment is analysed in terms error and accuracy between the reference and experimental graph. The analyzation of error is to evaluate the amount of error occur during the comparison graph between the reference and the method of cubic polynomial. Meanwhile, the evaluation for accuracy is identify the accuracy of cubic polynomial method in matching with the reference of human hips motion.

Based on the result of experiment 1 above, we can conclude that by implementing the cubic polynomial method able to generate a smooth and identical motion with the human hips motion [13] for each profile. Meanwhile, in terms of jerk for position, velocity and acceleration profile shown that the jerk occurs are lesser for each profile with 9.34320759 rad/s^3 during the loading phase (0 – 10%). However, higher amount of jerk produce during the terminal swing (87 – 100%) with 167.1771093 rad/s^3. Thus, it is shown that by using the method of cubic polynomial is able to create a lesser jerk on the orthotic device. Besides that, in terms of error and accuracy for experiment 1 shows that highest error is occur during the veloctiy profile. Thus, lower accuracy is produce in tracking the motion of reference human hips cycle [13].

Meanwhile, for experiment 2 ,we notice that only 7-phases can prodvide the accuracy in matching the reference hips motion for every profile compares to other phases. Then, in terms of error occur within the profile shows that 2-phase generates the highest error with 0.576178748, 73.96388671 rad/s for position and velocity while for acceleration 4-phase is 20.97233218 rad/s. It is illustrate that the performance of 7-phase are better than the other phases in tracking the reference motion of human hips cycle. This is because 7 phase able to produce many points in connectiong one time cycle to another which provide better accuracy compares to 2 or 4 phase which produce less than four point in connecting one time cycle to another.

To conclude this project, the method of cubic polynomial has the ability in matching the biomechanical analysis of human hips motion [13]. However, the ability of reducing a jerk to the smallest amount are not possible in this project due the higher amount of jerk that presented during terminal swing at 0.87s as shown in Table 3.1 and Figure 4.7.

Suggestion and Recommendation

Based on the result obtain, several suggestion are made in order to improve the performance of jerk. First, organise an analysis in reducing an error which provide higher accuracy in matching the biomechanical analysis of human hips motion [13]. Second, by implementing higher order method than cubic polynomial where can provide more coefficient values and points in connecting on time time cycle to another.

REFERENCES

[1] Z. Taha, A. P. P. A. Majeed, M. Yashim, W. Paul, A. Ghaffar, and A. Rahman, "Preliminary Investigation on the Development of a Lower Extremity Exoskeleton for Gait Rehabilitation : A Clinical Consideration," 2015.

[2] Timothy Alan Swift ,"Control and Trajectory Generation of a Wearable Mobility Exoskeleton for Spinal Cord Injury Patients "University of California, Berkeley, 2011

[3] M. H Rahman, M. Saad "Exoskeleton Robot for Rehabilitation of Elbow and Forearm Movements", Morocco, 2010

[4] R. Jimenez-Fabian and O. Verlinden, " Review of control algorithms for robotic ankle system in lower-limb orthoses, prostheses and exoskeletons, " University de Mons, Belgium, May 2012

[5] G. J. Gelderblom, M. De Wilt, G. Cremers, and A. Rensma, "Rehabilitation robotics in robotics for healthcare; A roadmap study for the European Commission," International Conference on Rehabilitation Robotics, Jun. 2009.

[6] J. G. Nutt, C. D. Marsden, P. D. Thompson, "Human walking and higher-level gait disorders, particularly in the elderly", Neurology Feb 1993,

[7] O. Franch, L. Calandre, J. Álvarez-Linera, E. D. Louis, F. Bermejo-Pareja, and J. Benito-León, "Gait disorders of unknown cause in the elderly: Clinical and MRI findings, " J. Neurol. Sci, 2009.

[8]Jamshidi N, Rostami M, Najarian S, Menhaj M B, Saadatnia M, Firooz S. " Modelling of human walking to optimise the function of ankle-foot orthosis in Guillan-Barre patients with drop foot", Singapore Med J 2009.

[9] Flansbjer UB, Miller M, downham D, Lexell J, " Progressive resistance training after stroke: effects on muscle strength, muscle tone, gait performance and perceived participation", J Rehabil Med 2008.

