Biomechanical Analysis of Human Gait for Bipedal Robotic Applications

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***Abstract*— Gait is the traversing of human leg from one point to another for the purpose of walking while expending least possible energy during the process. The human gait cycle consists of 8 different phases in which movement of the legs occur. The optimum profile of the foot trajectory for the bipedal application is selected to be cycloidal and a gait generation model is used for the estimation of co-ordinates of points across the pattern. The joint angles can be determined using the method of Inverse Kinematics. Finally, a concept model of a human like Biped robot is created and it has been demonstrated that the human gait can be successfully translated to robotic applications.**

Keywords—Gait; Biomechanics; Robotics; Inverse Kinematics; Human structure

I. INTRODUCTION

The Basic requirement for achieving Bipedal Robotic Walking similar to humans is achieved through the detailed study of human gait patterns. Human traverses his/her leg from one point to another with the application of forces along the thigh and shin muscles according to a specific pattern called as a Gait Pattern. This gait pattern is used for walking which consists of the periodic movement of alternate legs in the pattern for locomotion. A perfect gait pattern is one in which there is the application of least possible forces for maximum possible distance traversed by the foot of the human. Dynamics of different parts of body translates the Centre of Gravity (C.G) of the body during different phases and stances in the pattern ultimately thrusting the body forward. The position of CG with respect to time is calculated throughout the gait cycle. An efficient method of calculating the C.G and Zero Moment Point has been discussed in the paper "Estimation of Estimation of Zero Moment Point using Centre of Gravity based Method" [4]. Thus, by studying the gait patterns of humans we can determine an optimum walking pattern for a bipedal robot which would decrease battery power requirement for joint actuation.

II. HUMAN LEG ANATOMY

A. Leg Structure

The Human leg structure consists of the Hip joint to which the Femur thigh bone is connected, the knee cap and the lower shin bones, Tibia and Fibula which are connected to ankle joint.

B. Gait Analysis

Generally, a human gait cycle is divided into 8 different phases which are helpful in designing the walking pattern of our biped robot. Considering Ankle Joint, when the foot is bent upwards, the position is termed as dorsal flexion while when it is bent towards downwards from the neutral position, it is termed as plantar flexion. In terms of Hip joint, when the Femur is rotated in the forward direction, it is termed as Flexion while when it rotated behind the torso, it is termed as Hyperextension [2]. The 8 phases of human gait can be summarized as given below:

a. Initial Contact (IC): In the initial position of our gait cycle, the heel is in contact with the ground. The ankle joint is at the neutral position, the knee is 0 to 5 degrees flexion and hip is at 20 degree flexion position.
b. Loading Response (LR): During this cycle, the shock is absorbed by knee and ankle joints and forward motion is provided by the heel and this position contributes to load transmission and stability. After 12% of the total gait cycle, the ankle is at 5 to 10 degree Plantar Flexion position. Knee and Hip are at 20 degree flexion position.
c. Mid-Stance (MST): In this phase, the forward motion of Tibia takes place which leads to shifting of C.G to the front of ankle. After 31% of total gait cycle, ankle joint is at 5 degree dorsal flexion, knee is at 0-5 degree flexion and hip is at 0 degree flexion positions.
d. Terminal Stance (TST): During this phase, heel is lifted from the ground and dorsal extension at ankle takes place. After 50% of the total gait cycle, ankle joint is 10 degree dorsal flexion, knee is at 0-5 degree flexion and hip is at 20 degree hyperextension positions.
e. Pre-Swing (PSW): At this position, the ankle is rotated downwards from neutral position. After 62% completion of gait cycle, the ankle joint is at 15 degree Plantar flexion position, knee is at 40 degree flexion position and hip is at 10 degree hyperextension position.
f. Initial Swing (ISW): During this phase, minimum of 55 degree knee flexion takes place for sufficient ground clearance. After 75% of the gait cycle, the

ankle joint is at 5 degree plantar flexion position, knee is at 60-70 degree flexion position and hip is at 15 degree flexion position.

g. Mid Swing (MSW): In this phase, the ankle joint is brought at neutral zero position and hip flexion is increased to 25 degree. After completing 87% of the gait cycle, ankle joint is at the neutral position, and knee and hip are at 25 degree flexion position.

h. Terminal Swing (TSW): In this phase, the knee joint is extended to neutral flexion and the gait is prepared for the next cycle.

The 8 positions according to the phases as discussed above are shown in Figure 1 [3].

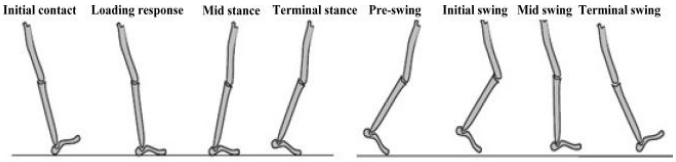

Figure 1: Phases of human gait pattern

In the Bipedal Application, for simplicity and efficiency, we have divided our gait cycle in 4 phases starting from Pre-Swing up to Terminal Swing of human gait cycle.

III. Gait Motion Analysis

Gait Motion Analysis deals with the study of foot trajectories and profiles. There are various trajectories of foot motion which take place in day to day walking of a human. However, the most efficient trajectory profile proved to be a cycloidal profile. A gait generation model has been used for the creation of the foot trajectory during the gait phases [1]. We have used the equations:

$$x_a(t) = \frac{-l_s * \cos*\left(\frac{3.14t}{T}\right)}{2}$$

$$y_a(t) = r * (1 - \cos t_r)$$

Where, ls = Step length, t = time step = 0.01 sec, T = Total time required to complete one step = 1 sec, t_r = Angle in radian and r = radius.

