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Human Fall Control System for Disabled People Using Double Inverted Pendulum

A dissertation submitted for the degree of

Bachelor of Science in Computer Science and Engineering

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Declaration

We hereby declare that the thesis “Human Fall Control System for Disabled People Using Double Inverted Pendulum” is based on the results found by ourselves under the supervision of Professor Dr. Md. Haider Ali. It has been carried out for the degree of Bachelor of Science in Computer Science and Engineering. Materials of work used here are found by other researchers are acknowledged by reference. This Thesis, neither in whole or part has been previously submitted for any degree.

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INDEX

LIST OF FIGURES

LIST OF TABLES

Abstract

Self-balancing is an important role of human body which helps us to stand, to walk or swaying on feet. Without balancing, our body may fall because our legged system can't hold if there is any disturbance. In this research, we are going to introduce a model for dynamic balancing by using double inverted pendulum (DIP). We have calculated center of gravity (COG) over base support (BS) which is known as pivot point (PP) of the body for dynamic balancing. The objective of this research is to develop a workable "human-fall-control-system" which will be extremely useful for disable personal as it would assist in analysis and studying their motion.

Chapter 1

INTRODUCTION

1. Introduction

Walking and standing are common behaviors of people which we preform thousands of time every day and everywhere. In normal circumstances, people barely can stand still for a long period of time without any kind of external support [1-2]. People take isolated steps to change the position of their feet and walk around a bit to help balancing. Human falls connected to the loss of balance are a major cause of injury or death for the elderly population and the disable people. Without balance, our leg movement cannot hold our body upright and we may fall after any dynamic disturbance like slipping or trip [2-5]. Therefore, balancing is critical in legged movement. Human gait is a very complex behavior which requires delicate coordination of the central nervous system (CNS), muscles and the limbs and also the understanding of the human gait is limited [6-8]. Experiments tell us that for dealing with fall control people use a mixture of strategies like the ankle strategy that fixes all joints except the ankle and hip strategy that is characterized by a large bending at the hips [8]. During quiet standing the body is in continuous movement at all its joints and the body center of mass (COM) displays a random looking motion in front of the ankle joints. Shifting the COM manipulates the moment created by the gravitational force and allow us to balance and not to fall and it is highly related to control of a Double Inverted Pendulum (DIP) which is also unstable like elderly or disable people [9]. Since human balancing is more like DIP, we want our application also to behave as such. And therefore, we present a Double Inverted Pendulum Model (DIPM) of human balancing to control falling.

1.1 Motivation

One billion people, or 15% of the world's population, experience some form of disability, and disability prevalence is higher for developing countries. One-fifth of the estimated global total, or between 110 million and 190 million people, experience significant disabilities. [10-11] If we even go outside for a walk it is highly probable to encounter someone with motion disability. It is a huge problem still it receives very few attention and we mostly use very old methods to treat them. The old methods take long time and fails in many cases meanwhile the suffer and the pain gets worse. They almost get isolated from their society and very few able to live a normal life. So analyzing and knowing their motion will enable us to learn better about their condition and hence develop better method to treat their problem.

1.2 Aim and Objectives

The primary aim of our research was to introduce a new system for physically imbalanced people. Our main target was to design an abstract model to introduce balancing solutions for human body. There has been a lot of work done in this field using various methods, algorithms and techniques. For example, In Linear Inverted Pendulum Model (LIPM) usually uses three techniques ankle, hip strategies [1-5,12]. But it is difficult to implement such system for disabled people using LIPM because fall control is largely dependent on proper foot placement as our foot stay in contact to ground that makes gravitational force to be zero. Human balancing can also be solved by utilizing Human Linkage Model and providing a solution to prevent human fall using Intelligent Passive Walker (IPW) [13]. IPW uses Laser Range Finder (LRF) and their fall control algorithm is based on the subject's state described by the support polygon and walking pattern of the subject. The main drawbacks of these methods are that they are not entirely based on human body but biped robots. Therefore, a proper method is needed for human balancing mechanism for disabled personals.

Our work was a step by step procedure and the whole process is summarized here in our research report. The main work flow of our thesis are as follows:

1. Studying related works and develop relevant concepts.
2. Identifying proper model.
3. Develop a suitable algorithm for the system
4. Collect relevant data and testing.
5. Experiment and result analysis
6. Decision and conclusion.

Chapter 2

BACKGROUND STUDIES

2. Background Studies

2.1 Simple Pendulum

A pendulum is a mass attached with strings attached from a pivot point to allow free swing. When it is moved away from its equilibrium position it restores it restores the stable position by moving back to it due to gravity. And if it is released from a height the restoring force along with the gravity oscillates about the stable position oscillating back and forth. The time needed to return to the position back from where it was displaced is the time period. The time period is dependent on the length of the strings and a little on the degree of its amplitude [5].

2.1.1 Equations of Energy:

Potential Energy = $mgl(1 - cos\ \theta)$

Kinetic Energy = $\frac{1}{2}\ I\ w^2$ Where moment of Inertia, $I\ = ml^2$

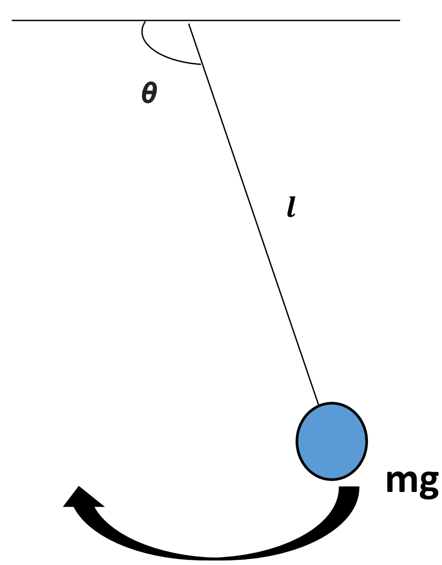

Figure 1: Simple Pendulum

2.2 Simple Inverted Pendulum

A simple pendulum has its Centre of mass above its pivot. In most studies to keep the system simple the swing of pendulum is restricted to only one plane. The pendulum can be kept stable in one of 2 ways one is moving the pendulum and another is by a torque in the pivot point. And so, in many cases it is implemented using cart to make it stable. It is one of the most widely used model for studying human locomotion [14].

2.2.1 Equations of energy of Simple Inverted Pendulum

Kinetic Energy $=\frac{1}{2}mv^{2}$

Potential Energy = $mgl(1 - Cos\ \theta)$

2.2.2 Equations of energy of Inverted Pendulum and Cart

Kinetic Energy $= \frac{1}{2}mv^{2} + \frac{1}{2}\ mw^{2}$

Potential Energy = $mgl\ (1 - Cos\ \theta)$

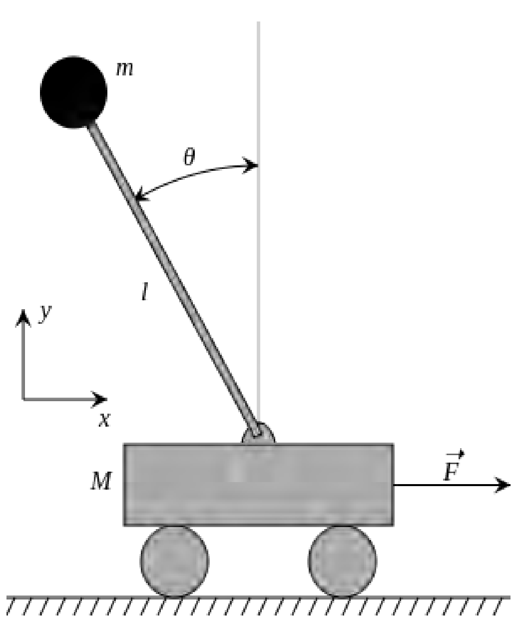

Figure 2: Simple Inverted Pendulum Cart

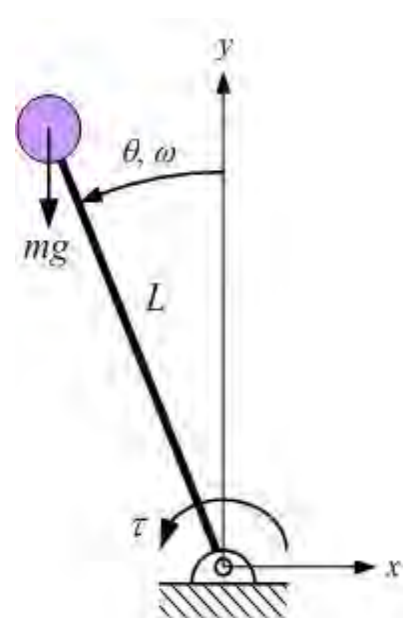

Figure 3: Simple Inverted Pendulum

2.3 Double Link Pendulum

A double link pendulum is composed of two simple pendulums attached with one another that has wide range of dynamic behavior with a strong sensitivity to initial conditions. The motion of this pendulum can be described using differential equation and is chaotic in most cases [15]. Like the simple inverted pendulum in most cases it is constrained to one plane and in addition in many cases length of pendulum and masses are considered equal.