[10] Loudon J, et al." The clinical Orthopaedic assessment guide". 2nd ed. Kansas: Human Kinetics, 2008.

[11] Rai, Jaynendra Kumar, and Ravi Tewari. " Quintic polynomial trajectory of biped robot for human-like walking" In communications, control, signal and processing(ISCCSP), 2014

[12] Marwan Qaid Mohammed, Muhammad Fahmi Miskon, Mohd Bazli Bin Bahar, "Generating High Accuracy Motion Profiling Based on Biomechanical Analysis Techniques For Exoskeleton System',Center of Excellence in Robotic and Industrial Automation, Malaysia Melaka

[13] Gabriele Bovi, Marco Rabuffetti, Paolo Mazzoleni, Maurizio Ferrarin ," A multiple-task gait analysis approach : kinematic, kinetic and EMG reference data for healthy young and adult subjects", Polo Technologico, IRCCS S.Maria Italy, 2010

[14] Shultz SJ et al. "Examination of musculoskeletal injuries". 2nd ed, North Carolina: Human Kinetics, 2005.

[12] Alessandro Gasparetto, Vanni Zanotto, "A technique for time-jerk optimal planning of robot trajectories", Udine Italy,2007

[13] Ali, S.A. & Mohd Anuar, Khalil & Muhammad Fahmi Miskon , " Trajectory Planning For Exoskeleton Robot By Using Cubic And Quintic Polynomial Equation " Universiti Teknikal Malaysia Melaka, 2016

[14] Alessandro Gasparetto, Vanni Zanotto, "A new method for smooth trajectory planning of robot manipulators", Udine Italy,2006

[15] J.Peters, S.Schaal, “Learning to Control in Operational Space”, International Journal of Robotics Research, Vol.27, No.2, 197-212, 2008.

[16] Marwan Qaid Mohammed, Muhammad Fahmi Miskon, Mohd bazli bin bahar, Sari abdo ali. “Comparative Study Between Quintic and Cubic Polynomial Equations Based Walking Trajectory of Exoskeleton System “ Universiti Teknikal Malaysia Melaka, August 2017.

[13] Albano lanzutti,” Smooth trajectory planning algorithms for industrial robots: an experimental evaluation” universita' di udine, udine – italy ,2011

[14] Ben Ezair, Tamir Tassa and zvi Shiller, “Planning high order trajectories with general initial and final conditions and asymmetric bound”,The international journal of robotics research, 2014

[15] Vanni Zanotto, Alessandro Gaparetto, Albano Lanzutti, Paolo Boscariol, Renato Vidoni, “ Experimental validation of Minimum Time- Jerk Algorithm for Industrial Robot”,Udine, Italia,2011

[16] Pierre-Jean Barre, Richard Bearee, Pierre Borne, and Eric Dumetz, “Influence of a jerk controlled movement law on the vibratory behaviour of high-dynamics systems”, Journal of Intelligent and Robotic Systems

[17] Robert L. William II, “Simplified Robotics Joint-Space Trajectory Generation with a Via Point using a single Polynomial “Ohio University Athens,2013

[18] Piazzi and Visioli, “ Global minimum- jerk trajectory planning of robot maniplators “. IEEE Transaction on Industrial Electronics47(1): 140-149 , 2000

[19] Liu S, “ An on-line reference trajectory generator for smooth motion of impulse-controlled industrial manipulators “,Maribor, Slovenia 5 july 2002

[20] Lambrechts P, Boerlage M and Steinbuch M, “Trajectory planning and feed forward design for high performance motion system “,July 2004

[21] Macfarlane and Croft, “Jerk Bounded manipulator trajectory planning : Design for real time applications “, IEEE Transaction on Robotics and Automation, 2003

[22] Petrinec and Kovacic, “ Trajectory planning algorithm based on the continuity of jerk “,Athens, 29 June 2007

