" I hereby declare that I have read through this report entitle " Modeling Sit to Stand Motion of Humanoid Robot using Telescopic Inverted Pendulum for Predicting Stable Motion " and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Mechatronics) "

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Date : ....

MODELING SIT TO STAND MOTION OF HUMANOID ROBOT USING TELESCOPIC INVERTED PENDULUM FOR PREDICTING STABLE MOTION

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A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Mechatronic Engineering

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2013/2014

I declare that this report entitle " Modeling Sit to Stand Motion of Humanoid Robot using Telescopic Inverted Pendulum for Predicting Stable Motion " is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Sit to Stand (STS) motion is a challenging motion for any humanoid robot. Hence, development in humanoid robotics system is essential. In biomechanical fields, several models have been developed through observation of STS motion from human subjects. One of the models developed is based on telescopic inverted pendulum (TIP) concept which is an inverse kinematics concept. TIP model is the most suitable for STS trajectory generation since that TIP model focuses on motion of center of mass of human body in Cartesian space. However, the suitability of TIP model for representing the STS motion of humanoid robot is unknown. Furthermore, the resulting torque (Nm) from motion generated by TIP model has not been validated hence the accuracy of the robot when implementing the STS trajectory from the model is unknown. Therefore, the research on modeling STS motion of humanoid robot using TIP for predicting stable motion is proposed for the contribution to the development of humanoid robotics field as well as rehabilitation, prosthetic and exoskeleton robots. The objectives of this project is to model and validate sit to stand behavior using TIP model by simulation prove and to validate accuracy of TIP model in representing STS motion by comparing the output torque with three-link multi-segment robot. This project is carried out by MATLAB simulation in terms of the TIP model output and three-link multi-segment robot torque. The theoretical (based on three-link multi-segment robot) and actual (based on TIP model) torque (Nm) acted on COM are compared and analyze using statistical technique in terms of mean, percentage error and RMSE. Based on the analysis, there is high accuracy exist for TIP model in representing seat-off movement since the RMSE value is only 0.4207 and there is inaccurate for the seat-unloading phase. The deviation from actual value may be due to the model doesn't taking account of momentum components. Therefore, in future, these all parameters must be taken into account in order to increase the accuracy of TIP model in representing STS motion.

ABSTRAK

Pergerakan duduk dan berdiri (STS) merupakan pergerakan yang mencabar bagi semua jenis robot humanoid. Oleh itu, pembangunan dalam bidang robotik humanoid adalah penting. Dalam bidang-bidang biomekanik, beberapa model telah diciptakan melalui pemerhatian daripada pergerakan STS manusia. Salah satu model yang diciptakan adalah berdasarkan konsep teleskopik terbalik bandul (TIP) yang berkaitan dengan konsep kinematik songsang. Model TIP adalah antara yang paling sesuai untuk STS generasi trajektori kerana model ini menumpu kepada pergerakan pusat jisim (COM) tubuh manusia dalam ruang Cartesian. Walau bagaimanapun, kesesuaian model ini untuk mewakili pergerakan STS untuk robot humanoid masih tidak diketahui. Tambahan pula, torque daripada pergerakan yand terhasil oleh model TIP masih belum disahkan dan ketepatan robot apabila melaksanakan trajektori STS dari model itu tidak ketahui. Oleh itu, penyelidikan ke atas kestabilan pergerakan STS robot humanoid dijalankan untuk sumbangan kepada pembangunan bidang robotik humanoid. Objektif projek ini adalah untuk megesahkan kelakuan STS meggunakan model TIP dari segi simulasi dan eksperimen dan untuk megesahkan ketepatan model TIP dalam mewakili gerakan STS dengan membandingkan output torque dengan tiga-dimensi robot. Projek ini dilaksanakan dengan simulasi MATLAB dari segi output model TIP dan tiga-dimensi robot torque. Nilai torque teori (berdasarkan tiga-dimensi robot) dan nilai torque sebenar (berdasarkan model TIP) bertindak pada COM dibandingkan dan dianalisis dengan penggunaan kaedah statistic dari segi mean, peratusan error dan RMSE. Berdasarkan analisis, ketepatan untuk model TIP mewakili pergerakan bangun dari kerusi adalah tinggi dengan RMSE yang bernilai 0.4207 tetapi bagi pergerakan masa duduk, ketepatan adalah rendah. Sisihan dari nilai sebenar mungkin disebabkan oleh model TIP tidak mengambil kira komponen momentum. Oleh itu, pada masa akan dating, semua parameter tersebut mesti diambil kira untuk meningkatkan ketepatan model TIP dalam mewakili gerakan STS.

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CHAPTER 1

INTRODUCTION

The first chapter includes motivation, problem statement (involving research questions and hypothesis), project objectives, scope of the project, list of contribution of this project in the development of humanoid robotics field and outline of the dissertation.

1.1 Motivation

An excellent robot including humanoid robot should be able to perform anthropomorphic actions such as walking, running, jumping as well as sitting and standing up from a chair. The motion of sitting and standing up from a chair seems to be easier and is our common routine everyday but actually it is a challenging motion for elderly people and those with mobility disorders. The humanoid robots also facing difficulty in performing sit to stand (STS) motion since that they unable to maintain balance while performing the actions, unless they bolted to the floor.

The study related to stability of STS motion of humanoid robots is important for contribution in robotics field and preventing the robot from falling down when it moves from a large support position to much smaller one above the feet. From the research [3], precise COM control is a key to be successful in performing the STS motion. As the center of mass (COM) position is lower, its stability is increase. Hence, in this paper, we are modeling the stable STS motion of humanoid robot by investigating the displacement of COM position and couple vector using telescopic inverted pendulum model to prevent damage on a costly humanoid robot.

1.2 Problem Statement

Sit to Stand (STS) is a challenging motion for any humanoid robot. Hence, development in humanoid robotics system is essential. In biomechanical field, several models have been developed through observation of STS motion from human subjects. One of the models developed is based on telescopic inverted pendulum (TIP) concept which is an inverse kinematics concept. TIP is the most suitable for STS trajectory generation since that TIP focuses on motion of center of mass of human body in Cartesian space. However, the suitability of using the TIP model for humanoid STS motion is unknown. Furthermore, the resulting torque (Nm) from motion generated by TIP model has not been validated hence the accuracy of the robot when implementing the STS trajectory from the model is unknown.

1.2.1 Research Questions

1. Does the telescopic inverted pendulum model output suitable used to describe the behavior of STS motion of humanoid robots?
2. What are the relationship between the torque (Nm) and the TIP equation? Does the relationship predicted from TIP model able to stabilize and balance a humanoid robot when applying the STS trajectory?
3. How the cubic polynomial profile could be used to predict the STS trajectory?
4. What are the relationship between the torque (Nm) and the parameters of cubic polynomial profile?
5. How much the percentage of accuracy of TIP model in representing STS motion by making comparison with three-link multi-segment robot?

1.2.2 Hypothesis

1. The couple vectors predicted by the telescopic inverted pendulum model for STS trajectory profile will be the same with the couple vector produce by humanoid robot.
2. The torque magnitude and position of humanoid robots could be correlated to the couple vector in the TIP model.
3. The mathematical models created from TIP model will be able to apply in a humanoid robot for STS stability purpose although with different mass and configuration in any sitting condition.

1.3 Project Objectives

- To model and validate sit to stand behavior using telescopic inverted pendulum model by simulation prove.
- To validate accuracy of TIP model in representing STS motion by comparing the output torque with three-link multi-segment robot.

1.4 Scope of the Project

i. The research is focused on model and validates sit to stand motion using telescopic inverted pendulum model.
ii. The displacement of COM position is referred to the available sources.
iii. The sit to stand motion is performed in selected configuration of sitting condition including height of seated position.
iv. The performance of TIP model is discussed in terms of accuracy.
v. The simulation and analysis is done by MATLAB software.
vi. The results predicting from TIP model in terms of torque is compared with the output torque obtained from three-link multi-segment humanoid robot for accuracy estimation.

1.5 List of Contribution

Studies in STS contribute much in the development of humanoid robotics field as well as rehabilitation, prosthetic and exoskeleton robots. The development of robotics encourages the good impact to society, economy and nation. However, in Malaysia, the study related to robotics field only begins recently and thus require more attention and bring toward successful.

(a) Contribution to Society

Innovation of humanoid robots and exoskeleton robots will contribute to the improvement of working lifestyle in hazardous, dirty or toxic environments. The robots can be assist humans from performing dangerous tasks in unsatisfactory condition, repeated and demeaning but is compulsory for manufacturing. Furthermore, the research will also assist paraplegic or mobility disorders person in the development of rehabilitation and exoskeleton robots to enhance their sit to stand abilities and assist them to be a normal human.

(b) Contribution to Economy

The application of robotics in manufacturing sector will enhance Malaysia economy by increasing the efficiency of productivity. The automation technique enable the manufacturing carried out continuously since the robots able to perform repeated, hard and boring tasks for a long period. Besides that, the expert of Malaysia in robotics field can encourage the investment of foreigner and hence boost the growth of economy. Malaysia can also provide healthcare service of the robots.

(c) Contribution to Nation

The exposure to robotics field will strengthen Malaysia technological capability and hence enhance Malaysia's reputation and put Malaysia to be in the same league with nation from developed countries such as Japan, United States and so on. This will lead to increasing of nation morale by having a good achievement to be proud of. In addition, foreign investors will realize Malaysia is a potential country and hence bring Malaysia for national development.

1.6 Outline of the Dissertation

i. Chapter 1 describes engineering problem designated and goals to be achieved as well as limitations of the research work.

ii. Chapter 2 describes published information related to sit to stand motion and performance indices used for evaluation of the model.

iii. Chapter 3 describes method designed to evaluate the performance of sit to stand model in terms of accuracy.

iv. Chapter 4 describes the findings obtained and analysis using statistical techniques as well as the interpretation of the result obtained with proof.

v. Chapter 5 concludes the findings and describes the future research.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

This chapter highlights past studies related to sit to stand (STS) motion and also theoretical background that is necessary for the development of a stable STS motion trajectory of humanoid robot using telescopic inverted pendulum (TIP) model. There are few parts divided in this chapter. The first part focuses on the center of mass (COM) trajectory of STS motion. Accurate knowledge of robot COM position throughout the trajectory is important in planning a stable STS motion without falling. The second part is about the robotics background that is required for generating COM trajectory in developing a successful STS motion trajectory. The third part is followed by the design parameters involved in this STS research and the forth part is about the performance indices used to measure the performance of the TIP system generated. The fifth part highlights the comparison among the available solutions developed for representing STS motion. At last, this chapter is ended by summarization of the past studies (gap of knowledge).

2.1 Center of Mass (COM) Trajectory for STS Motion

Center of mass (COM) has been considered as an essential point for humanoid robot motion. A consistent COM trajectory allows the performing of a stable sit to stand motion. The COM trajectory tracks a path of COM through a sagittal plane of the human demonstrator. Figure 2.1 describes a human demonstration of a sit to stand action and a corresponding humanoid robot sit to stand action based on the human demonstration, according to one embodiment of the invention. As shown in the Figure 2.1, the COM of a human demonstrator and a humanoid robot varies from one support position (seated) to another (standing).

The human demonstrator 101 starts in a seated position 100 on a chair 104a. In the seated position 100, the COM 103a of the human demonstrator 101 is above the chair 104a. When the human demonstrator 101 stands at 110 and 120 respectively, the COM 103a of the human demonstrator 101 lowers slightly to 103b, and then increases to 103c. In the standing position at 130, the COM 103a of the human demonstrator 101 is located at 103d, directly above the feet of the human demonstrator 101.