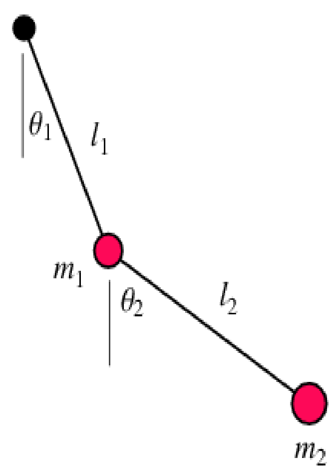

Figure 4: Double Link Pendulum

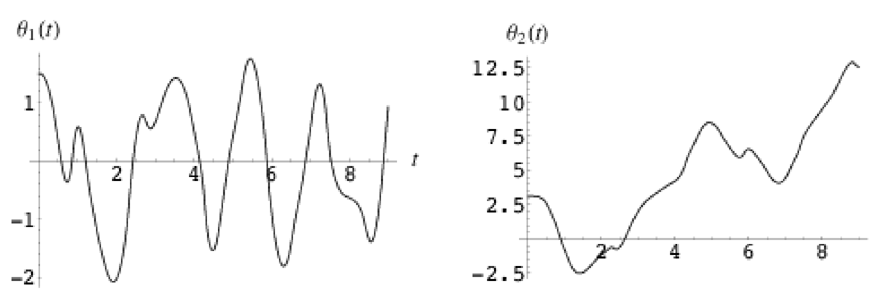

Figure 5: Variation of θ_1 & θ_2 with time in DLP

2.4 Pole Placement Approach of controlling Double Inverted Pendulum

This method utilizes the characteristics of double inverter pendulum (DIP) model is a less complicated model of the anterior-posterior motion of a standing human at its up-up position. In this approach, the modeling is done through a series of complex equation. At first the Lagrange is calculated using the kinetic and potential and hence Euler-Lagrange equation and then linearized. Then the linearized form is used to derive the state space model equation of the system. Then the Eigen value of the state matrix is used to determine the stability of the system. Then a feedback control system is implemented. The system is then tested with and without input system. [16]

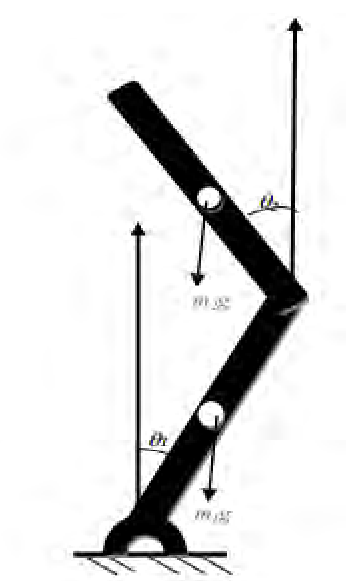

Figure 6: Double Inverted Pendulum

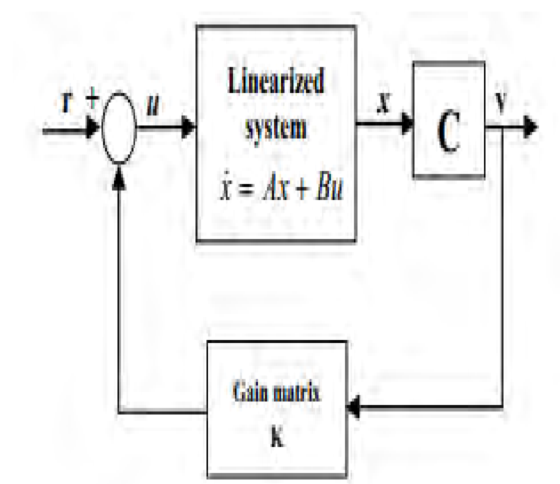

Figure 7: Control Diagram of Pole Placement

2.5 Linear Inverted Pendulum Model

The primary model which is used to understand foot placement techniques' in locomotion of biped is the linear inverted pendulum model Three crucial balancing strategies that have been used for humans consists of the ankle, hip and foot placement strategies. The LIPM is modeled to a bipedal based system which can utilize double support and generated a dynamic balance controller based system on foot placing and double stance length. The model can stand and move at user-desired speed to compensate for temporary external disturbances and permanent ones it accelerates or decelerates. The dynamic stability controller smoothly integrates producing continuously-state gait patterns and compensating disturbances. Step length and double support length that the controller generates to adjust stability is the reason of these behaviors. The gait patterns outputs in clearly stated average speeds. [1-4]

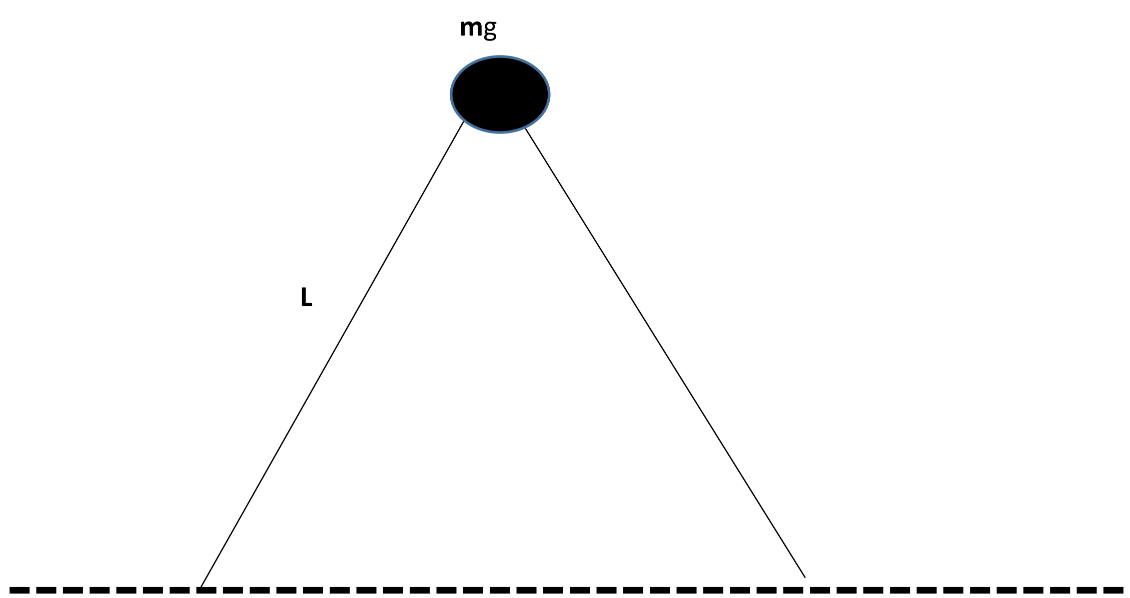

Figure 8: Bipedal Inverted Pendulum

2.6 Intelligent Passive Walker (IPW)

Human balancing can also be solved by utilizing Human Linkage Model and providing a solution to prevent human fall using Intelligent Passive Walker (IPW). IPW uses Laser Range Finder (LRF) to find the position of the user and calculate the COG which is coincident to the cog found using motion capturing system, VICON450. Using the distribution of COG during walking and support polygon a stability region is developed. If the user's cog is displaced out of the region the user will fall and to prevent that a brake force is applied.

But the walker can't walk properly in all terrain if the maximum braking force is not dynamic then it will not be able to support everyone e.g. 150N maximum braking force and LRF is also unable to give a proper model for people wearing baggy clothes [13-14].