APPENDICES

APPENDIX

A . Code for Experiment 1

```
i=0;
thetaf = 4.289575458; % final angle

for t = 0:0.5:0.1
tf=0.1; % final time
theta0 = 0.04294014; %initial angle
a0 = theta0;
i = i+1;
a1 = 5.35326362; % velocity value
a2 = (3/tf^2)*(thetaf-theta0);  % cubic coefficient
a3 = (-2/tf^3)*(thetaf-theta0); %cubic coefficient
time(i,1) = t;
theta(i,1) = a0 + a1*t + a2*t^2 + a3*t^3;  %position
thetadot(i,1) = a1 + 2*a2*t + 3*a3*t^2; % velocity
thetaddot(i,1) = 2*a2 + 6*a3*t;          % acceleration
end


 for t = 0.101:0.5:0.3
tf=0.3;
theta0 = 7.75888319; %initial angle
a4 = theta0;
a5 = -5.420284748; %velocity value
a6 = (3/tf^2)*(thetaf-theta0);
a7 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a4 + a5*t + a6*t^2 + a7*t^3; %position
thetadot(i,1) = a5 + 2*a6*t + 3*a7*t^2;   % velocity
thetaddot(i,1) = 2*a6 + 6*a7*t;     % acceleration
 end

  for t = 0.301:0.5:0.5
tf=0.5;
theta0 = 5.109390545; %initial angle
a8 = theta0;
a9 = -0.24746323; % velocity value
a10 = (3/tf^2)*(thetaf-theta0);
a11 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a8 + a9*t + a10*t^2 + a11*t^3; %position
thetadot(i,1) = a9 + 2*a10*t + 3*a11*t^2;  % velocity
thetaddot(i,1) = 2*a10 + 6*a11*t;      % acceleration
  end

 for t = 0.501:0.5:0.60
tf=0.6;
```

```
theta0 = 20.297005653; %initial angle
a12 = theta0;
a13 = -6.06396198; % velocity value
a14 = (3/tf^2)*(thetaf-theta0);
a15 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a12 + a13*t + a14*t^2 + a15*t^3; %position
thetadot(i,1) = a13 + 2*a14*t + 3*a15*t^2;   % velocity
thetaddot(i,1) = 2*a14 + 6*a15*t;        % acceleration
 end

 for t = 0.601:0.5:0.73
tf=0.73;
theta0 = -112.504782696; %initial angle
a16 = theta0;
a17 = 1.9401766; % velocity value
a18 = (3/tf^2)*(thetaf-theta0);
a19 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a16 + a17*t + a18*t^2 + a19*t^3; %position
thetadot(i,1) = a17 + 2*a18*t + 3*a19*t^2;   % velocity
thetaddot(i,1) = 2*a18 + 6*a19*t;       % acceleration
 end

 for t = 0.7301:0.5:0.87
tf=0.87;
theta0 = -98.122700118; %initial angle
a20 = theta0;
a21 = 0.62487724; % velocity value
a22 = (3/tf^2)*(thetaf-theta0);
a23 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a20 + a21*t + a22*t^2 + a23*t^3; %position
thetadot(i,1) = a21 + 2*a22*t + 3*a23*t^2;   % velocity
thetaddot(i,1) = 2*a22 + 6*a23*t;       % acceleration
 end

for t = 0.8701:0.5:1
tf=1;
theta0 = -24.289575458; %initial angle
a24 = theta0;
a25 =  -3.171350578; % velocity value
a26 = (3/tf^2)*(thetaf-theta0);
a27 = (-2/tf^3)*(thetaf-theta0);
i = i+1;
time(i,1) = t;
theta(i,1) = a24 + a25*t + a26*t^2 + a27*t^3; %position
thetadot(i,1) = a25 + 2*a26*t + 3*a27*t^2;   % velocity
thetaddot(i,1) = 2*a26 + 6*a27*t;        % acceleration
end

%--------------------------------------
  t0 = 0:0.01:1;
  x1 = time;

 % Position Reference
 x0 = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];
```

```
 y0 = [0.507613778 6.04294014 4.55888319 2.309390545 -4.297005653 -
2.484782696 0.122700118 4.289575458];
 p0 = pchip(x0,y0,t0);

% Velocity Reference
 xv = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];
 yv = [0 55.35326362 -7.42028475 -11.24746323 -66.06396198
13.94017660 18.62487724 32.05288723];
 pv = pchip(xv,yv,t0);

% Acceleration Reference
 xa = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];  % ori acc
 yac = [0 9.660967018 -5.478025511 -0.333984328 -9.567283877
10.74104333 0.584024648 -2.926276451]; % ori acc
 pac = pchip(xa,yac,t0);

% Position Cubic
y1 = theta;
p1 = pchip(x1,y1,t0);

% Velocity Cubic
 ya = thetadot;
 pa = pchip(x1,ya,t0);

% Acceleration Cubic
y2 = thetaddot;
p2 = pchip(x1,y2,t0); % acc cubic


figure(1) % Position
plot(x0,y0,'o',t0,p0,'r') % Position Reference
hold on
plot(x1,y1,'o',t0,p1) % Position Cubic
xlabel('Time(t,sec)','FontSize',14)
ylabel('Angle(degrees)','FontSize',14)
title('\it{Position Profile for Hip}','FontSize',16)

figure(2) % Velocity
plot(xv,yv,'o',t0,pv)% Velocity Reference
hold on
plot(x1,ya,'o',t0,pa) % velocity Cubic
xlabel('Time(t,sec)','FontSize',14)
ylabel('Speed (degree/sec)','FontSize',14)
title('\it{velocity Profile for Hip}','FontSize',16)

figure(3) % Acceleration
plot(xa,yac,'o',t0,pac); % Acceleration Reference
hold on
plot(x1,y2,'o',t0,p2) % Acceleration Cubic
xlabel('Time(t,sec)','FontSize',14)
ylabel('Velocity(degrees/sec^2)','FontSize',14)
title('\it{Acceleration Profile for Hip}','FontSize',16)
```