The humanoid robot 151 sit to stand action is emulating the COM trajectory of human demonstrator 101 so that it won't fall over. The identity of the COM trajectory 107a of the human demonstrator 101 and the COM trajectory 107b of the humanoid robot 151 allows the maintenance of sit to stand action in stable condition. [18]

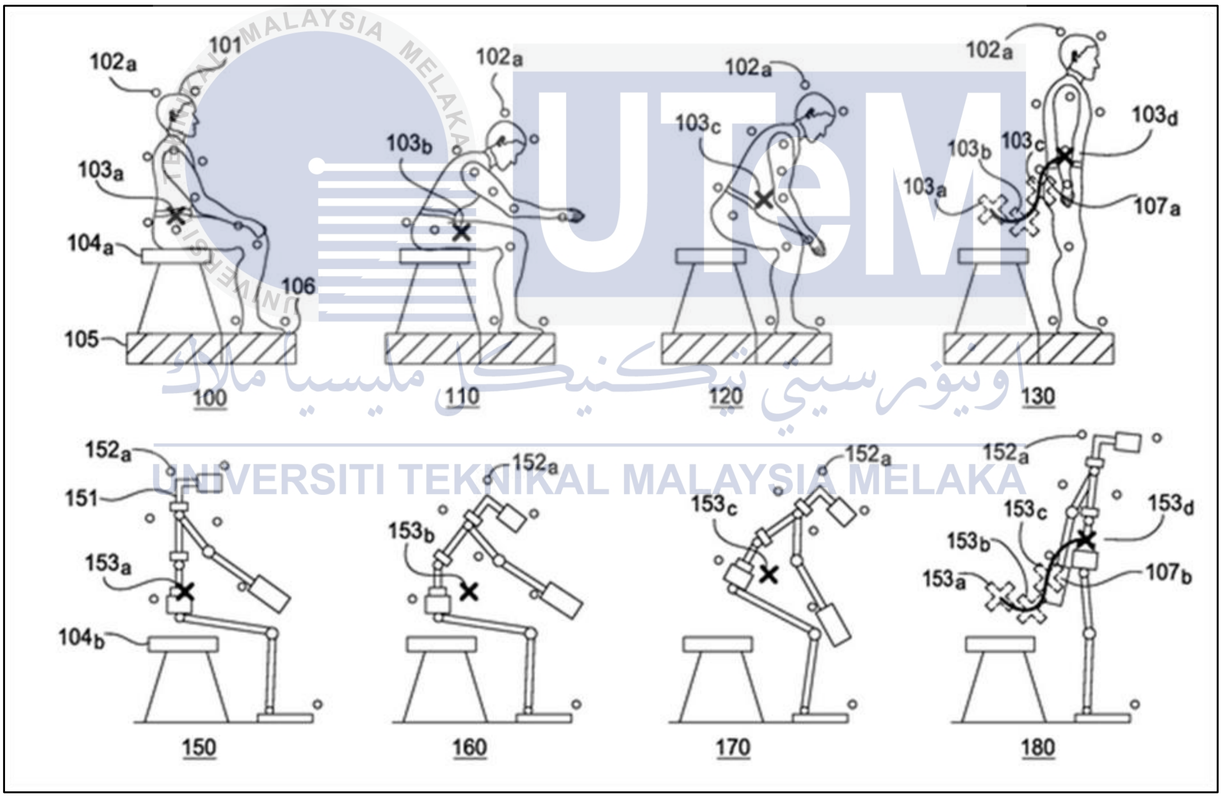


Figure 2.1: Procedure for generating humanoid robot STS motion trajectory from human demonstration [18]

2.2 Robotics Background for STS Motion

In this sub-section, theoretical robotics background that is required to develop a successful STS motion of humanoid robot is detailed up. The first part mentions about the trajectory generation that is required for creating COM trajectory profile of a stable STS motion using TIP model. The second part details out the inverse kinematics concept that is required for calculating the angle of hip, knee and ankle of a three-link humanoid robot in performing STS motion by considering the COM position. The third part focuses on the manipulator dynamic theorem that is needed to study the effect of force in developing a stable STS motion. The last part is an overview of system block diagram that shows the relationship between STS motion trajectory generated by TIP model and humanoid robot.

2.2.1 Trajectory Generation

Trajectory generation is related to the computation of desired motion of a manipulator to be smooth in multidimensional space. Trajectory refers to a time function of position, velocity, and acceleration for each degree of freedom. There are two methods to specify a trajectory or path through space which are joint-space schemes and Cartesian-space schemes. Joint-space schemes are defined as a path generation in which the path shapes (in space and in time) are described in terms of functions of joint angles while Cartesian-space schemes are described in terms of functions of Cartesian coordinates.

Planning in joint-space schemes are the simplest and easiest ways to compute compared with Cartesian-space schemes since that each joint motion is calculated independently from other joints, there is basically no problem with singularities of the mechanism. Joint-space schemes are using application of cubic polynomials concept. Theoretically, position, velocity, and acceleration profile of the joint can be calculated using the equations of cubic polynomials as shown in the following:

Position: $\theta(t) = \theta_0 + \frac{3}{t_f^2}(\theta_f - \theta_0)t_2 - \frac{2}{t_f^3}(\theta_f - \theta_0)t^3$ (2.1)

Velocity: $\dot{\theta}(t) = \frac{6}{t_f^2}(\theta_f - \theta_0)t - \frac{6}{t_f^3}(\theta_f - \theta_0)t^2$ (2.2)

Acceleration: $\ddot{\theta}(t) = \frac{6}{t_f^2}(\theta_f - \theta_0) - \frac{12}{t_f^3}(\theta_f - \theta_0)t$

(2.3)

Where θ_0 = initial angle of the motion, θ_f = final angle of the motion, t_f = rising time of the motion, and t = variable time domain. [19, pp.201-225]

2.2.2 Inverse Kinematic Theorem

Imagine a scenario of a robot that wants to perform STS motion regarding the current seat position. In order to stand up, the robot needs to bring its end effectors away from the seat. Given the whole body COM position of standing position, the robot needs to calculate the angles of each of its joint. Consider the three-link planar manipulator is introduced to solve the inverse kinematic solution. [19, pp.101-127]

The kinematic equation of the 3DOF robot is given as:

$$ {}^{B}_{W}T = {}^{0}_{3}T = \begin{bmatrix} c_{123} & -s_{123} & 0 & l_1c_1 + l_2c_{12} \\ s_{123} & c_{123} & 0 & l_1s_1 + l_2s_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Note: $c_{123} = \cos(\theta_1 + \theta_2 + \theta_3)$ and $s_{123} = \sin(\theta_1 + \theta_2 + \theta_3)$

The orientation and the position of the goal point with respect to the base are given as:

$$ {}^{B}_{W}T = \begin{bmatrix} c_{\Phi} & -s_{\Phi} & 0 & x \\ s_{\Phi} & c_{\Phi} & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Given that:

$$c_{\Phi} = c_{123} \tag{2.4}$$

$$s_{\Phi} = s_{123} \tag{2.5}$$

$$x = l_1 c_1 + l_2 c_{12} \tag{2.6}$$

$$y = l_1 s_1 + l_2 s_{12} \tag{2.7}$$

Square equation (2.6) and (2.7) and then add the result, equation (2.8) is obtained.

$$x^2 + y^2 = l_1^2 + l_2^2 + 2 l_1 l_2 c_2 \tag{2.8}$$

$$c_2 = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2} \tag{2.9}$$

Assuming the goal is in the workspace, s_2 is expressed as

$$s_2 = \pm\sqrt{1 - c_2^2} \tag{2.10}$$

Finally

$$\theta_2 = Atan2(s_2, c_2) \tag{2.11}$$

Having found θ_2, equation (2.6) and (2.7) can be solved for θ_1. Rewrite equation (2.6) and (2.7) in the form

$$x = k_1 c_1 - k_2 s_1 \tag{2.12}$$

$$y = k_1 s_1 + k_2 c_1 \tag{2.13}$$

Where

$$k_1 = l_1 + l_2 c_2 \tag{2.14}$$

$$k_2 = l_2 s_2 \tag{2.15}$$

In order to solve an equation of this form, a change of variables are performed.

$$r = +\sqrt{k_1^2 + k_2^2} \tag{2.16}$$

$$\gamma = Atan2(k_2, k_1) \tag{2.17}$$

$$k_1 = r cos\gamma \tag{2.18}$$

$$k_2 = r sin\gamma \tag{2.19}$$

Equation (2.14) and (2.15) can now be written as:

$$\frac{x}{r} = cos\gamma cos\theta_1 - sin\gamma sin\theta_1 \quad (2.20)$$

$$\frac{y}{r} = cos\gamma sin\theta_1 + sin\gamma cos\theta_1 \quad (2.21)$$

Rearranging those gives:

$$\cos(\gamma + \theta_1) = \frac{x}{r} \quad (2.22)$$

$$\sin(\gamma + \theta_1) = \frac{y}{r} \quad (2.23)$$

Using the arctangent we get:

$$\gamma + \theta_1 = Atan2\left(\frac{y}{r}, \frac{x}{r}\right) = Atan2(y, x) \quad (2.24)$$

$$\theta_1 = Atan2(y, x) - Atan2(k_2, k_1) \quad (2.25)$$

$$\theta_1 + \theta_2 + \theta_3 = Atan2(s_\Phi, c_\Phi) = \Phi \quad (2.26)$$

Finally

$$\theta_3 = \Phi - \theta_1 - \theta_2 \quad (2.27)$$

2.2.3 Manipulator Dynamics

The external forces or torques required for the STS motion of a manipulator can be described using Newton-Euler equations. If the linear and angular accelerations of the mass center of each link are available, then Newton-Euler equations as followed can be applied to compute the inertial force and torque acting at the center of mass of each link.

$$F_i = m\dot{v}_{C_i} \quad (2.28)$$

$$N_i = {}^{C_i}I\dot{\omega}_i + \omega_i \times {}^{C_i}I\omega_i \quad (2.29)$$

Where $\{C_i\}$ has its origin at the center of mass of the link and has the same orientation as the link frame, $\{i\}$. [19, pp. 165-192]

2.2.4 System Block Diagram

Figure 2.2 shows the relationship between the STS motion trajectory generator and the physical NAO humanoid robot. From the beginning, the desired angles will act as a source to the controller. A vector of joint torques, τ from the controller is then received by the robot. The manipulator's sensors in the block diagram allow the controller to read the vectors of joint angles. The feedback then is used to compute any error by finding the difference between the desired and the actual angles. As a result, the controller can compute actuator torques required to reduce the errors. [19, pp. 262-285]