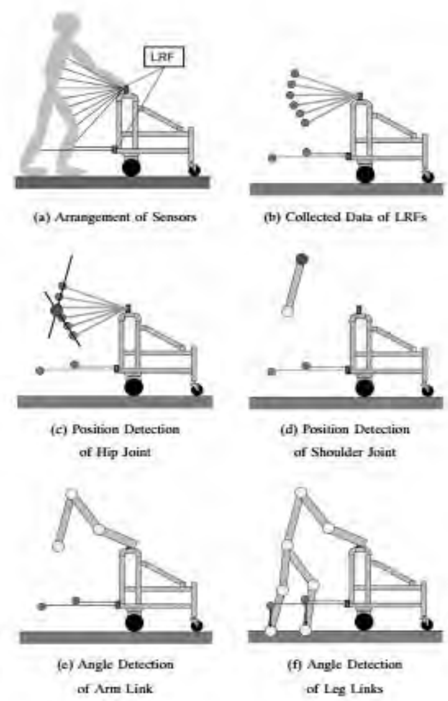

Figure 9: Use of LRF to generate human model for calculating COG

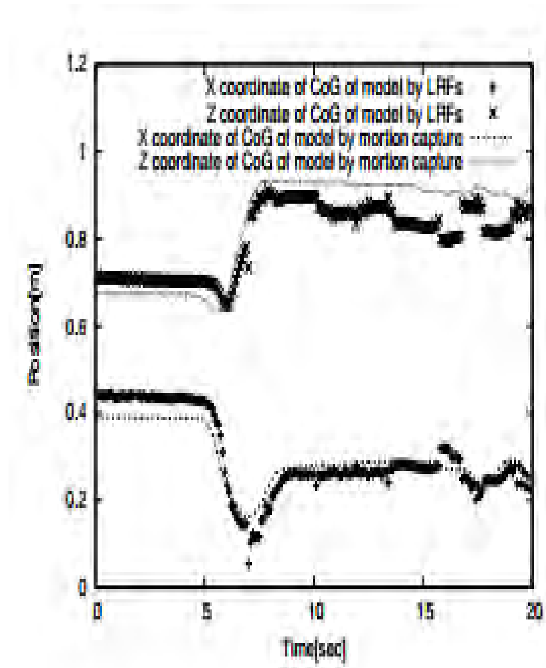

Figure 10: Comparison of COG using LRF and motion capturing system, VICON450

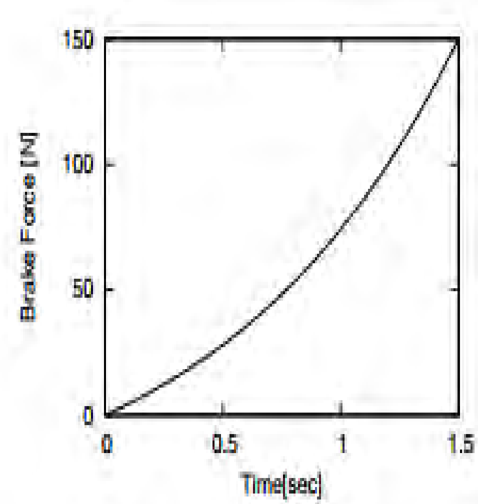

Figure 11: Sample of generating braking force

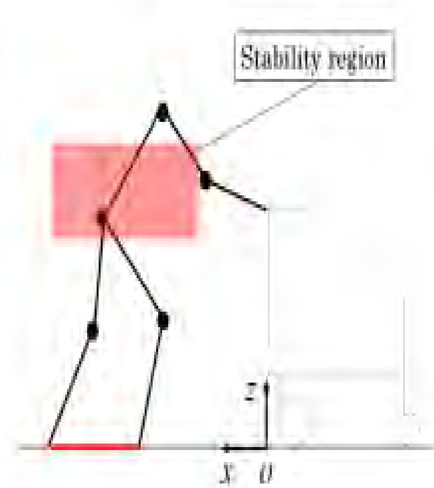

Figure 12: New stability region

2.7 Zero-Moment Point (ZMP)

Another concept of balance control is the Zero-Moment Point (ZMP) method which aims to generate biped gait by enforcing the balance of the human body with the aid of a set of pre-defined ZMP positions and focuses to control human stability rather than coordinating all the gaits [6]. The ZMP indicates the point on the ground where the resultant moments of the active forces will be zero. Forces include inertia, gravity and external forces from actuators although it does not include the ground action forces. The purpose is to keep ZMP within the predefined range and the COP always remains within the contact surface region between the foot and the ground [17-18]. ZMP method's advantage is the computation can be done efficiently. The main drawback of this method is that it is not naturally how human walk and pre-defined ZMP concept is usually does not exist.

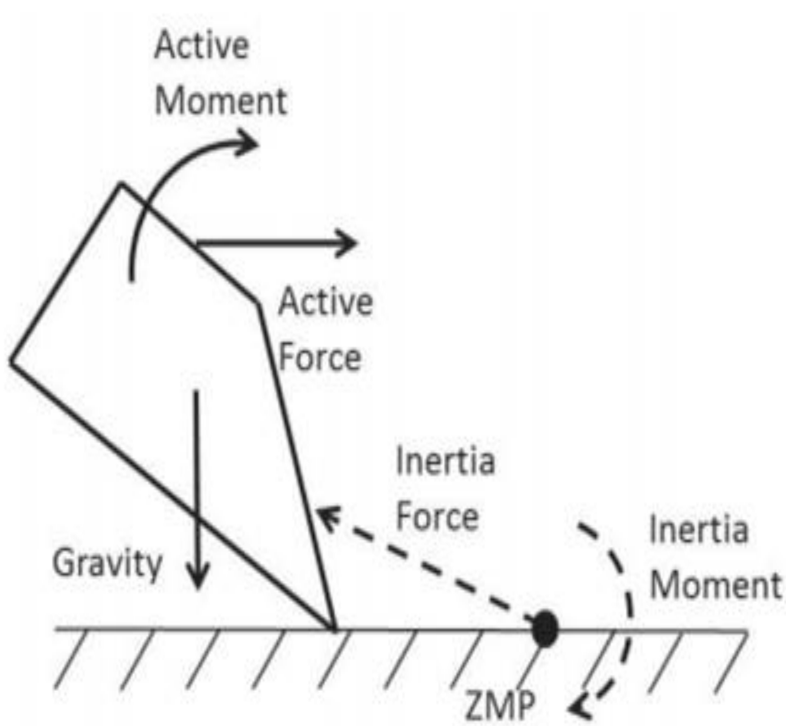

Figure 13: Active force balance by inertia at ZMP

Chapter 3

SYSTEM DESIGN AND METHODOLOGY

3. System Design and Methodology

3.1 Proposed Model

The double Inverted Pendulum Model (DIPM) represents the body above the ankles as a point mass and the two feet as a single foot and divide the foot into two links at knee point. It is assumed that the gap between the Center of Gravity (COG) and foot placement of the lumped body is constant. These assumptions require that compliance of the foot and movement at the knee, hip, and vertebral joints are inconsequential so that the single axis of rotation is fixed and so that the distance from the ankle joint, hip joint and foot placement to the COG of the body is constant. Therefore, this research proposes Double Inverted Pendulum Model (DIPM) which represents the forward dynamics principles of human walking and standing and have a control system to make the simulation robust to system variation and disturbances.

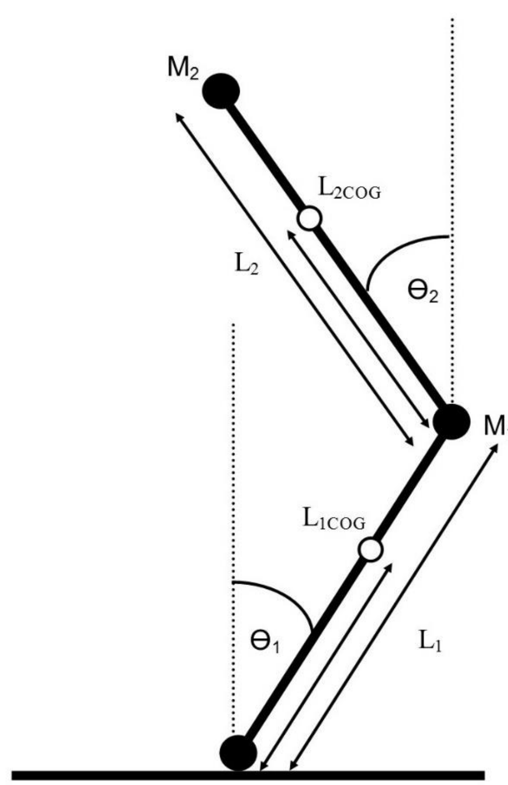

Figure 14: Double Inverted Pendulum Model

3.2 Mathematical Modeling

Balance is defined as the ability to maintain the center-of-gravity (COG) of an object within its base-of-support (BOS). The point about which the mass is evenly distributed is called the balance point which is also known as the COG point. At COG the net force/net torque of our body is zero. There is also some gravitational force consideration. But as our foot is placed to the ground the gravitational force would be zero at that foot placement point. Therefore, we need to calculate the energy generated between to COG of both links and if they create same magnitude torque with different direction than the net torque would be zero which is the first principle of balancing. The general torques across the joints keep limbs, joints, body segments in proper relationship to one another so that the COG falls within the BOS

The mechanism of the double inverted pendulum is shown in Figure 14 schematically. The mathematical model of DIP can be derived using the Euler-Lagrange equation. The form of the Euler-Lagrange equation used here is:

$$\frac{d}{dt}\left(\frac{dL}{d\dot{\theta}}\right) = \frac{d(L\,)}{d\theta} \text{ .... (1)}$$

Where L = T-V is a Lagrangian, T is kinetic energy and V is the potential energy.

From eq^{n} (1) for the 2nd order derivation we also find the energy functional τ.

$$\tau\ = \frac{d}{dt}\left(\frac{dL}{d\dot{\theta}}\right) - \frac{d(L)}{d\theta} \text{ .... (2)}$$

$\tau 1\ and\ \tau 2$ are the inputs generalized force vector produced by two actuators at the lower joint (ankle) and second at joint (knee), and θ1 and θ2 are angular positions of first arm, and second arm of the double pendulum.