B. Code for Experiment 2 (2,4,7 PHASE)

POSITION

```
i=0;
thetaf = 4.289575458; % final angle

for t = 0:0.5:0.6 % stance phase
tf=0.6;
theta0 = 0.297005653; %initial angle
a0a = theta0; i = i+1;
a1a = -10.06396198; %velocity value
a2a = (3/tf^2)*(thetaf-theta0);
a3a = (-2/tf^3)*(thetaf-theta0);
time2(i,1) = t;
theta2(i,1) = a0a + a1a*t + a2a*t^2 + a3a*t^3; %position
end


 for t = 0.601:0.5:1 % swing phase
tf=1;
theta0 = -1.0189575458; %initial angle
a4a = theta0;
a5a = -5.17135058; %velocity value
a6a = (3/tf^2)*(thetaf-theta0);
a7a= (-2/tf^3)*(thetaf-theta0);
i = i+1;
time2(i,1) = t;
theta2(i,1) = a4a + a5a*t + a6a*t^2 + a7a*t^3; %position
end


%------------------------------
  t0 = 0:0.01:1;
  x4 = time2; %2 phase
  x3 = time1; % 4 phase
  x1 = time; % 7 phase


 %  Position Reference
 x0 = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];
 y0 = [0.507613778 6.04294014 4.55888319 2.309390545 -4.297005653 -
2.484782696 0.122700118 4.289575458];
 p0 = pchip(x0,y0,t0);

%-----------------------------
y4 = theta2;
p4 = pchip(x4,y4,t0); % 2 phase position cubic

y3 = theta1;
p3 = pchip(x3,y3,t0); % 4 phase position cubic

y1 = theta;
p1 = pchip(x1,y1,t0); % 7 phase position cubic


%Plot
```

```
figure(1)
plot(x0,y0,'o',t0,p0,'r') % position Reference
hold on
plot(x4,y4,'o',t0,p4,'b')% 2 phase position cubic
hold on
plot(x3,y3,'o',t0,p3,'g')% 4 phase position cubic
hold on
plot(x1,y1,'o',t0,p1,'y')% 7 phase position cubic
xlabel('Time(t,sec)','FontSize',14)
ylabel('Angle(degrees)','FontSize',14)
title('\it{Position Profile for Hip}','FontSize',16)
```