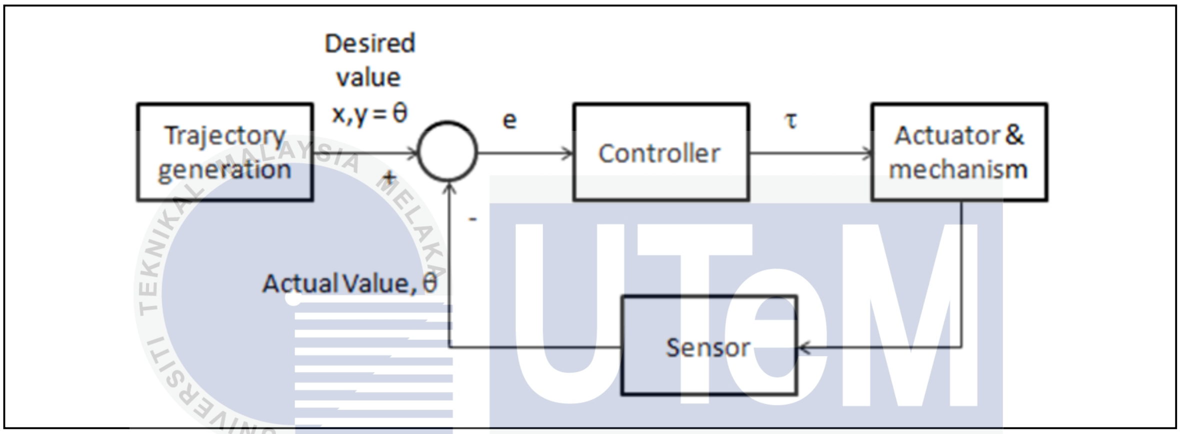


Figure 2.2: General block diagram of STS motion

2.3 Dynamics Characteristics of Three-Link Multi-Segment

Figure 2.3 shows a three-link segment model comprised of an upper body, a thigh and a lower leg and three joints included of a hip joint, a knee joint and an ankle joint that are used to perform STS motion. The dynamics parameters involved in the STS dynamic simulation are referred to Table 2.1. By given a trajectory point, the joint angle, $\boldsymbol{\theta}$, the joint angular velocity, $\dot{\boldsymbol{\theta}}$, and the joint angular acceleration, $\ddot{\boldsymbol{\theta}}$, the required vector of joint torques, $\boldsymbol{\tau}$ for performing STS motion can be calculated. The dynamics formula as followed is applied during the seat-off movement since the whole body is moved during that period.

$$\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\end{bmatrix} = \begin{bmatrix}M_{11} & M_{12} & M_{13}\\ M_{21} & M_{22} & M_{23}\\ M_{31} & M_{32} & M_{33}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\\ \ddot{\theta}_3\end{bmatrix} + \begin{bmatrix}h_1\\ h_2\\ h_3\end{bmatrix} + \begin{bmatrix}g_1\\ g_2\\ g_3\end{bmatrix} + \begin{bmatrix}D_1 & 0 & 0\\ 0 & D_2 & 0\\ 0 & 0 & D_3\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\\ \dot{\theta}_3\end{bmatrix} \quad (2.30)$$

$$= M\ddot{\theta} + h + g + D\dot{\theta}$$

$$M_{11} = J_1 + J_2 + J_3 + 2b_{12}\cos(\theta_2) + 2b_{13}\cos(\theta_2 + \theta_3) + 2b_{23}\cos(\theta_3)$$

$$M_{12} = M_{21} = J_2 + J_3 + b_{12}\cos(\theta_2) + b_{13}\cos(\theta_2 + \theta_3) + 2b_{23}\cos(\theta_3)$$

$$M_{13} = M_{31} = J_3 + b_{13}\cos(\theta_2 + \theta_3) + b_{23}\cos(\theta_3)$$

$$M_{22} = J_2 + J_3 + 2b_{23}\cos(\theta_3)$$

$$M_{23} = M_{32} = J_3 + b_{23}\cos(\theta_3)$$

$$M_{33} = J_3$$

$$J_1 = m_1 L_{c1}^2 + (m_2 + m_3)L_1^2 + I_1$$

$$J_2 = m_2 L_{c2}^2 + m_3 L_2^2 + I_2$$

$$J_3 = m_3 L_{c3}^2 + I_3$$

$$b_{12} = m_2 L_1 L_{c2} + m_3 L_1 L_2$$

$$b_{13} = m_3 L_1 L_{c3}$$

$$b_{23} = m_3 L_2 L_{c3}$$

$$h_1 = \{-b_{12}\sin(\theta_2) - b_{13}\sin(\theta_2 + \theta_3)\}(\dot{\theta}_2^2 + 2\dot{\theta}_1\dot{\theta}_2$$

$$- \{b_{13}\sin(\theta_2 + \theta_3) + b_{23}\sin(\theta_3)\}(\dot{\theta}_3^2 + 2\dot{\theta}_2\dot{\theta}_3 + 2\dot{\theta}_1\dot{\theta}_3)$$

$$h_2 = \{b_{12}\sin(\theta_2) + b_{13}\sin(\theta_2 + \theta_3)\}\dot{\theta}_1^2 - b_{23}\sin(\theta_3)(\dot{\theta}_3^2 + 2\dot{\theta}_2\dot{\theta}_3 + 2\dot{\theta}_1\dot{\theta}_3)$$

$$h_3 = \{b_{13}\sin(\theta_2 + \theta_3) + b_{23}\sin(\theta_3)\}\dot{\theta}_1^2 + b_{23}\sin(\theta_3)(\dot{\theta}_2^2 + 2\dot{\theta}_1\dot{\theta}_2)$$

$$g_1 = \{a_1\cos(\theta_1) + a_2\cos(\theta_1 + \theta_2) + a_3\cos(\theta_1 + \theta_2 + \theta_3)\}g$$

$$g_2 = \{a_2\cos(\theta_1 + \theta_2) + a_3\cos(\theta_1 + \theta_2 + \theta_3)\}g$$

$g_3 = a_3 \cos(\theta_1 + \theta_2 + \theta_3) g$

$a_1 = m_1 L_{c1} + (m_2 + m_3) L_1$

$a_2 = m_2 L_{c2} + m_3 L_2$

$a_3 = m_3 L_{c3}$

Meanwhile, during the seat-unloading period, only one link and one joint which is hip joint (joint 3) are involved since only the upper body is moved. Hence, the equation of motion only covered for torque 3. The formula is as followed: [21]

$$\tau_3 = M_{33} \ddot{\theta_3} + D_3 \dot{\theta_3} + g_3 \quad (2.31)$$

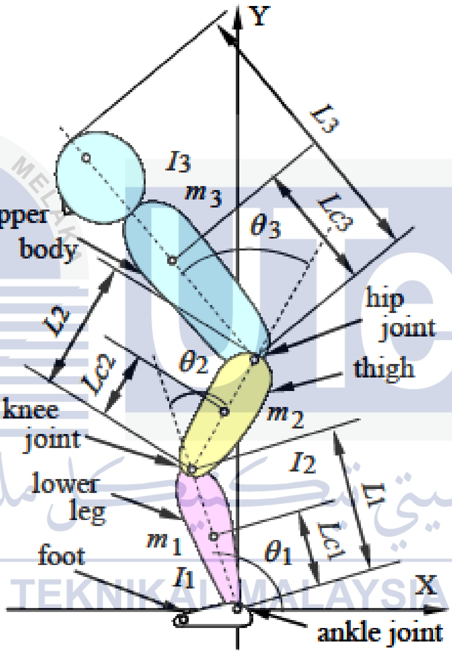


Figure 2.3: A three-link and three joint model of humanoid robot

Table 2.1: Dynamics parameters of three-link manipulator robot used for simulations

Parameter	Link 1	Link 2	Link 3
$L_i[m]$	0.4	0.3	0.6
$L_{ci}[m]$	0.195	0.228	0.3
$m_i[kg]$	7.738	16.644	45.990
$I_i[kgm^2]$	0.008	0.056	1.087
$D_i[Nm\ s/rad]$	0.440	1.050	3.750

2.4 Design Parameters

The parameters involved in STS research are:

i. COM position (x, y m)
ii. Angular velocity (rad/sec)
iii. Couple vector (Nm) acted on COM

2.5 Indicator of a Good STS Model

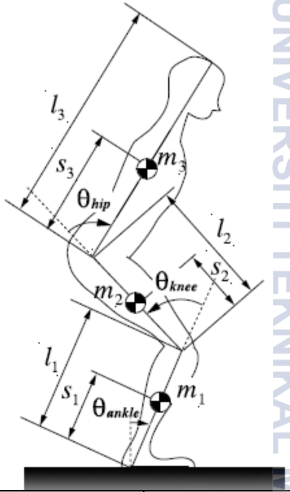
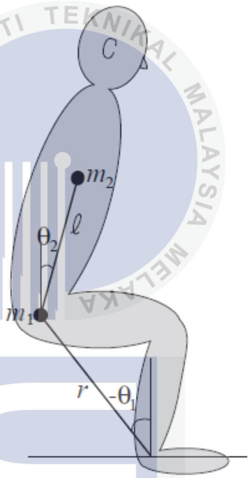
As a good STS model, the result predicted from TIP model should able to allow a humanoid robot perform STS motion in stable and accurate condition. A stable STS motion will prevent the humanoid robot from falling down and facing sitback failures. The robot should able to maintain its stability when it bends until a certain angle during execution of STS motion. Dynamic formulation is important to ensure the robot in stable condition at all the phases during STS motion.

The suitability of TIP model to represent STS motion of humanoid robot is unknown and haven't validated yet. The predicting result gained from TIP model also haven't investigated yet. Therefore, it is important to measure the accuracy of the result from TIP model with three-link multi-segment robot before apply onto the real robot in order to identify the suitability of TIP model in representing STS motion. The dynamics and kinematics properties of human and robot are different, thus error may be exist when applying the result onto the robot. Therefore, a detail research for indicating the behavior of model in representing STS motion is essential.

2.6 Comparison among Different Existing Model – Trade Off

In biomechanical field, there are several models have been developed for representing STS motion. Table 2.2 shows the comparison between available dynamic models for representing STS motion which including three-link inverted pendulum, two link elastic inverted pendulum, single rigid pendulum and telescopic inverted pendulum. These models are different from the aspect of data collection, instrumentation, modeling approach, performance parameter and manipulator dynamics applied. All these models are also having their limitation.

Table 2.2: Comparison between available dynamic models for representing STS motion

Model types	Three-link inverted pendulum		Two-link elastic inverted pendulum		Single rigid pendulum	Telescopic inverted pendulum
Model illustration or description					A model of foot segment used to introduce constraints on the dynamics of a three-joint planar model of standing.	A model representing musculoskeletal system that could vary its length (elastic).
Researchers	Hemami and Jaswa (1978)	Music et al. (2008)	Roberts and McCollum (1996)	Aissaoui et al. (2011)	Pai and Patton (1997)	Papa and Cappozzo (1999)
Data collected	Angles and angular rates	Inertial sensor type data and joint moments	-	Kinematics, kinetics and accelerometric surface data	-	Uniaxial load cell data
Instrumentation	Television camera-computer system	Inertial sensors, Optotrak optical motion analysis system	-	Complex laboratory setting (i.e.optoelectronic motion capture, force plate and inertial measurement	-	Two force platforms and photographic apparatus

				unit)		
Modeling approach	Derivation of open loop and feedback torques	Extended Kalman filter (EKF) design	Topological biomechanics	Correlation of conjugate momentum with accelerometric index	Optimization algorithm	Center of mass trajectory
Performance parameter	Internal feedback gains	Segment orientations, angular velocities and angular accelerations	Topological structure	Conjugate momentum	Center of mass velocity-position	Ground reaction forces
Manipulator dynamics	Newtonian or Lagrangian dynamics	Lagrangian and Newton-Euler inverse dynamics	Hamiltonian dynamics	Lagrangian dynamics (rotational and translational dynamics)	Dynamics of the pendulum	Newtonian-Euler dynamics
Limitation	Not clear that such algorithms are utilized by human in their everyday normal locomotion (no experimental evidence of magnitudes of feedback gains utilized by humans).	Valid only when there is no subject-seat interaction due to model limitations introduced in modeling phase.	Lose predictability of following a specific trajectory of a particular model given a set of initial conditions.	Limited to analysis of sagittal motion of STS.	Defined only in second phase of STS after seat-off event.	Did not describe transition phase and show discontinuities at seat-off instant.

2.7 Summary of Literature Review

The studies of sit to stand motion (STS) contribute much in robotics field especially in the field of rehabilitation [1], exoskeleton [2] as well as humanoid robotics. A motion control algorithm is applied in a robotic walking support system to assist elderly people with mobility problem perform STS based on the desired support knee torque [1]. In exoskeleton robotics [2], a Human Machine Interface (HMI) is developed for the purpose of sensing and translating user's natural gestures into desired motion in safety condition.