3.2.1 Equation of Motion and Energy

The equations of motion of this dynamical system can be derived with the help of Lagrangian and Hamilton Theorems:

$$x_1 = l_{1cog}\sin\theta_1$$

$$y_1 = l_{1cog}\cos\theta_1$$

$x_2 = l_{2cog} \sin\theta_2 + l_1 \sin\theta_1$

$y_2 = l_{2cog} \cos\theta_2 + l_1 \cos\theta_1$

Differentiating above equations in terms of *t* we get,

$\dot{x_1} = \dot{\theta}_1 l_{1cog} \cos\theta_1$

$\dot{y_1} = -\dot{\theta}_1 \, l_{1cog} \sin\theta_1$

$\dot{x_2} = \dot{\theta}_2 l_{2cog} \cos\theta_2 + \dot{\theta}_1 \, l_1 \cos\theta_1$

$\dot{y_2} = -\dot{\theta}_2 l_{2cog} \sin\theta_2 - \dot{\theta}_1 \, l_1 \sin\theta_1$

Therefore, the Kinetic Energy (T) and the Potential Energy (V) we get for the both links:

$$T_1 = \frac{1}{2}(m_1 {l_{1cog}}^2 + I_1){\dot{\theta}_1}^2$$

$$= \frac{1}{2} m_1 ({l_{1cog}}^2 + {l_{1cog}}^2){\dot{\theta}_1}^2$$

$$= m_1 {l_{1cog}}^2 {\dot{\theta}_1}^2$$

$$T_2 = \frac{1}{2} m_2 \left({\dot{x_2}}^2 + {\dot{y_2}}^2\right) + \frac{1}{2} I_2 {\dot{\theta}_2}^2$$

$$= \frac{1}{2} m_2 \{(\dot{\theta}_2 l_{2cog} \cos\theta_2 + \dot{\theta}_1 \, l_1 \cos\theta_1)^2 + (-\dot{\theta}_2 l_{2cog} \sin\theta_2 - \dot{\theta}_1 \, l_1 \sin\theta_1)^2\} + \frac{1}{2} I_2 {\dot{\theta}_2}^2$$

$$= \frac{1}{2} m_2 \{(\dot{\theta}_2 l_{2cog} \cos\theta_2)^2 + \left(\dot{\theta}_1 l_1 \cos\theta_1\right)^2 + 2\dot{\theta}_1 \dot{\theta}_2 l_1 l_{2cog} \cos\theta_1 \cos\theta_2$$

$$+ (-\dot{\theta}_2 l_{2cog} \sin\theta_2)^2 + (-\dot{\theta}_1 l_1 \sin\theta_1)^2 + 2\dot{\theta}_1 \dot{\theta}_2 l_1 l_{2cog} \sin\theta_1 \sin\theta_2\} + \tfrac{1}{2} I_2 {\dot{\theta}_2}^2$$

$$= \frac{1}{2} m_2 \{{\dot{\theta}_2}^2 {l_{2cog}}^2 \cos^2\theta_2 + {\dot{\theta}_1}^2 {l_1}^2 \cos^2\theta_1 + 2\dot{\theta}_1 \dot{\theta}_2 l_1 l_{2cog} \cos\theta_1 \cos\theta_2$$

$$+ {\dot{\theta}_2}^2 {l_{2cog}}^2 \sin^2\theta_2 + {\dot{\theta}_1}^2 {l_1}^2 \sin^2\theta_1 + 2\dot{\theta}_1 \dot{\theta}_2 l_1 l_{2cog} \sin\theta_1 \sin\theta_2\} + \tfrac{1}{2} I_2 {\dot{\theta}_2}^2$$

$$= \frac{1}{2} m_2 \{{\dot{\theta}_2}^2 {l_{2cog}}^2 + {\dot{\theta}_1}^2 {l_1}^2 + 2\dot{\theta}_1 \dot{\theta}_2 l_1 l_{2cog} \cos(\theta_1 - \theta_2)\} + \frac{1}{2} m_2 {l_{2cog}}^2 {\dot{\theta}_2}^2$$

$$= \frac{1}{2} m_2\{2\dot{\theta}_2{}^2 l_{2cog}{}^2 + \dot{\theta}_1{}^2 l_1{}^2 + 2\dot{\theta}_1\dot{\theta}_2 l_1 l_{2cog}\cos(\theta_1 - \theta_2)\}$$

$$V_1 = m_1 g l_{1cog}\cos\theta_1$$

$$V_2 = m_2 g(l_{2cog}\cos\theta_2 + l_1\cos\theta_1)$$

Therefore, the Lagrangian of the links,

$$L_1 = m_1 l_{1cog}{}^2\dot{\theta}_1{}^2 - m_1 g l_{1cog}\cos\theta_1$$

$$L_2 = m_2\dot{\theta}_2{}^2 l_{2cog}{}^2 + \tfrac{1}{2} m_2\dot{\theta}_1{}^2 l_1{}^2 + m_2\dot{\theta}_1\dot{\theta}_2 l_1 l_{2cog}\cos(\theta_1 - \theta_2) - m_2 g l_{2cog}\cos\theta_2 + m_2 g l_1\cos\theta_1$$

Using these above equations of L_1 and L_2 in Euler-Lagrange equation we get,

$$\tau_1 = \frac{d}{dt}\left(\frac{dL_1}{d\dot{\theta}_1}\right) - \frac{d(L_1)}{d\theta_1}$$

$$= 2m_1 l_{1cog}{}^2\ddot{\theta} - m_1 g l_{1cog}\sin\theta_1 \text{ ------------ (3)}$$

$$\tau_2 = \frac{d}{dt}\left(\frac{dL_2}{d\dot{\theta}_2}\right) - \frac{d(2)}{d\theta_2}$$

$$= 2m_2\ddot{\theta}_2 l_{2cog}{}^2 + m_2\ddot{\theta}_1 l_1 l_{2cog}\cos(\theta_1 - \theta_2) - m_2\dot{\theta}_1\dot{\theta}_2 l_1 l_{2cog}\sin(\theta_1 - \theta_2)$$

$$-m_2 g l_{2cog}\sin\theta_2 \text{ ------------ (4)}$$

After linearizing the equations of energy and motion:

$$\dot{\theta}_1 \approx \dot{\theta}_1 \approx 0$$

$$\tau_2 = 2m_2\ddot{\theta}_2 l_{2cog}{}^2 + m_2\ddot{\theta}_1 l_1 l_{2cog}\cos(\theta_1 - \theta_2) - m_2 g l_{2cog}\sin\theta_2$$

From eq^n (1),

$$\frac{d}{dt}\left(\frac{dL_1}{d\dot{\theta}_1}\right) = \frac{d(L_1)}{d\theta_1}$$

$$2m_1 l_{1cog}{}^2\ddot{\theta}_1 = m_1 g l_{1cog}\sin\theta_1$$

$\therefore \ddot{\theta}_1 = \frac{1}{2}\frac{g}{l_{1cog}} \sin\theta_1$--------------- (5)

From eq^n (4) and eq^n (5),

$$2m_2\ddot{\theta}_2 {l_{2cog}}^2 + m_2\ddot{\theta}_1 l_1 l_{2cog}\cos(\theta_1 - \theta_2) - m_2 g l_{2cog}\sin\theta_2 = 0$$

$$2m_2\ddot{\theta}_2 {l_{2cog}}^2 = m_2 g l_{2cog}\sin\theta_2 - m_2\ddot{\theta}_1 l_1 l_{2cog}\cos(\theta_1 - \theta_2)$$

$$\ddot{\theta}_2 = \frac{m_2 g l_{2cog}\sin\theta_2 - m_2\ddot{\theta}_1 l_1 l_{2cog}\cos(\theta_1 - \theta_2)}{2m_2 {l_{2cog}}^2}$$

$$= \frac{1}{2}\{\frac{g}{l_{2cog}}\sin\theta_2 - \frac{1}{2}\frac{l_1}{l_{2cog}}\frac{g}{l_{1cog}} l_{2cog}\sin\theta_1\cos(\theta_1 - \theta_2)\}$$

3.3 Body Parameter Equations

3.3.1 Center of Gravity detection in dynamic position

When there is a movement of any object the Center of Gravity (COG) of that object changes each time. For balancing, that the net force (in Newtonian theorem) or the net energy (Hamilton or Lagrangian theorem) [19] at the point of COG becomes zero. The COG changes its position to the Base support of our body or any other balancing object respectively. Therefore, it vital that the COG must be detected properly and then at that point the net energy (Torque) must be calculated.