VELOCITY

```
i=0;
thetaf = 4.289575458; % final angle

for t = 0:0.5:0.6 % stance phase tf=0.6;
theta0 = -5.297005653; %initial angle
a0a = theta0;
i = i+1;
a1a = -8.06396198;
a2a = (3/tf^2)*(thetaf-theta0);
a3a = (-2/tf^3)*(thetaf-theta0);
time2(i,1) = t;
thetadot2(i,1) = a1a + 2*a2a*t + 3*a3a*t^2;   % velocity
end


 for t = 0.601:0.5:1 % swing phase
 tf=1;
theta0 = -6.0189575458; %initial angle
a4a = theta0;
a5a = -1.17135058; %velocity
a6a = (3/tf^2)*(thetaf-theta0);
a7a= (-2/tf^3)*(thetaf-theta0);
  i = i+1;
time2(i,1) = t;
thetadot2(i,1) = a5a + 2*a6a*t + 3*a7a*t^2;   % velocity
end



%---------------------------------
  t0 = 0:0.01:1;
  x4 = time2; %2 phase
  x3 = time1; % 4 phase
  x1 = time; % 7 phase

%Velocity Reference
xv = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];
yv = [0 55.35326362 -7.42028475 -11.24746323 -66.06396198
13.94017660 18.62487724 18.05288723];
pv = pchip(xv,yv,t0);

% Velocity Cubic
y4 = thetadot2;
p4 = pchip(x4,y4,t0); % 2 phase velocity cubic

y3 = thetadot1;
```

```
p3 = pchip(x3,y3,t0); % 4 phase velocity cubic

ya = thetadot;
pa = pchip(x1,ya,t0); % 7 phase velocity cubic

figure(2)
plot(xv,yv,'o',t0,pv,'r')% ori velo
hold on
plot(x4,y4,'o',t0,p4,'b')% 2 phase velo cubic
hold on
plot(x3,y3,'o',t0,p3,'g')% 4 phase position cubic
hold on
plot(x1,ya,'o',t0,pa,'y') % 7 phase velo cubic
```

ACCELERATION

```
i=0;
thetaf = 4.289575458; % final angle

for t = 0:0.5:0.6 % stance phase
tf=0.6;
theta0 = 1.297005653; %initial angle
a0a = theta0;
i = i+1;
a1a = -1.06396198;
a2a = (3/tf^2)*(thetaf-theta0);
a3a = (-2/tf^3)*(thetaf-theta0);
time2(i,1) = t;
thetaddot2(i,1) = 2*a2a + 6*a3a*t; % acceleration
end


for t = 0.601:0.5:1 % swing phase
tf=1;
theta0 = -20.0189575458; %initial angle
a4a = theta0;
a5a = -1.17135058; %velocity
a6a = (3/tf^2)*(thetaf-theta0);
a7a= (-2/tf^3)*(thetaf-theta0);
i = i+1;
time2(i,1) = t;
thetaddot2(i,1) = 2*a6a + 6*a7a*t;     % acceleration
end

%--------------------------------
  t0 = 0:0.01:1;
  x4 = time2; %2 phase
  x3 = time1; % 4 phase
  x1 = time; % 7 phase

% Acceleration Reference
  xa = [0 0.1 0.3 0.5 0.6 0.73 0.87 1];
  yac = [0 9.660967018 -5.478025511 -0.333984328 -9.567283877
10.74104333 0.584024648 -2.926276451]; % ori acc
  pac = pchip(xa,yac,t0);
```

```
% Acceleration Cubic
y4 = thetaddot2;
p4 = pchip(x4,y4,t0); % 2 phase acc cubic

y3 = thetaddot1;
p3 = pchip(x3,y3,t0); % 4 phase acc cubic

y2 = thetaddot;
p2 = pchip(x1,y2,t0); % 7 phase acc cubic

 figure(3)
 plot(xa,yac,'o',t0,pac); % ori acc
 hold on
 plot(x4,y4,'o',t0,p4,'b')% 2 phase acc cubic
 hold on
 plot(x3,y3,'o',t0,p3,'g')% 4 phase acc cubic
 hold on
 plot(x1,y2,'o',t0,p2,'y') % 7 phase acc cubic
```