Besides standing, walking and jumping, STS motion also plays an important role in making a humanoid robot more humanlike. The research [3] identified the human's center of mass (COM) trajectory as a guide for the humanoid robot. The kinematics and dynamics characteristics of humanoid robotics are different with human, hence, [4] focused on the analysis of the characteristics of sitting states, standing states as well as state transition from sitting to standing for humanoid robot using generalized function (G_F) set. It concluded that the more supported points, the less force have to be applied for STS.

There are many challenging problems exist in performing STS motion such as the liftoff from chair problem. The liftoff from chair problem happens when initial liftoff, hip contacts the chair again and foot touches the floor become much smaller in a shorter time [3, 7]. The phenomena was proven clinically in [8] where the findings shown that a lot of parameters including torque at each joint and COM position should be control at this point within a short time. As a result, sitback failures occur when the problem is failed to overcome [7].

To overcome the problem, a humanoid STS control system should include (1) phase and trajectory planning and (2) proper motion control [3] so that the zero moment point (ZMP), center of pressure (COP) and center of mass (COM) are in accurate position for performing a stable STS motion.

In planning a successful phase and desired trajectory, there are few constraints of robot have to be considered and resolved. One of the limitations is that at sitting position, a humanoid robot's ankle joint is unable to provide sufficient force to maintain the STS motion in balance equilibrium if the robot bends forward too much [5]. There is few researches focus on how to plan a proper phase and trajectory in STS motion. For example, P.O. Riley [7] introduces stability strategy and momentum-transfer while S.S.M. Coghlin [9] represents STS motion by knee strategy and trunk hip strategy for the purpose of overcoming the constraints of the humanoid robot. Besides investigating the need of the STS motion, W. Fu-Cheng [10] proposes implementation of Alexander STS technique into the robot motion to obtain proper COM position so that to stabilize STS movement.

2.7.1 Sit to Stand Motion Model

STS motion model is vital 1) for estimating the torque and forces at each joint, 2) for analyzing factors that influence the joint torque and the ground reaction force, and finally 3) for simulating the STS motion. In the field of robotics, recorded STS motion from human demonstration is mapped to the humanoid robot STS trajectory [3, 5, 11]. However, it taken time for approaches since the kinematics and dynamics properties of human and robot are different. Therefore, STS motion model is developed for the purpose of planning suitable trajectory for a designated humanoid robot.

In the field of biomechanics, several non-linear dynamic models of STS motion such as three-link inverted pendulum [12-13], two link elastic inverted pendulum [14-15], single rigid pendulum [16] and telescopic inverted pendulum (TIP) [17] have been developed for the purpose of studying the structural stability, balance and energy transfer during execution of STS task.

On a three link model in sagittal plane with three degrees of freedom of motion [12-13], equations of STS motion and control algorithms are studied for producing desired STS trajectories. The proposed three link model represents three segments of human body which are torso, thigh and leg segment. Open loop and feedback torques are derived to estimate appropriate feedback gains for the study of postural control and structural stability of STS motion [12]. Meanwhile, the model [13] focuses on STS motion analysis using inertial sensors.

From the development of a non-linear two link elastic inverted pendulum [14-15], conjugate momentum has proved to be robust to assess STS stability. Besides conjugate momentum, center of mass (COM) plays an important controlled variable in balancing a STS movement. The study [16] is using an inverted pendulum model with a foot segment for determination of a set of feasible COM velocity-position combination.

Originally, TIP model is developed for the purpose of helping those with mobility disorders [17]. TIP model is used to describe the kinematic and dynamic behavior of STS motion by using a pivot point varying its length. Among the existence models, TIP model is the most suitable for planning and analyzing a proper humanoid robot STS trajectory since it represents the STS motion and COM of the robot in Cartesian space. The instantaneous orientation in space of the TIP link that is of the relevant local frame relative to the base frame is represented using sequence of two rotations as shown in the following equations:

$$F = ma_{CM} \cdot \hat{l} - mg \cdot \hat{l} \tag{2.32}$$

$$C = \frac{d([J]\omega)}{dt} + \omega \times [J]\omega - \hat{l} \times mg \tag{2.33}$$

$$[J] = \begin{bmatrix} ml^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & ml^2 \end{bmatrix} \tag{2.34}$$

$$\omega = \begin{bmatrix} 0 & 1 & 0 \\ \sin\theta_F & 0 & 1 \\ \cos\theta_F & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_S \\ \dot{\theta}_F \\ 0 \end{bmatrix} \tag{2.35}$$

Where F and C is the force and couple vector supplied by the model's actuator, m represents the mass of the relevant body portion, $\hat{l}$ indicates the link versor, a_{CM} is the COM acceleration, mg is the gravitational force, $\hat{l} \times mg$ is its moment with respect to the centre of the hinge, J is the inertia matrix, ω is the angular velocity and θ_F and θ_S are the angles describing the rotations. F which is referred to the frontal actuator is corresponding with the lateral rotation while S which is referred to the sagittal actuator is corresponding with the forward and backward rotation. For STS motion, only forward and backward rotations are exist.

Based on the equations, it is shown that TIP has high potential being used to estimate the optimum couple vector of humanoid robot STS motion with respecting to the robot COM position and mass. In addition, appropriate position, speed and acceleration profile at any instantaneous time could also be gained from the equations.

However, the suitability of using the TIP model for humanoid robot STS motion is unknown and hasn’t been validated yet. Furthermore, the resulting torque (N) from motion generated by TIP model has not been validated hence the stability of the robot when implementing the STS trajectory from the model is unknown.

CHAPTER 3

RESEARCH METHODOLOGY

The methodology implemented in this project is MATLAB simulation. This chapter details out the type of simulation carried out to measure the validity and reliability of the STS research by using TIP model.

3.1 Validation of TIP Model

TIP model is used to describe the kinematic and dynamic behavior of STS motion by using a pivot point varying its length. As mentioned in literature review part, TIP model is the most suitable for planning and analyzing a proper humanoid robot STS trajectory since it represents the STS motion and COM of the robot in Cartesian space.

By referring to the schematic diagram in research [17] as shown in Figure 3.1, the behavior of STS motion is corresponding to the COM position of the relevant body portion. TIP 1 model is only considered the head-arm-torso (HAT) COM for the preceding seat-unloading period while TIP 2 model is considered the whole body (WB) COM for the seat-off period. The two TIP models are inapplicable during the transient phase of seat-unloading.

Therefore, in this section, COM trajectory for STS motion is first generated based on the desired end-effector position (from seat position to standing position) in Figure 3.1 by using cubic polynomial theorem. With the parameters gained from the COM trajectory such as initial and final angles to perform STS motion, appropriate position, velocity and acceleration profile at any instantaneous time are then generated in order to simulate the TIP model output in terms of couple vector that is required in performing STS motion. The couple vector obtained is representing the torque required for STS motion.

For the purpose of validation for the result obtained from TIP model, a three-link multi-segment robot that is similitude with the real humanoid robot is simulated in MATLAB software in order to study the kinematics and dynamics behavior of STS motion. Firstly, by assuming that the feet are fixed parallel to the floor, the first link is set to be the combined knees (lower legs), the second link to be the combined thighs (upper legs) and the third link to represent the upper body including arms and head, a simulation for the three-link multi-segment robot in performing STS motion is generated. The STS movement of the robot is based on the rotations angles and angular velocity of hip, knee and ankle that are obtained by inverse kinematic and jacobians theorem. The end-effector of the STS movement of three-link multi-segment robot is according to the COM position obtained from the TIP model.

With the parameters gained from the kinematics simulation, dynamic equations that mentioned in literature review part are then applied to obtain the torque required to achieve the desired end-effector position (from seat position to standing position). The dynamic parameters of three-link multi-segment is based on Table 2.1 as mentioned in literature review. The formulation of dynamics is important for controlling the STS motion of TIP model and three-link multi-segment robot. The negative sign of torque value indicates that the rotation is in forward direction while the positive sign of torque indicates that the rotation is in backward direction.

Based on the output simulation from TIP model and three-link multi-segment robot, the required vector of joint torques in performing STS motion is analyze and compared in order to measure the validity of TIP model in representing STS motion of robot. Statistical method is implemented for the validation of result. The mean, percentage error and root mean square error are calculate to check the deviation and the accuracy of TIP model in representing STS motion of humanoid robot.

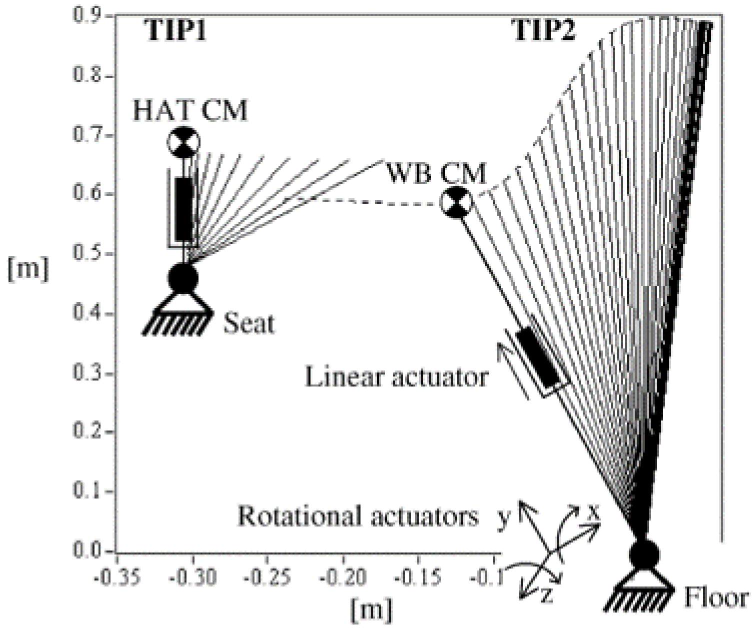


Figure 3.1: Schematic representation of two TIP models employed for description of STS [17]

3.2 Objectives of MATLAB Simulation

The objectives of the MATLAB simulation are listed as below:

i. To simulate the COM trajectory of TIP model

ii. To simulate STS motion of a three-link multi-segment robot by considering COM position created using TIP model.

iii. To study the kinematic and dynamic behavior of STS motion performing by TIP model and three-link multi-segment robot.

iv. To demonstrate the output response's graph and describe the performance between TIP model and three-link multi-segment robot in terms of torque.

v. To analyze and evaluate the accuracy of TIP model in representing STS motion of humanoid robot by using statistical method.

3.3 Method of Analysis

The analysis of STS motion is mainly separated into two parts. One part is regarding to the TIP models and another part is regarding to the three-link multi-segment robot.

3.3.1 Simulation of COM Trajectory

Based on the initial and end COM position as shown in Figure 3.1, cubic polynomial equation of TIP models for the description of STS motion are generated. By assuming the initial COM position for seat-unloading (TIP 1) is 0.7m, the final COM position is 0.65m and the position interval is 0.125m, the COM trajectory equation for TIP 1 is as followed:

$$seat(x) = 0.7 - 9.6x^2 + 51.2x^3 \quad (3.1)$$

By assuming the initial COM position for seat-off (TIP 2) is 0.6m, the final COM position is 0.9m and the position interval is 0.125m, the COM trajectory equation for TIP 2 is as followed:

$$seatoff(x) = 0.9 - 57.6x^2 - 307.2x^3 \quad (3.2)$$

Where x represent the variable COM position domain.