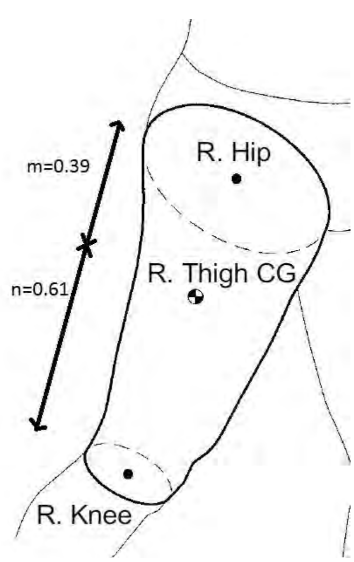

Figure 15: Location of COG of the right thigh

In our research, we had to identify the COG of calf and thigh as they both were considered as the link1 and link2 of our DIPM. In order to calculate the positions of COG, we needed two sets of information: the locations of the joint centers or segment endpoints of thigh/calf and the body segment parameter data [20]. Using the mean data of Chandler et al. (1975) [20] and the following equations for predicting center of gravity locations has been derived:

$$P_{thigh,cog} = P_{knee} + (0.61)(P_{knee} - P_{hip})$$

$$P_{calf,cog} = P_{knee} + (0.58)(P_{ankle} - P_{knee})$$

3.3.2 Marker Placement Model for Joint Position Detection

One of our main problem for detecting COG of body segment was the start and end point of that segment. As human body is based on a skeleton structure therefore all the forces work respect to bones and their position. Therefore, for detecting the COG of thigh and calf we needed to know the underlying skeleton position of our Hip joint (Sacrum), Knee joint (Femoral Epicondyle) and Ankle joint (Lateral Malleolus) [20].

Some systems, such as the commercially available OrthoTrak product from Motion Analysis Corporation uses marker system (up to 25 markers) [20] to detect the underlying skeleton positions. For our research, this was too many markers, and the use of bulky triads on each thigh and calf severely could encumber the subject. The advantage of this approach is that the markers are easier to track in 3-D space [20]. The 3- step strategy used to calculate the positions of the hip, knee, and ankle joints on both sides of the body is as follows:

1. Select three markers for the segment of interest.

2. Create an orthogonal u, v, w reference system based on these three markers.

3. Use prediction equations based on anthropometric measurements and the u, v, w reference system to estimate the joint center positions. [20]

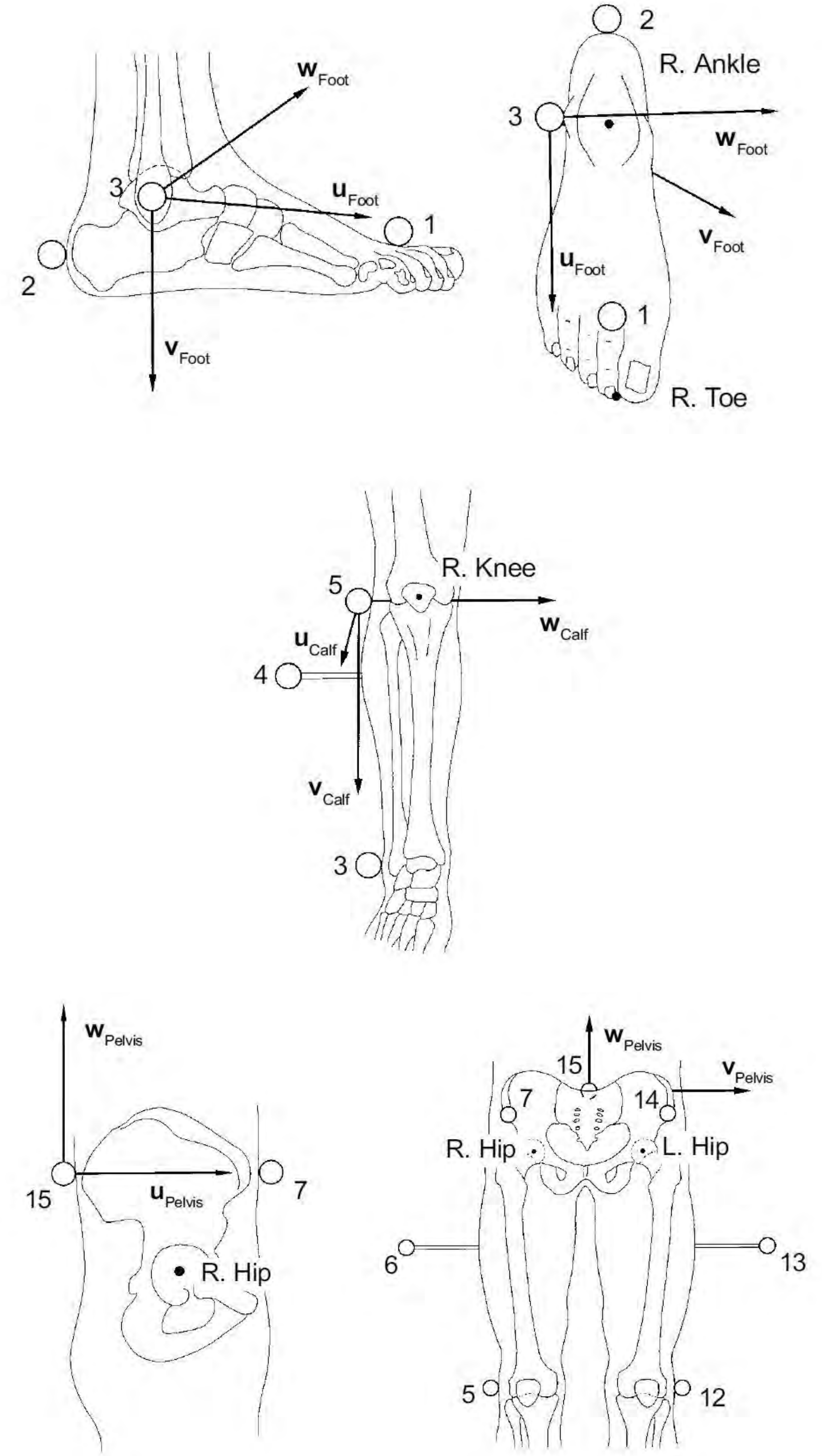

Figure 16: Marker Placement Model

$P_{ankle} = P_{lateral\ malleolus}$

$= (+(0.16)(foot\ length)_{u_{foot}},$

$+(0.392)(malleolus\ height)_{v_{foot}},$

$+(0.498)(malleous\ width)_{w_{foot}})$

$P_{knee} = P_{femoral\ eicondyle}$

$= (+(0.000)(knee\ diameter)_{u_{calf}},$

$+(0.000)(knee\ diameter)_{v_{calf}},$

$+(0.005)(knee\ diameter)_{w_{calf}})$

$P_{hip} = P_{sacrum}$

$= (+(0.598)(ASIS\ breadth)_{u_{pelvis}},$

$+/-(0.344)(ASIS\ breadth)_{v_{pelvis}},$

$+(0.290)(ASIS\ breadth)_{w_{pelvis}})$

3.3.3 Body Segment Mass

Mass of each body segment of our body is related with the total body mass and the dimensions of those segment of interest. As mass is related to density and volume, the segment mass should be related to a composite parameter which has the dimensions of length and depends on the volume of the segment. We assumed our thigh and calf segment as cylindrical therefore, based on the data in Chandler et al. (1975) [20], mass of body segment equations can be derived as follows:

$$Mass\ of\ thigh = (0.1032)(Total\ Body\ Mass) + (12.72)(thigh\ length)(mid - thigh\ circumference)^2 + (-1.023)$$

$$Mass\ of\ calf = (0.0226)(Total\ Body\ Mass) + (31.33)(calf\ length)(calf\ circumference)^2 + (0.016)$$

Chapter 4

EXPERIMENTS AND RESULT ANALYSIS

4. Experiment and Result Analysis

4.1 Data Collection

We have used dataset from "Dynamics of Human Gait" book's example and data table [20]. In addition, from the experiment of six cadaver's studies by Chandler, Clauser, McConville, Reynolds, and Young (1975) [20]. We have also taken some raw data from 15 normal people for identifying the balancing factor parameter on average.

Person No.	Right Calf Angle (θ_1)	Left Calf Angle (θ_1)	Right Thigh Angle (θ_2)	Left Thigh Angle (θ_2)
1	34	40	35	35
2	35	41	34	37
3	40	38	36	42
4	44	48	31	31
5	33	38	33	39
6	32	34	40	46
7	30	35	35	50
8	33	38	32	30
9	43	50	33	53
10	33	39	35	45
11	45	52	40	55
12	32	40	32	32
13	37	42	30	40
14	35	43	31	31
15	38	45	32	42

Table 1: Balancing angle range for balanced people

From Table 1, we have assumed some average angle range for both left calf, thigh and right calf, thigh of normally balanced people to simulate for disable personals.

4.2 Experiment

Firstly, we have taken the θ_1 and θ_2 value of balancing range for normal people to identify the optimum tolerable value of angles. Then we simulated our disable personals according to the normal people balancing range. We have considered other variables like mass and length of body segment as constant. We also considered some assumption of attribute values for linearization of our equation solving.

Therefore, to find out the energy and torque in the base of support (BOS) and center of gravity (COG) we simulated calf angles from 0 to 45 deg. for θ_1 while leaving θ_2 constant at 0 degree and 30 degree for right leg, 0 degree and 45 degree for left leg. We also simulated the thigh angles from 0 to 45 degree for θ_2 while leaving $\theta_1$constant at 0 degree and 30 degree for right leg, 0 degree and 45 degree for the left leg. We also considered the Angular (Phi) position of ground plane for dynamic positioning and COG detection. As our foot was connected with the ground directly we considered gravitational force at that point is zero.