3.3.2 Simulation of Position, Velocity and Acceleration Profile

By applying the cosine rule concept and distance formula as followed, the angle required for the rotation of TIP and the length of link varied for each rotation are obtained.

$$l = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (3.3)$$

$$\cos^{-1} A = \frac{b^2 + c^2 - a^2}{2(b)(c)} \quad (3.4)$$

With the parameters gained from the COM trajectory such as initial and final angles to perform STS motion, appropriate position, velocity and acceleration profile at any instantaneous time are created for TIP 1 and TIP 2.

By assuming the initial angle for seat unloading (TIP 1) is 90°, the final angle is 59.84° and the time duration for motion during seating period is 1s, the position, velocity and acceleration profile equations for TIP1 are as followed:

Position: $$\theta(t) = 90 - 90.48t^2 + 60.32t^3 \quad (3.5)$$

Velocity: $$\dot{\theta}(t) = -180.96t + 180.96t^2 \quad (3.6)$$

Acceleration: $$\ddot{\theta}(t) = -180.96 + 361.92t \quad (3.7)$$

By assuming the initial angle for seat-off (TIP 2) is 101.784° , the final angle is 90° and the time duration for seat-off motion is 1.5s, the position, velocity and acceleration profile equations for TIP1 are as followed:

Position: $$\theta(t) = 101.784 - 15.712t^2 + 6.983t^3 \quad (3.5)$$

Velocity: $$\dot{\theta}(t) = -31.424t + 20.949t^2 \quad (3.6)$$

Acceleration: $$\ddot{\theta}(t) = -31.424 + 41.898t \quad (3.7)$$

Where t is the variable time domain.

3.3.3 Simulation of TIP Model Output – Couple Vector

The parameters obtained from the cubic polynomial theorem which involved angular velocity, acceleration and variation of length of TIP link are then included in the TIP couple vector formula as stated in equation 2.31 of literature review part in order to generate TIP model output.

$$C = \frac{d([J]\omega)}{dt} + \omega \times [J]\omega - \hat{l} \times mg \quad (3.8)$$

The variation of length of TIP link that is included in the couple vector equation is referred to the STS COM profile generated in MATLAB for the particular phases. For the angular velocity, ω equation stated in equation 2.33, the θ_F which is represent the angle for lateral rotation is zero since the STS motion only include the forward and backward movement. In order to standardize the couple vector (torque) unit for the comparison purpose, the TIP output model is multiplied with the formula as the following since the TIP output in research [17] is normalized to the product body mass times stature.

$$C\ [Nm] = Nkg^{-1} \times kg \times \frac{1}{l} \tag{3.9}$$

3.3.4 Kinematics Simulation for Three-Link Multi-Segment Robot

For the validation purpose of TIP model, a three-link multi-segment robot simulation is essential for the determination of the accuracy of TIP model in representing STS motion. The parameters involved in the three-link multi-segment robot is similitude with the body segment ratio of human being and it is parallel to the length of TIP link. With the inverse kinematics and jacobians equation mentioned in literature review, the angles and angular velocity of hip, knee and ankle that are required to perform STS motion are obtained. The end-effector of the STS movement of three-link multi-segment robot is according to the COM position obtained from the TIP model. It means that for the motion during seating position, the upper body is bending forward until the final HAT COM position which equal to 0.65m is achieved. For the seat-off movement, the WB COM of the three-link multi-segment robot is stopped at 0.9m.

3.3.5 Dynamics Simulation for Three-Link Multi-Segment Robot

By applying the dynamics equation 2.30 as stated in literature review part, the dynamic behavior of STS motion in three-link multi-segment robot could be analyzed. The dynamics parameters of three-link multi-segment robot that is similitude to the ratio of body segment is referred to the Table 2.1 as stated in literature review part. Since the seat-off motion is included the movement of whole body, therefore all the torques for ankle joint, knee joint and hip joint are taking into account. The three-link dynamics equation taking account of moment of inertia, coriolis, centrifugal and viscous force vector.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} + \begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \tag{3.10}$$

For the motion during seating position, it only involved the movement of upper body, therefore only hip joint (joint 3) is taking into account.

$$\tau_3 = M_{33}\ddot{\theta}_3 + D_3\dot{\theta}_3 + g_3 \tag{3.11}$$

3.3.6 Accuracy Analysis

In order to approach the main objective of this project which is to validate STS behavior of TIP model, output torque of three-link multi-segment robot is generated for the comparison purpose. The result obtained is validated by applying the mean, percentage error and root mean square error (RMSE) formula as followed for checking the deviation and the accuracy of TIP model in representing STS motion of humanoid robot.

Mean:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{3.12}$$

Percentage error:

$$\%error = \left|\frac{theoretical - experimental}{theoretical}\right| \times 100\% \tag{3.13}$$

RMSE:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{n}} \tag{3.14}$$

CHAPTER 4

RESULT AND DISCUSSION

In this section, it describes the findings obtained from TIP model and three-link multi-segment robot. The analysis of result for the validation purpose is also described in this section by using statistical techniques.

4.1 Simulation for TIP Model

The simulation of TIP model is focused on the COM trajectory, position, velocity and acceleration profiles as well as the model output in terms of couple vector that representing the torque required for performing STS motion.

4.1.1 COM Trajectory of TIP Models

As mentioned in methodology part, two TIP models that are corresponding to the COM position of the relevant body portion are employed for the description of STS. The two TIP models employed for the analysis of STS are in temporal sequence that represented two different systems. TIP 1 represents only the movement of head-arms-torso (HAT) system during initiation of STS movement and ended just before the hip are lift off from the seat (before seat unloading). Therefore, TIP 1 joins the HAT COM with the midpoint between the hips.

TIP 2 corresponds to the following loss of contact with the seat (seat-off) related to the whole body (WB) movement. Hence, TIP 2 is represented the telescopic link joined the WB COM with the midpoint between the ankles. The two TIP models are inapplicable during the transient phase of seat unloading. The parameters involved in TIP models are referred to the similitude of the real three-link multi-segment robot as mentioned in methodology part in order to validate the model output in terms of torque. Figure 4.1 shows a schematic representation of the two models employed for the description of STS motion that is simulated using MATLAB software.

The movement of TIP 1 and TIP 2 are illustrated and described by referring to the Figure 4.2 and Figure 4.3 respectively. Based on Figure 4.2, it can be seen that the upper body of the humanoid robot required moving forward first before the hip are lift off from the seat for the purpose to lower down its HAT COM position and hence maintain its stability.

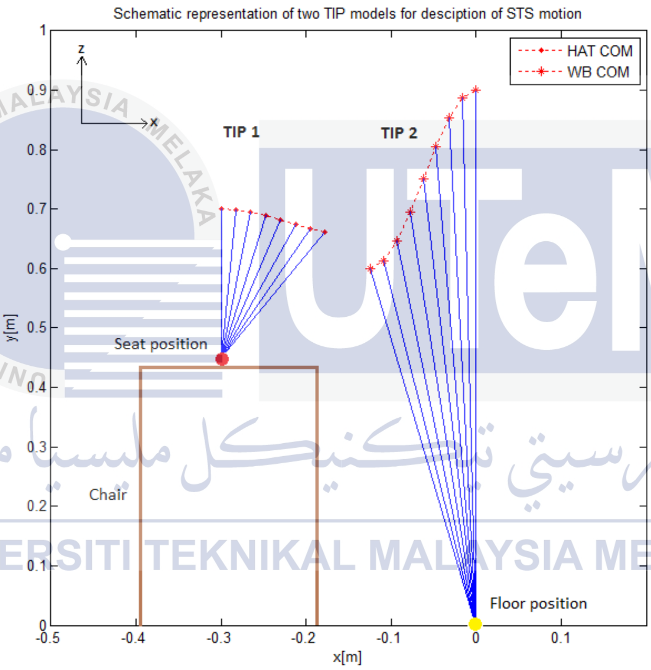


Figure 4.1: Schematic representation of two TIP models using for the description of STS motion

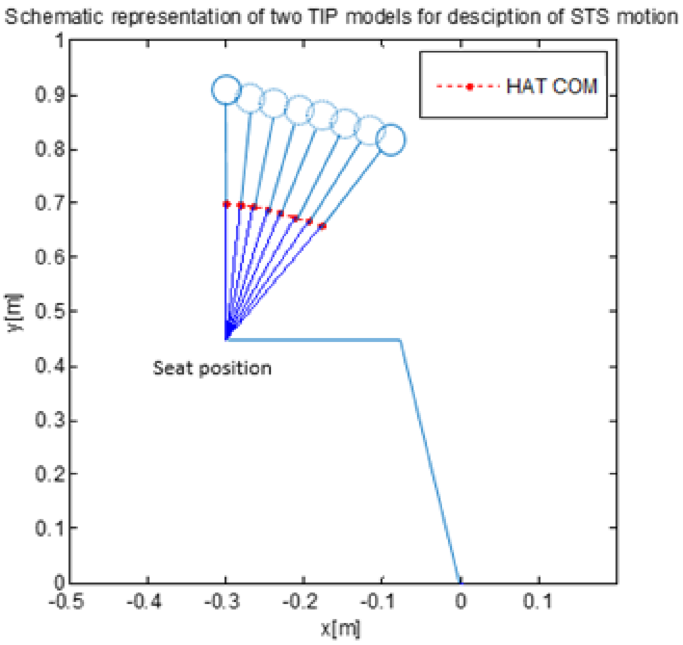


Figure 4.2: Illustration of STS motion for TIP 1 before seat unloading by considered only HAT COM

In Figure 4.3, by referring to the left-side diagram, when the humanoid robot stands at 170 and 180, the COM 153c increases from COM 153b to COM 153d and hence generates a COM trajectory 107b. The COM trajectory 107b generated is similar like a cubic polynomial profile. With the comparison between the left-side diagram and right-side simulation in Figure 4.3, it can be proved that the WB COM trajectory generated after seat off using simulation software is valid since the STS trajectory pattern for both are similar.

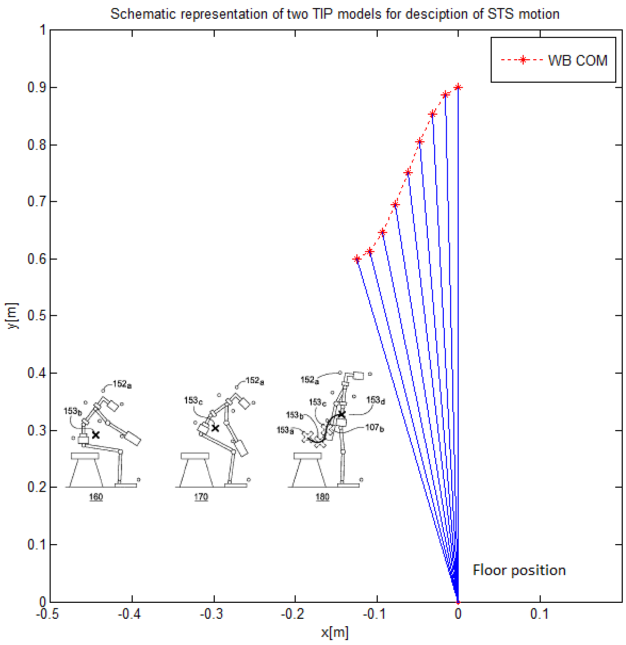


Figure 4.3: Illustration of STS motion for TIP 2 after seat off by comparing with humanoid robot whole body COM trajectory

4.1.2 TIP Cubic Polynomial Profiles

With the parameters gained from the COM trajectory such as initial and final angles to perform STS motion, cubic polynomial profiles in terms of position, velocity and acceleration at a time duration of seat-unloading (TIP 1) 1s and seat-off (TIP 2) 1.5s are generated in order to simulate the TIP model output in terms of couple vector that is required in performing STS motion.

4.1.2.1 Position, Velocity, Acceleration Profiles of TIP 1

By referring to Figure 4.1, angles position of TIP 1 that involved during preceding seat-unloading are calculated using cosine rule mentioned in methodology part. Link of TIP 1 is performed seat-unloading motion for a time duration of 1s from an angle position of 90° to 59.84°. With the initial and final angles obtained, a position versus time profile as shown in Figure 4.4 is then simulated by applying the cubic polynomial equation. Consequently, the velocity and acceleration profile are also generated as shown in Figure 4.5 and Figure 4.6 respectively.

Based on Figure 4.4, the angles of the link is decreased along the seat-unloading motion until the angle is reached at 59.84° in order to lower down HAT COM position and hence stabilize the body. In Figure 4.5, it shows that there is zero velocity at beginning since there is no any movement. For the first time duration of 0.5s, the link's velocity is decreased until it reached at maximum velocity of 44.3363° $s^{-1}$and then it is increased until zero velocity after 0.5s for the purpose to balance the gravity. The negative sign of velocity indicates that the movement is in negative direction (moving backwards).

In Figure 4.6, there is a negative acceleration for the seat-unloading motion. It indicates that the link of TIP 1 is moving backwards (negative velocity) at an increasing speed.

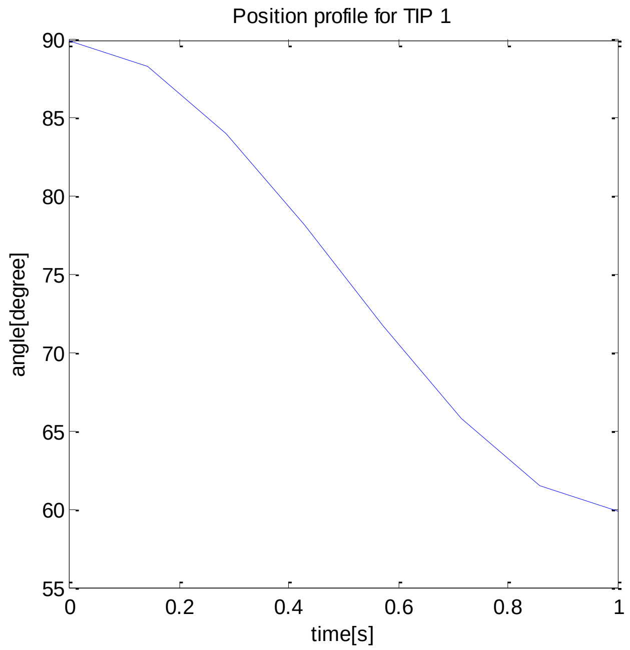


Figure 4.4: Position versus time profile for TIP 1 during seat-unloading

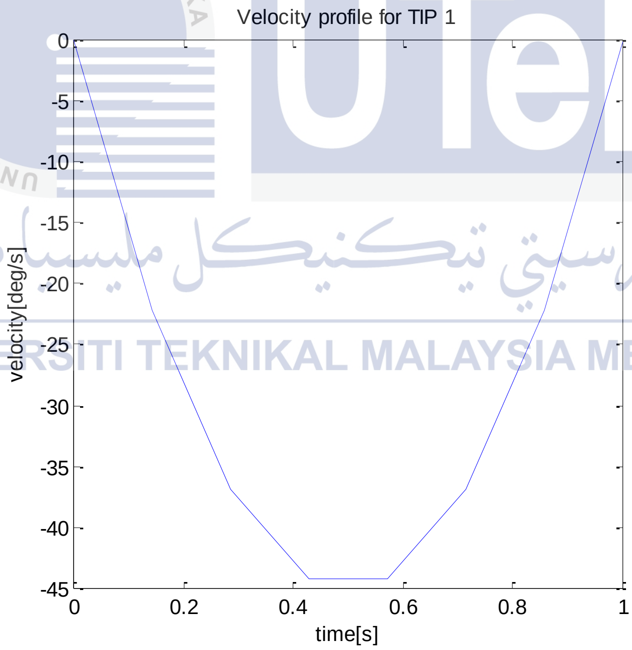


Figure 4.5: Velocity versus time profile for TIP 1 during seat-unloading

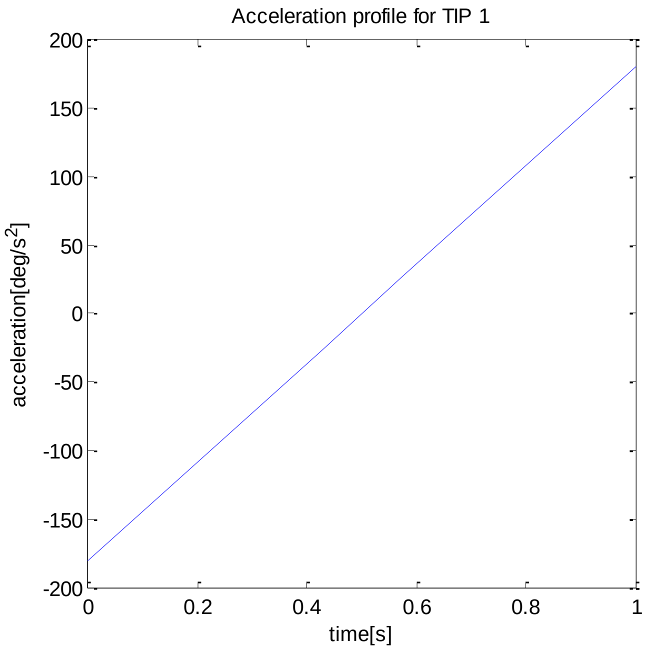


Figure 4.6: Acceleration versus time profile for TIP 1 during seat-unloading

4.1.2.2 Position, Velocity, Acceleration Profiles of TIP 2

By referring to Figure 4.1, angles position of TIP 2 that involved during seat-off are calculated using cosine rule mentioned in methodology part. Link of TIP 2 is performed seat-off motion for a time duration of 1.5s from an angle position of 101.784° to 90°. With the initial and final angles obtained, a position versus time profile as shown in Figure 4.7 is then simulated by applying the cubic polynomial equation. Consequently, the velocity and acceleration profile are also generated as shown in Figure 4.8 and Figure 4.9 respectively.

Based on Figure 4.7, the angles of the link is decreased along the seat-off motion until the angle is reached at 90°. The angle position of 90° indicates that the link is perfectly stand up. In Figure 4.8, it shows that there is zero velocity before the link is starting execute the seat-off motion. For the first time duration of 0.75s, the link's velocity is decreased until it reached at maximum velocity of 11.78° $s^{-1}$and then it is increased until zero velocity after 0.75s for the purpose to balance the gravity. The negative sign of velocity indicates that the movement is in negative direction (moving backwards).

In Figure 4.9, there is a negative acceleration for the seat-off motion. It indicates that the link of TIP 2 is moving backwards (negative velocity) at an increasing speed.

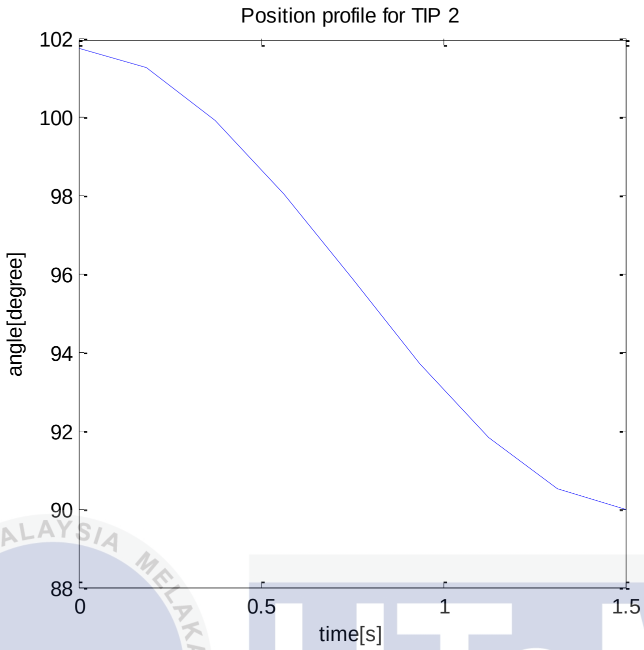


Figure 4.7: Position versus time profile for TIP 2 during seat-off

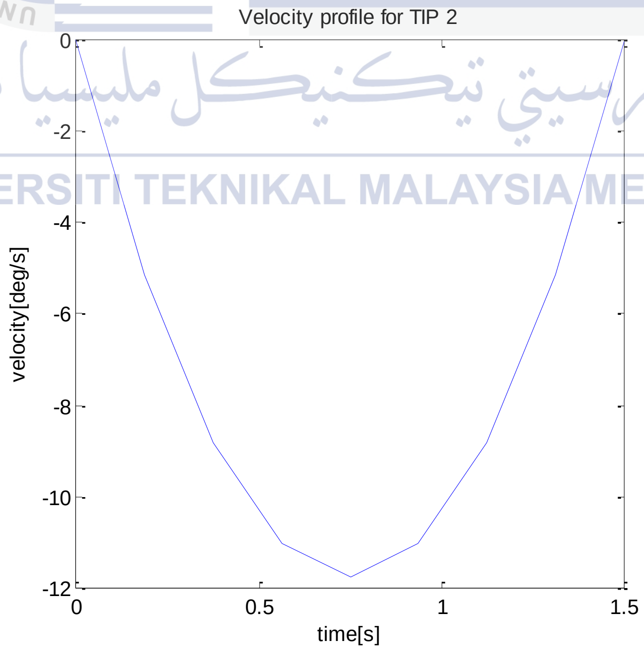


Figure 4.8: Velocity versus time profile for TIP 2 during seat-off

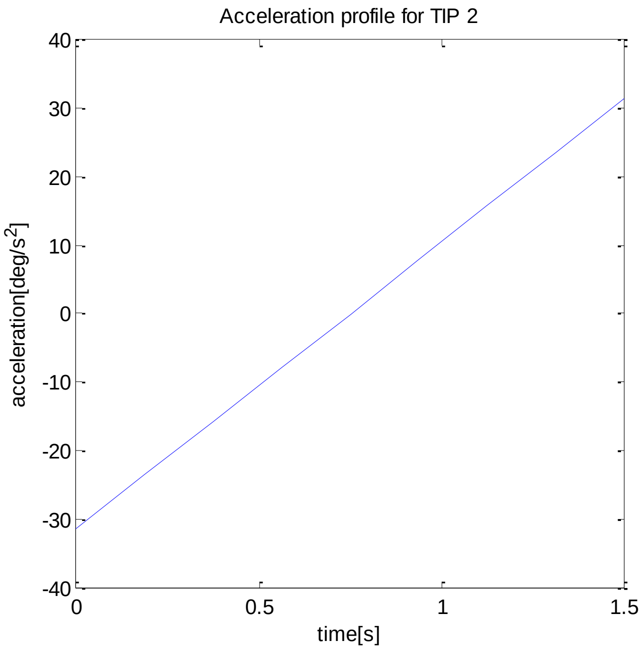


Figure 4.9: Acceleration versus time profile for TIP 2 during seat-off

4.1.3 TIP Model Output – Couple Vector

With the angle position, velocity and acceleration profiles data obtained from cubic polynomial technique and also length of link obtained from Figure 4.1, the model output for TIP 1 and TIP 2 in terms of couple vector, C that represents torque, τ required for performing seat-off motion are generated as shown in Figure 4.10 and Figure 4.11 respectively by applying the equation 3.8 in methodology part. The couple vectors obtained are normalised to the product body mass times stature. For this simulation, the positive value of torque indicates that the movement is rotated in counter-clockwise while the negative value of torque indicates that the movement is rotated in clockwise.