Body parameter used for simulation is as follows:

Mass of the subject, m = 64.99 kg

Length of the calf (Right) = 0.430 m

Length of the calf (Left) = 0.430 m

Length of the thigh (Right) = 0.460 m

Length of the thigh (Left) = 0.465 m

Right Middle Thigh Circumference = 0.450 m

Left Middle Thigh Circumference = 0.440 m

Right Middle Calf Circumference = 0.365 m

Left Middle Calf Circumference = 0.365 m

Knee Diameter (Right) = 0.108 m

Knee Diameter (Left) = 0.112 m

ASIS Breadth Length (Right) = 0. 240 m

ASIS Breadth Length (Left) = 0. 240 m

Length of Foot (Right) = 0.260 m

Length of Foot (Left) = 0.260 m

Right Malleolus Height = 0.60 m

Left Malleolus Height = 0.60 m

Right Malleolus Width = 0.074 m

Left Malleolus Width = 0.073 m

Gravitational acceleration constant, g = 9.81 m/s^2

4.3 Result Analysis

After simulation, we plotted our Theta (θ) vs Torque (τ) values for both legs with both angles of calf and thigh. We got different graphs that shows the interactions points where τ_1= $\tau_2$with different direction where the net Energy in COG is Zero.

We have seen when calf in stance position only θ_2 has affect in balance where as if we moved our bottom part of leg both the angles θ_1 and θ_2 changed and at some points the resultant torque became zero. That is the balancing range of angles.

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	0	15	16	No
64.99	1	0	14	16	No
64.99	2	0	14	15	No
64.99	3	0	14	15	No
64.99	4	0	14	14	Yes
64.99	5	0	13	14	No
64.99	6	0	13	14	No
64.99	7	0	13	13	Yes
64.99	8	0	13	13	Yes
64.99	9	0	12	13	No
64.99	10	0	12	12	Yes
64.99	11	0	12	12	Yes
64.99	12	0	12	11	No
64.99	13	0	11	11	Yes
64.99	14	0	11	11	Yes
64.99	15	0	11	10	No
64.99	16	0	11	10	No
64.99	17	0	10	10	Yes
64.99	18	0	10	9	No
64.99	19	0	10	9	No

Table 2: Experimental result for right calf rotational degrees with thigh angle 0 degree

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	30	15	16	No
64.99	4	30	14	16	No
64.99	8	30	13	15	No
64.99	12	30	12	14	No
64.99	16	30	11	13	No
64.99	20	30	10	12	No
64.99	24	30	9	10	No
64.99	28	30	8	9	No
64.99	32	30	7	8	No
64.99	34	30	7	7	Yes
64.99	35	30	6	7	No
64.99	36	30	6	7	No
64.99	37	30	6	7	No
64.99	38	30	6	6	Yes
64.99	39	30	6	6	Yes
64.99	40	30	5	6	No
64.99	41	30	5	6	No
64.99	42	30	5	5	Yes
64.99	43	30	5	5	Yes
64.99	44	30	5	5	Yes

Table 3: Experimental result for right calf rotational degrees with thigh angle 30 degree

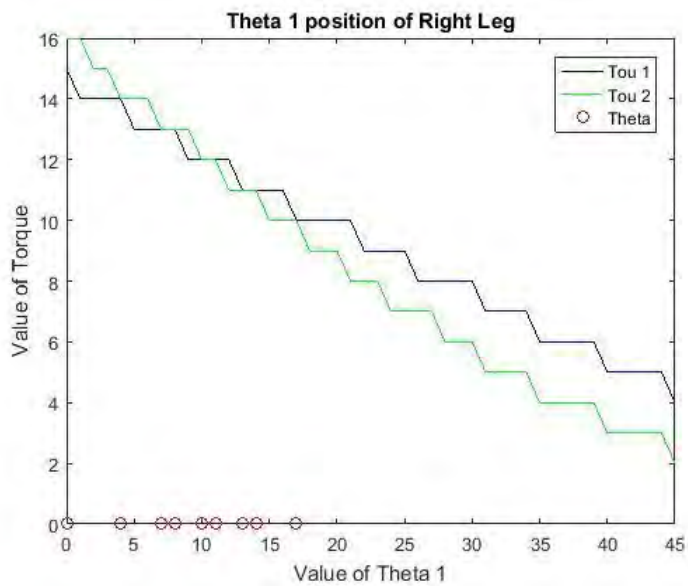

Figure 17: Balanced angle for right calf with thigh angle 0 degree

In this graph, for constant right thigh angle of 0 degree with the right calf degrees of 4,7,8 ,10,11,13,14 and 17 we are getting intersecting point of τ_1 and τ_2. So, for those angles of right calf the system is balance.

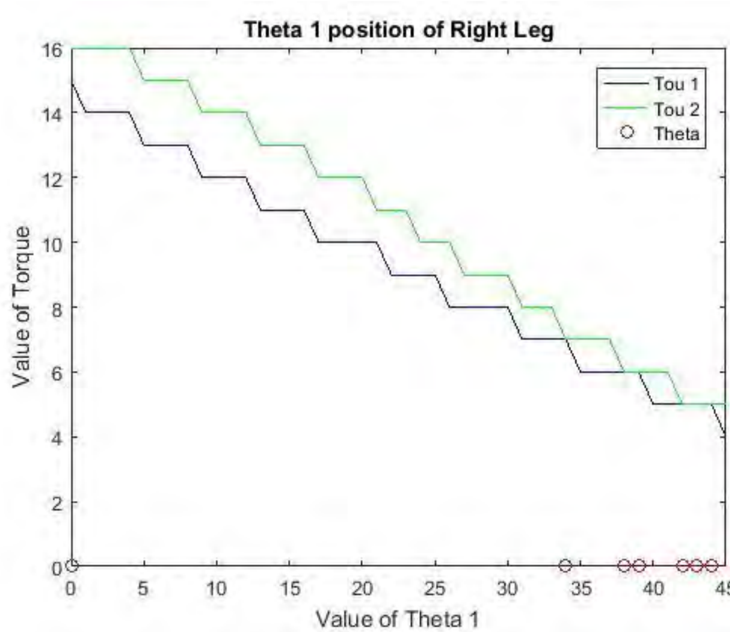

Figure 18: Balanced angle for right calf with thigh angle 30 degree

In this graph, for constant right thigh angle of 30 degree with the right calf degrees 34,38,39,43 to 45 we are getting intersecting point of τ_1 and τ_2. So, for those angles of right calf the system is balance.

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	0	15	16	No
64.99	0	3	15	16	No
64.99	0	6	15	16	No
64.99	0	9	15	17	No
64.99	0	12	15	17	No
64.99	0	15	15	17	No
64.99	0	18	15	17	No
64.99	0	21	15	17	No
64.99	0	24	15	17	No
64.99	0	27	15	16	No
64.99	0	30	15	16	No
64.99	0	37	15	16	No
64.99	0	38	15	15	Yes
64.99	0	39	15	15	Yes
64.99	0	40	15	15	Yes
64.99	0	41	15	15	Yes
64.99	0	42	15	15	Yes
64.99	0	43	15	15	Yes
64.99	0	44	15	14	No
64.99	0	45	15	14	No

Table 4: Experimental result for right thigh rotational degrees with calf angle 0 degree

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	30	0	8	6	No
64.99	30	5	8	6	No
64.99	30	10	8	7	No
64.99	30	16	8	8	Yes
64.99	30	17	8	8	Yes
64.99	30	18	8	8	Yes
64.99	30	19	8	8	Yes
64.99	30	20	8	8	Yes
64.99	30	21	8	8	Yes
64.99	30	22	8	8	Yes
64.99	30	23	8	8	Yes
64.99	30	24	8	8	Yes
64.99	30	25	8	8	Yes
64.99	30	26	8	8	Yes
64.99	30	27	8	8	Yes
64.99	30	28	8	8	Yes
64.99	30	29	8	8	Yes
64.99	30	35	8	9	No
64.99	30	40	8	9	No
64.99	30	45	8	9	No

Table 5: Experimental result for right thigh rotational degrees with calf angle 30 degree

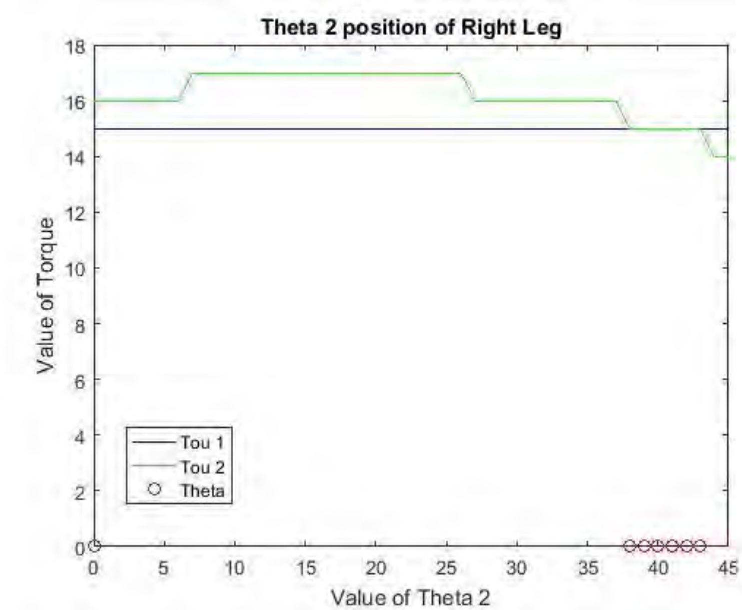

Figure 19: Balanced angle for right thigh with calf angle 0 degree

In this graph, for constant right calf angle of 0 degree with the right thigh degrees of 38 to 43 we are getting intersecting point of τ_1 and τ_2. So, for those angles of right thigh the system is balance.