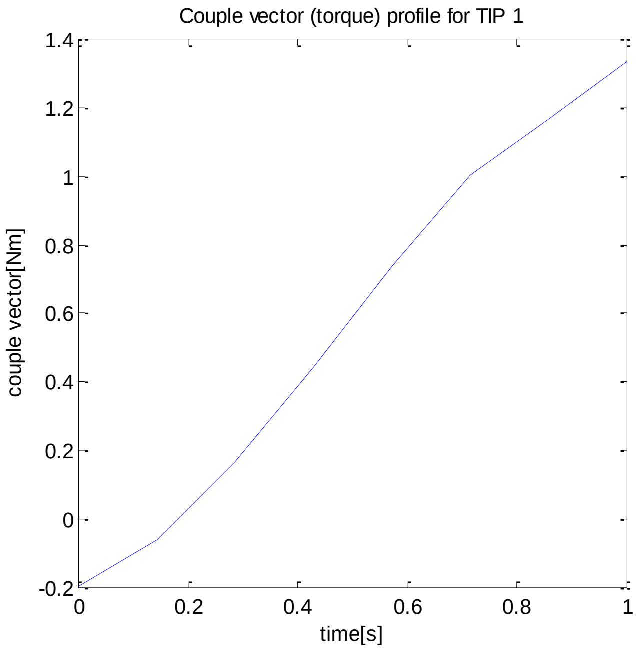


Figure 4.10: Couple vector (torque) profile for TIP 1 during seat-unloading

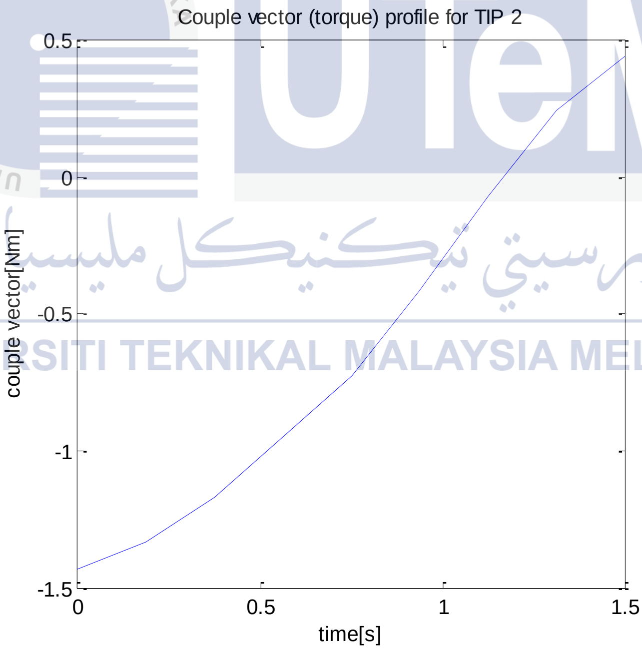


Figure 4.11: Couple vector (torque) profile for TIP 2 during seat-off

4.2 Simulation for Three-Link Multi-Segment Robot

For the purpose to approach the objective of this project, the study of kinematics and dynamics behavior of three-link multi-segment robot in performing STS motion is important to measure the accuracy of TIP model in representing STS motion.

4.2.1 Kinematic Simulation of STS Motion

By input the length of each joint into inverse manipulator kinematics and jacobians equations, a simulation of three-link multi-segment robot for executing STS motion is generated as shown in Figure 4.12. The end-effector of the robot is corresponding with the COM position for particular portion of body. The COM position is referred to the similitude of TIP models. The first joint with black colour dot is corresponding with ankle joint, the second joint with green colour dot is corresponding with knee joint and the third joint with yellow colour dot is corresponding with hip joint. For the phase before seat unloading, the red colour part shows clearly only the upper body is bending down in order to maintain the stability of the body and the end effector is corresponding with the HAT COM. For the phase after seat-off, the blue colour part shows the involvement of three joint in performing seat-off motion and hence produce the cubic polynomial trajectory corresponding with WB COM.

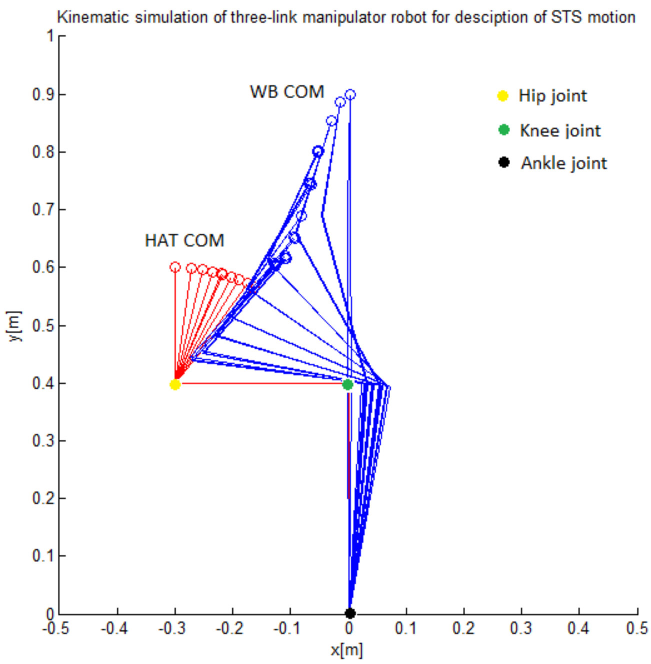


Figure 4.12: Kinematic simulation of three-link manipulator robot in performing STS motion

4.2.2 Dynamic Simulation of STS Motion

With the parameters obtained from kinematic simulation which involved angle and angular velocity for each step of STS phases, the three-link manipulator output in terms of torque is generated using MATLAB software by applying the dynamic equation mentioned in methodology parts. For the STS phases before seat-unloading, only torque for hip joint (link 3) is included since only the upper body is moved during seating period. Therefore, Figure 4.13 only display the output torque of hip joint (link 3). For the STS phases after seat-off, it is covered the torque for all the three joints since whole body is moved during seat-off period. Hence, the simulation output as shown in Figure 4.14 is included the torque for all the three joint. The time taken for the seat-unloading motion is assumed as 1s and seat-off motion is 1.5s.

The pattern of the torque simulation as shown in Figure 4.14 for all three joints is similar with the graph simulation in research [22]. It indicates that the torque data from three-link multi-segment robot is reliable and it is validate to compare with the TIP model output in terms of couple vector.

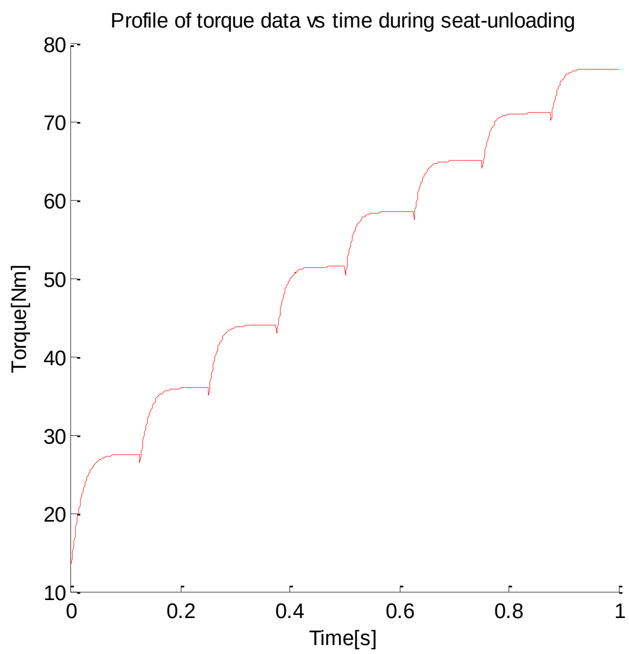


Figure 4.13: Profile of torque data vs time during seat-unloading for hip joint

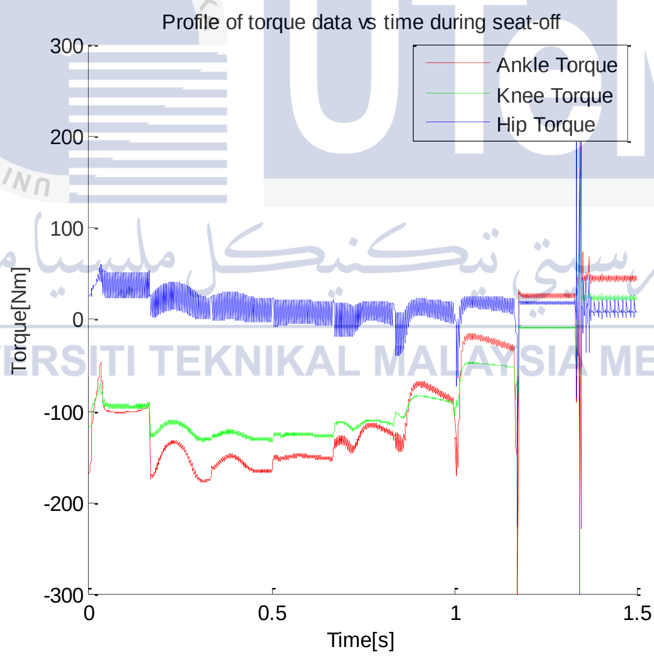


Figure 4.14: Profile of torque data vs time during seat-off for ankle, knee and hip joint

4.3 Validation of Result

In order to validate the result obtained from TIP model for the study of STS behavior, statistical method is essential for the analysis between TIP model and three-link multi-segment robot. The result is separated and compared in two phases, one is seat unloading phase and another one is seat-off phase.

4.3.1 Result of TIP 1 Model During Seat-Unloading

Based on the schematic diagram in Figure 4.1, it indicates that the TIP 1 model is hinged at the midpoint of hip and only involved the movement of upper body. Therefore, it can be compared with the hip torque of three-link multi-segment that required for the seat-unloading motion.

For the comparison purpose, the unit of torque for both must be similar. Since the TIP 1 model output as shown in Figure 4.11 is normalized to the product body mass times stature, therefore it is necessary to make the torque unit of TIP model equivalent with the torque unit of three-link multi-segment robot by multiplying with the body mass and one per length of link. Since the TIP 1 link is shorten within the seat-unloading period, therefore, the length of TIP 1 link for each period is varied. By assuming the upper body mass is equal to 45.99 kg and the length of link is referred to the schematic diagram in Figure 4.1, a simulation graph of the output in terms of torque for TIP 1 model and three-link multi-segment robot is then generated and compared as shown in Figure 4.15.

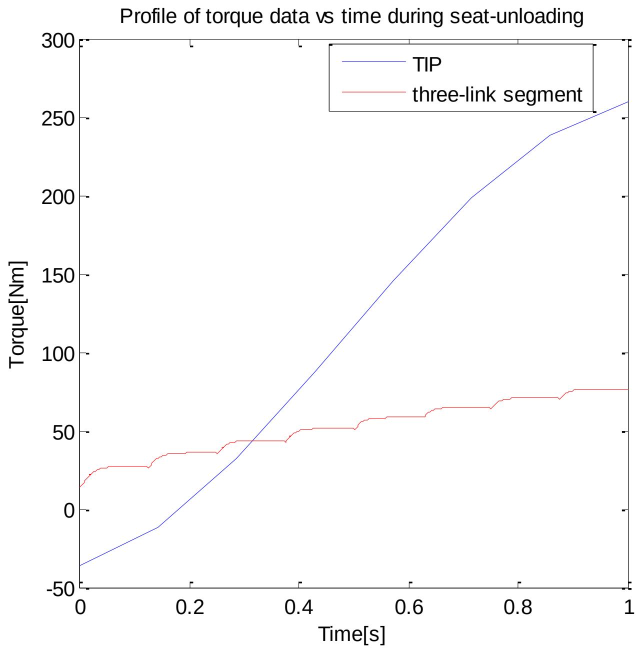


Figure 4.15: Comparison of hip torque data between TIP 1 model and three-link segment during seat-unloading

Table 4.1: Torque analysis between TIP 1 model and three-link multi-segment at initiation and termination of STS movement during seat-unloading phase

	Torque (Nm)		Percentage error (%)
	Hip joint of three-link segment	TIP 1 model	
Initiation	13.4663	-2.2696	116.85
Termination	76.8774	14.4553	81.20
Mean	52.7661	6.1101	88.42

Based on the Table 4.1, three-link multi-segment robot required torque of 13.4663Nm to begin the STS motion during seated position in backward direction while the TIP model required torque of 2.2696Nm for the rotation in forward direction. The percentage error for the torque required for the initiation of seat-unloading movement between real robot and TIP model is definitely high, which is 116.85%. The percentage error for the torque on seat-unloading termination and the average mean also in the high rate that are 81.20% and 88.42% respectively. The inaccuracy of TIP model in representing the seat-unloading phase may be is due to the TIP model isn't taking account of angular inertia effects as mentioned in journal [17].

The root mean square error is calculated in order to find the difference between the torque values for hip joint of real three-link multi-segment robot and TIP 1 model that proposed to represent the seat-unloading motion.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{n}}$$

$$= \sqrt{\frac{(52.7661 + 6.1101)^2}{808}}$$

$$= 2.071$$

Based on the calculation, the RMSE value is 2.071, it indicates that the deviation from actual value is very high since a good system's RMSE value is within the range of 0 to 1. Therefore, it shows that more research is needed to focus on seat-unloading phase and other momentum components should include in the TIP model design in the future.

4.3.2 Result of TIP 2 Model During Seat-Off

At this stage, the TIP model output in terms of couple vector cannot be compared directly to any of the joint torques involved in three-link multi-segment robot during seat-off phase. As shown in the Figure 4.14, the most influential joint is ankle joint (joint 1) since it carries most burden during standing. The hip joint isn't contributed much during seat-off since it is moved backward to balance the body. Of course the hip and knee joints are also influence the movement, but at this stage of study, assuming it is negligible and it must be taken into account in the future study. Therefore, the comparison in terms of torque is make between the TIP 2 and ankle joint since the TIP model schematic diagram in Figure 4.1 also indicates that the TIP 2 model is hinged at the midpoint of ankle.

For the comparison purpose, the unit of torque for both must be similar. Since the TIP 2 model output as shown in Figure 4.11 is normalized to the product body mass times stature, therefore it is necessary to make the torque unit of TIP model equivalent with the torque unit of three-link multi-segment robot by multiplying with the body mass and one per length of link. Since the TIP 2 link is elongated within the seat-off period, therefore, the length of TIP 2 link for each period is varied. By assuming the body mass is equal to 70.372 kg and the length of link is referred to the schematic diagram in Figure 4.1, a simulation graph of the output in terms of torque for TIP 2 model and three-link multi-segment robot is then generated and compared as shown in Figure 4.16.

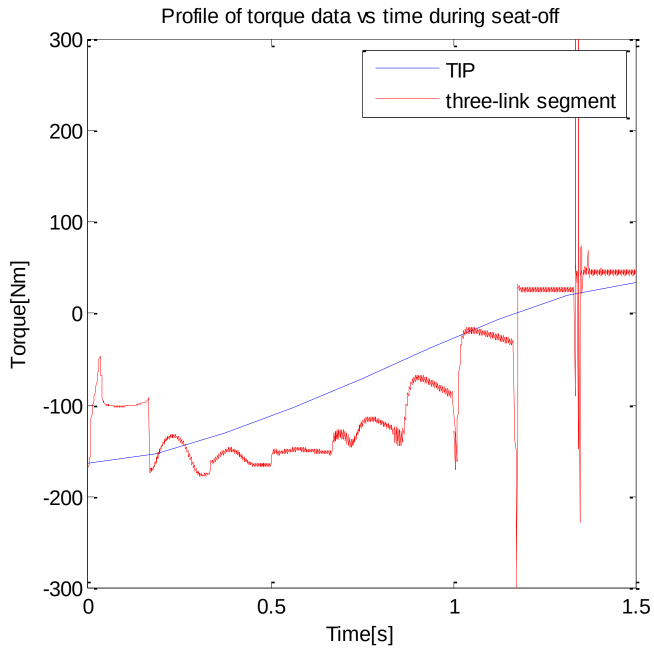


Figure 4.16: Comparison of ankle torque data between TIP 2 model and three-link segment during seat-off

Table 4.2: Torque analysis between TIP 2 model and three-link multi-segment at seat-off and termination of STS movement

	Torque (Nm)		Percentage error (%)
	Ankle joint of three-link segment	TIP 2 model	
Seat-off	-169.5094	-164.6403	2.87
Termination	43.4182	34.7395	19.99
Mean	-83.4357	-67.9285	18.59

Based on the Table 4.2, three-link multi-segment robot required torque of 169.5094Nm to execute the seat-off movement in forward direction while the TIP model only required torque of 164.6403Nm. The percentage error for the torque required for the initiation of seat-off movement between real robot and TIP model is only 2.87%. It indicates that there is high accuracy for the TIP model in representing the real three link manipulator robot in analyzing STS motion. The percentage error for the torque on seat-off termination and the average mean have a little bit high that are 19.99% and 18.59% respectively due to the several phenomena such as momentum components are not exactly included in the model.

The root mean square error is calculated in order to find the difference between the torque values for ankle joint of real three-link multi-segment robot and TIP model that proposed to represent the STS motion.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2}{n}}$$

$$= \sqrt{\frac{(-83.4357+67.9285)^2}{1359}}$$

$$= 0.4207$$

Based on the calculation, the RMSE value is only 0.4207, it is considered low. Therefore, it shows that the objective of this project is approached since the TIP 2 model performance in representing seat-off motion of humanoid robot is in the rate of high accuracy.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

In conclusion, center of mass (COM) is an essential point for planning a stable sit to stand motion of humanoid robot. TIP model has allowed the creation of COM trajectory for the description of STS motion but the suitability of TIP model for representing STS motion is unknown and has not been validated yet in other research paper. Therefore, in this project, it is focused on the accuracy of TIP model in representing STS motion by making comparison between a three-link multi-segment robot.

Based on the findings and analysis, the RMSE obtained shows that there is high accuracy exist for TIP model in representing the seat-off movement but for the motion during seated position (seat-unloading), it is inaccurate. The deviation from actual value may be due to the TIP model doesn't taking account of moment of inertia, coriolis, centrifugal and viscous force vector that are taking account by three-link multi-segment robot. For the seat-unloading phase, may be these factor is essential for the purpose of balancing the center of gravity of body.

In future work, the torque of ankle, knee and hip for the three-link multi-segment robot must be taken into account in making comparison between the TIP model output in terms of couple vector during seat-off movement. For the next research, the ground reaction force that required to stabilize the robot should be compare to linear actuator force exist in TIP model. Besides that, the momentum components also must be taken into account in developing the TIP model in order to enhance the accuracy of TIP model in representing STS motion.

REFERENCES

[1] Chuy, O., et al. *Approach in Assisting a Sit-to-Stand Movement Using Robotic Walking Support System*. in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. 2006.

[2] Strausser, K.A. and H. Kazerooni. *The development and testing of a human machine interface for a mobile medical exoskeleton*. in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*. 2011.

[3] Mistry, M., et al. *Sit-to-stand task on a humanoid robot from human demonstration*. in *Humanoid Robots (Humanoids), 2010 10th IEEE-RAS International Conference on*. 2010.

[4] Kaicheng, Q., et al. *Analysis of the state transition for a humanoid robot SJTU-HR1 from sitting to standing*. in *Mechatronics and Automation, 2009. ICMA 2009. International Conference on*. 2009.

[5] Pchelkin, S., et al. *Natural sit-down and chair-rise motions for a humanoid robot*. in *Decision and Control (CDC), 2010 49th IEEE Conference on*. 2010.

[6] Sugisaka, M. *A control method for soft robots based on artificial musles*. in *Mechatronics, ICM2007 4th IEEE International Conference on*. 2007.

[7] Riley, P.O., R. Popat, and D.E. Krebs. *Momentum analysis of sitback failures in sit-to-stand trials*. in *Engineering in Medicine and Biology Society, 1995., IEEE 17th Annual Conference*. 1995.

[8] Millington, P.J., B.M. Myklebust, and G.M. Shambes, *Biomechanical analysis of the sit-to-stand motion in elderly persons.* Archives of physical medicine and rehabilitation, 1992. **73**(7): p. 609-617.

[9] Coghlin, S.S. and B.J. McFadyen, *Transfer strategies used to rise from a chair in normal and low back pain subjects.* Clinical Biomechanics, 1994. **9**(2): p. 85-92.

[10] Fu-Cheng, W., et al. *Optimization of the Sit-to-Stand Motion*. in *Complex Medical Engineering, 2007. CME 2007. IEEE/ICME International Conference on*. 2007.

[11] Sadeghi, M., et al., *A bio-inspired modular hierarchical structure to plan the sit-to-stand transfer under varying environmental conditions.* Neurocomputing, 2013. **118**(0): p. 311-321.

[12] Hemami, H. and V.C. Jaswa, *On a Three-Link Model of the Dynamics of Standing up and Sitting down.* Systems, Man and Cybernetics, IEEE Transactions on, 1978. **8**(2): p. 115-120.

[13] Musić, J., R. Kamnik, and M. Munih, *Model based inertial sensing of human body motion kinematics in sit-to-stand movement.* Simulation Modelling Practice and Theory, 2008. **16**(8): p. 933-944.

[14] Roberts, P.D. and G. McCollum, *Dynamics of the sit-to-stand movement.* Biological cybernetics, 1996. **74**(2): p. 147-157.

[15] Aissaoui, R., R. Ganea, and K. Aminian, *Conjugate momentum estimate using non-linear dynamic model of the sit-to-stand correlates well with accelerometric surface data.* Journal of biomechanics, 2011. **44**(6): p. 1073-1077.

[16] Pai, Y.-C. and J. Patton, *Center of mass velocity-position predictions for balance control.* Journal of biomechanics, 1997. **30**(4): p. 347-354.

[17] Papa, E. and A. Cappozzo, *A telescopic inverted-pendulum model of the musculo-skeletal system and its use for the analysis of the sit-to-stand motor task.* Journal of Biomechanics, 1999. **32**(11): p. 1205-1212.

[18] Michael MISTRY, A.M., Katsu Yamane, Jessica Kate Hodgins, *Robot action based on human demonstration*. 2012, Disney Enterprises, Inc.: United States.

[19] Craig, J.J., *Introduction To Robotics Mechanics and Control*. Third Edition ed. 2005, United Sates of America: Pearson Education, Inc.

[20] Chandler,R.F., Cluster, C.E., McConville, J.T., Reynolds H.M., Young, J.W., *Investigation of inertial properties of the human body*. Report No. AMRL-TR-74-137, Wright-Patterson Air Force Base, OH, 1975.

[21] Matsui, T. and Wada, K., *Dynamics-Switching Optimal Control Model for Reproducing Human Rising Movements from a Chair*. Journal of Biomechanical Science and Engineering, Vol. 8, No. 1 (2013), pp. 1-16.

[22] H. Yamasaki, H. Kambara, Y. Koike. *The Dynamic Optimization of STS Movement*. Fundamental and Applied Metrology, pp. 2135-2140, 2009