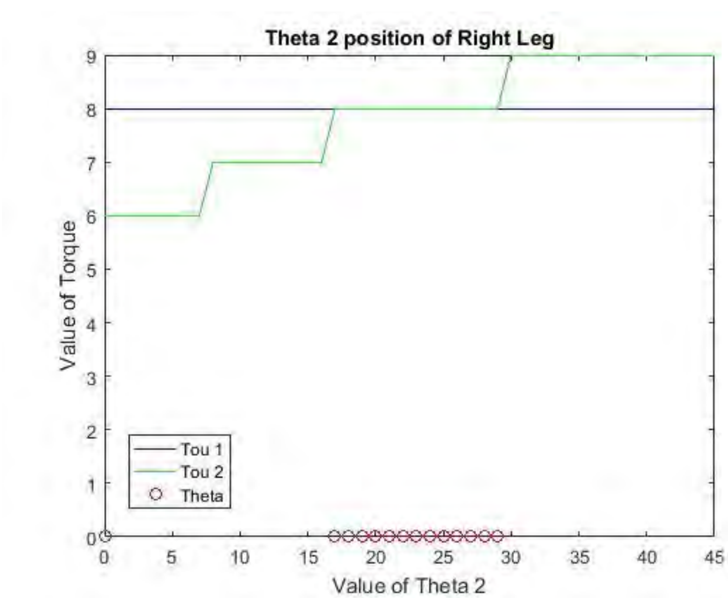

Figure 20: Balanced angle for right thigh with calf angle 30 degree

In this graph, for constant right calf angle of 30 degree with the right thigh degrees of 16 to 29 we are getting intersecting point of $\tau_1$and τ_2. So, for those angles of right thigh the system is balance.

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	0	10	20	No
64.99	3	0	9	19	No
64.99	6	0	9	17	No
64.99	9	0	8	16	No
64.99	12	0	8	14	No
64.99	15	0	7	13	No
64.99	18	0	7	12	No
64.99	21	0	6	10	No
64.99	24	0	6	9	No
64.99	27	0	5	8	No
64.99	30	0	5	7	No
64.99	33	0	5	6	No
64.99	36	0	4	5	No
64.99	39	0	4	5	No
64.99	40	0	4	4	Yes
64.99	41	0	4	4	Yes
64.99	42	0	3	4	No
64.99	43	0	3	4	No
64.99	44	0	3	3	Yes
64.99	45	0	3	3	Yes

Table 6: Experimental result for left calf rotational degrees with thigh angle 0 degree

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	45	10	11	No
64.99	1	45	10	10	Yes
64.99	5	45	9	10	No
64.99	7	45	9	9	Yes
64.99	10	45	8	9	No
64.99	11	45	8	8	Yes
64.99	13	45	8	8	Yes
64.99	14	45	7	8	No
64.99	18	45	7	7	Yes
64.99	19	45	7	7	Yes
64.99	20	45	7	6	No
64.99	21	45	6	6	Yes
64.99	24	45	6	6	Yes
64.99	26	45	6	5	No
64.99	29	45	5	5	Yes
64.99	32	45	5	4	No
64.99	35	45	4	4	Yes
64.99	38	45	4	3	No
64.99	42	45	3	3	Yes
64.99	45	45	3	2	No

Table 7: Experimental result for left calf rotational degrees with thigh angle 45 degree

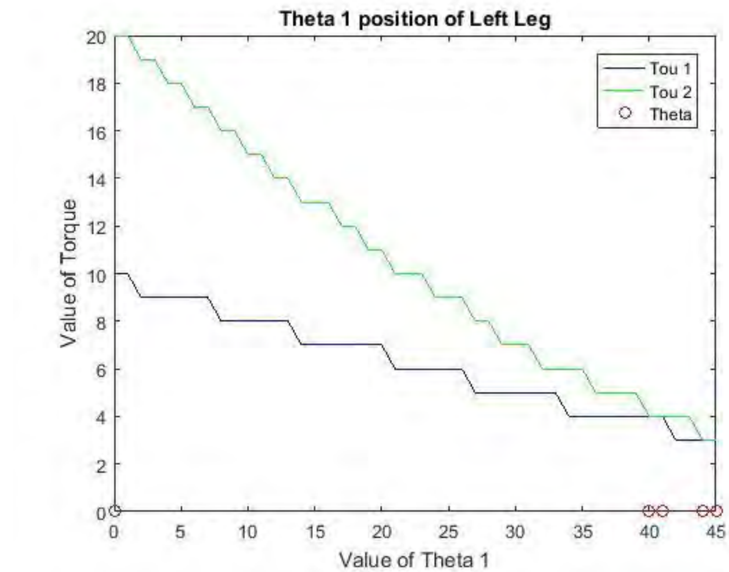

Figure 21: Balanced angle for left calf with thigh angle 0 degree

In this graph, for constant left thigh angle of 0 degree with the left calf degrees of 40,41,44 and 45 we are getting intersecting point of τ_1 and τ_2. So, for those angles of left calf the system is balance.

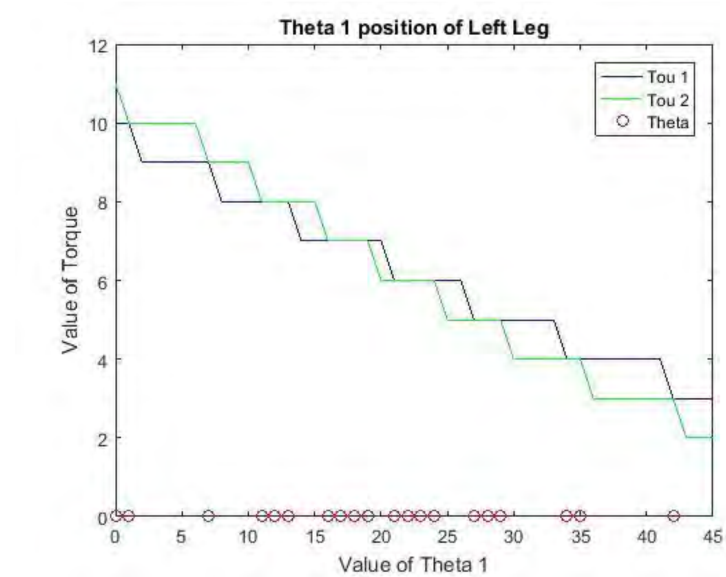

Figure 22: Balanced angle for left calf with thigh angle 45 degree

In this graph, for constant left thigh angle of 45 degree with the left calf degrees of 1,7,11,13,18,19,21,24,29,35 and 42 we are getting intersecting point of$\tau_1$and τ_2. So, for those angles of left calf the system is balance.

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	0	0	14	16	No
64.99	0	4	14	16	No
64.99	0	8	14	15	No
64.99	0	12	14	15	No
64.99	0	15	14	14	Yes
64.99	0	16	14	14	Yes
64.99	0	17	14	14	Yes
64.99	0	18	14	14	Yes
64.99	0	19	14	14	Yes
64.99	0	20	14	14	Yes
64.99	0	22	14	13	No
64.99	0	25	14	13	No
64.99	0	28	14	12	No
64.99	0	31	14	12	No
64.99	0	34	14	11	No
64.99	0	37	14	10	No
64.99	0	40	14	10	No
64.99	0	43	14	9	No
64.99	0	44	14	9	No
64.99	0	45	14	9	No

Table 8: Experimental result for left thigh rotational degrees with calf angle 0 degree

Weight(kg)	Calf Angle (deg.)	Thigh Angle (deg.)	Calf Torque (Nm)	Thigh Torque (Nm)	Balance
64.99	45	0	4	2	No
64.99	45	4	4	3	No
64.99	45	8	4	3	No
64.99	45	12	4	3	No
64.99	45	14	4	4	Yes
64.99	45	16	4	4	Yes
64.99	45	18	4	4	Yes
64.99	45	20	4	4	Yes
64.99	45	22	4	4	Yes
64.99	45	24	4	4	Yes
64.99	45	26	4	4	Yes
64.99	45	28	4	4	Yes
64.99	45	30	4	5	No
64.99	45	32	4	5	No
64.99	45	34	4	5	No
64.99	45	36	4	5	No
64.99	45	38	4	5	No
64.99	45	40	4	5	No
64.99	45	42	4	5	No
64.99	45	45	4	5	No

Table 9: Experimental result for left thigh rotational degrees with calf angle 45 degree

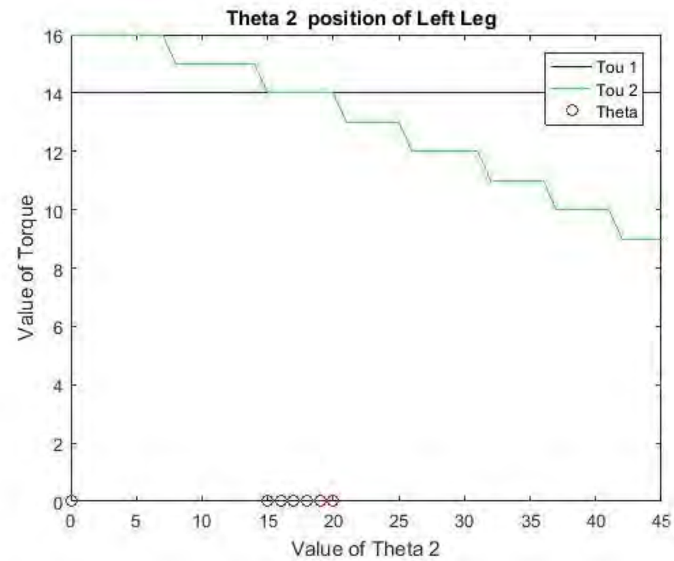

Figure 23: Balanced angle for left thigh with calf angle 0 degree

In this graph, for constant left calf angle of 0 degree with the left thigh degrees of 15 to 20 we are getting intersecting point of τ_1 and τ_2. So, for those angles of left thigh the system is balance.

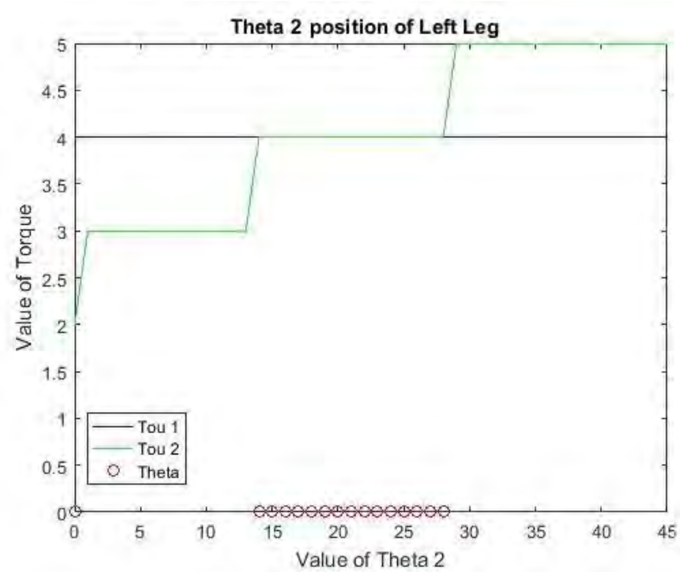

Figure 24: Balanced angle for left thigh with calf angle 45 degree

In this graph, for constant left calf angle of 0 degree with the left thigh degrees of 14 to 28 we are getting intersecting point of τ_1 and τ_2. So, for those angles of left thigh the system is balance.

Chapter 5

CONCLUSION AND FUTURE WORK

5. Conclusion

5.1 Conclusion

In our research, our study emphasized on the reasons to human balancing and what should be done for stable balancing and fall control. Our research introduces a theoretical balancing system for different stance position. The system presents the Double Inverted Pendulum Model (DIPM) for stability control of disable personals. The system works using the two rotational degrees of freedom at ankle joint and knee joint for both legs. It takes the mass and length of human subject and suggests the optimal standing angles to prevent falling.

In our research, we also tried to describe it as the most energy based control architecture as our system use the ankle torque and knee torque for balancing. Therefore, for disable personals those who don't have control over their body, their balance will be restored in such easy and efficient way possible. Finally, the description of stability control using DIPM, the rotational degree and the energy has been presented.

5.2 Future Work

In future, we wish to extend our research by adding more variable attributes and actuators for proper balancing for handicapped personals. Therefore, we hope the output of this research will be very helpful to develop stable human balance controlling and prevent of falling for the disable people.

Chapter 6

REFERENCES

1. REFERENCES

1. F. Parietti and H. Geyer, "**Reactive Balance Control in Walking Based On A Bipedal Linear Inverted Pendulum Model**," *2011 IEEE International Conference on Robotics and Automation*, Shanghai, 2011, pp. 5442-5447.
2. D. Winter, "**Human balance and posture control during standing and walking**," *Gait & Posture*, vol. 3, no. 4, pp. 193–214, December 1995.
3. F. B. Horak and L. M. Nashner, "**Central programming of postural movements: adaptation to altered support-surface configurations.**" *J Neurophysiol*, vol. 55, no. 6, pp. 1369–1381, Jun 1986.
4. J. Pratt, J. Carff, S. Drakunov, and A. Goswami, "**Capture point: A step toward humanoid push recovery**," in Proc. *6th IEEE-RAS Int Humanoid Robots Conf, 2006*, pp. 200–207
5. S. Kajita et al., "**Biped Walking Stabilization Based On Linear Inverted Pendulum Tracking**," Intelligent Robots and Systems (IROS), *2010 IEEE/RSJ International Conference* on, Taipei, 2010, pp. 4489-4496.
6. Sun, Jinming, "**Dynamic Modeling of Human Gait Using a Model Predictive Control Approach**," Ph.D. dissertations, *Marquette Univ*. Milwaukee, WI, 2015.
7. Shuuji Kajita, Osamu Matsumoto, and Muneharu Saigo, "**Real-time 3d walking pattern generation for biped robot with telescopic legs**," in Proceedings of the *IEEE International Conference on Robotics and Automation,* pages 2299–2306, Seoul, Korea, May 2001.
8. Shunsuke Kudoh and Taku Komura, "**C2 continuous gait-pattern generation for biped robots**," in Proceedings of *2003 IEEE International conference on Intelligent Robots and Systems*, pages 1135–1140, Las Vegas, NV, 2002.
9. B. Stephens, "**Integral control of humanoid balance**," *The Robotics Institute*, Carnegie Mellon Univ., Pittsburgh, PA, 2007.
10. A. Kot and A. Nawrocka, "**Double Inverted Pendulum For Human Hip Strategy Of Balance Modelling**," *2016 17th International Carpathian Control Conference (ICCC)*, Tatranska Lomnica, 2016, pp. 368-371.
11. The World Bank (2017, March 29), **Disability Overview** [Online], Available: *www.worldbank.org/en/topic/disability/overview.*

12. F. Wang, S. Zhao, Y. Lu and J. Xu, "**Balance Control Strategy of Humanoid Robot Based on Stiffness Control**," Cyber Technology in Automation, Control and Intelligent Systems (CYBER), *2013 IEEE 3rd Annual International Conference* on, Nanjing, 2013, pp. 195-200.
13. Y. Hirata, S. Komatsuda and K. Kosuge, "**Fall Prevention Control of Passive Intelligent Walker Based on Human Model**," *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Nice, 2008, pp. 1222-1228.
14. I. D. Lorum, "**Mechanisms for Human Balancing of An Inverted Pendulum Using The Ankle Strategy**," Ph.D. dissertation, School of Sport and Exercise Sciences, *Univ. of Birmingham*, Birmingham, UK, 2002.
15. Nita H. Shah and M. Yeolekar, "**Pole Placement Approach for Controlling Double Inverted Pendulum**," *Global Journals Inc*., Vol, 13, Issue 2, Ver. 1.0, 2013, USA.
16. Ohsumi, A. & Izumikawa, T. (1995), "**Non-linear control of swing-up and stabilization of an inverted pendulum**," Proceedings of the *34th IEEE Conference on Decision and Control*, Vol. 4.
17. Kearney, R. E. & Hunter, I. W. (1982), "**Dynamics of human ankle stiffness: variation with displacement amplitude**," in *Journal of Biomechanics* 15 No. 10, 753-756.
18. Page, R. L. (1978), "**The physics of human movement**," *Wheaton*, Exeter.
19. S. T. Thornton, J. B. Marion, "**Hamilton's Principle-Lagrangian and Hamilton Dynamics**," in *Classical Dynamics of Particles and Systems*, 3rd India Edition, Massachusetts: Cengage Learning, 2009.
20. C.L. Vaughan, B.L. Davis and J.C. O'Connor, "**Integration of Anthropometry, Displacements, and Ground Reaction Forces**," in *Dynamics of Human Gait*, 2nd Ed, South Africa: Kiboho, 1992.