After multiple iterations and optimizations, a step length of 0.3 meters has been selected. The link lengths for the Biped have been selected using the forward Kinematics while inverse Kinematics is used to find out the joint angles for tracing the gait profile.

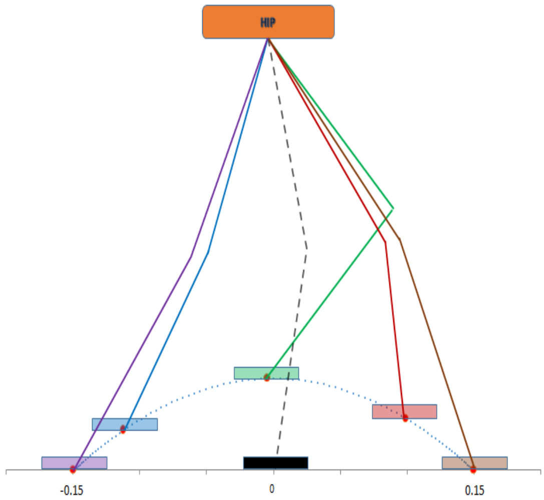

Figure 2: Generated Gait Profile

Figure 2 shows the generated gait profile for the Biped while table 1 describes the position of the foot for 0%, 24%, 50%, 74% and 100% of the gait trajectory.

Table 1: Calculated co-ordinates for points on the profile

Sr. No.	Percentage of completed Gait Cycle	x_a (m)	y_a(m)
1	0	-0.15	0
2	24	-0.11251	0.043733
3	50	-0.00471	0.099901
4	74	0.099197	0.056267
5	100	0.15	0

IV. JOINT ANGLE CALCULATIONS

There are 3 joints in a human leg: the hip joint, the knee joint and the ankle joint. From the gait trajectory, we can obtain the co-ordinates of points along the trajectory which can be used for estimation of the joint angles with the help of Inverse Kinematics. We use the simplest and most efficient method, the geometric method as there are only 3 joints per leg in the biped [1]. Figure 3 shows the geometric representation of the bipedal model.

We formulate the required equations using trigonometric formulae to calculate the joint angles.

$$A = \tan^{-1}\left[\frac{x}{y} - (L1 + L2)\right]$$

$$B = 90 - \tan^{-1}[\frac{x}{y} - (L1 + L2)]$$

$$(ce)^2 = [y - (L1 + L2)]^2 + x^2$$

$$\theta_1 = \theta_2 = 0$$

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$$\theta_4 = \frac{180 - \cos^{-1}\{L3^2 + L4^2 - [(y - L1 + L2)^2 + x^2]\}}{(2 * L3 * L4)}$$

$$\theta_3 = \frac{\tan^{-1}\left[\frac{x}{y} - (L1 - L2)\right] + \cos^{-1}[\{L3^2 + \{[y - L1 + L2]^2 + x^2\} - L4^2]}{2 * L3 * \{[y - (L1 + L2)]^2 + x^2\}^{\left(\frac{1}{2}\right)}}$$

$$\theta_5 = \frac{180 - (\cos^{-1}\{[y - L1 + L2]^2 + x^2\} + L4^2 - L3^2)}{2 * L4 * \{[y - L1 + L2]^2 + x^2\}^{\left(\frac{1}{2}\right)}} + 90 - \tan^{-1}[\frac{x}{y} - (l1 + L2]$$

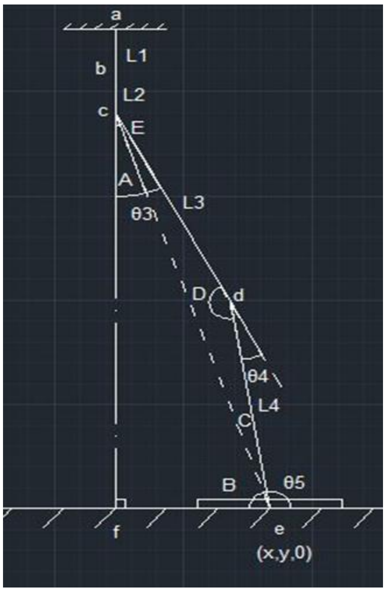

Figure 3: Joint Angle calculation using Inverse Kinematics

Where, x = x coordinate of the end effector, y = y coordinate of the end effector, θ_3= Angle of hip (Joint Angle), θ_4= Angle of knee (Joint Angle), θ_5=Angle of ankle (Joint Angle), ab = L1 = Length of Link 1, bc = L2 = Length of Link 2, cd = L3 = Length of Link 3, de = L4 = Length of Link 4

Table 2: Calculated joint angles for various positions

Percentage of completed Gait Cycle	Position of the thigh (θ_3)	Position of the Shin(θ_4)	Position of the Ankle(θ_5)
0	11.17° Hyperextension	12.8° Flexion	23.9° Dorsal Flexion
24	12.6° Flexion	54.53° Flexion	41.93° Dorsal Flexion
50	40.9° Flexion	83.2° Flexion	42.3° Dorsal Flexion
74	44.26° Flexion	61.78° Flexion	17.53° Dorsal Flexion
100	56.06° Flexion	13.04° Flexion	11.04° Plantar Flexion

Table 2 shows the joint angles at various positions calculated using the formulated equations while figure 4 shows the variation of the joint angles along the cycloidal gait profile generated above using inverse kinematics.

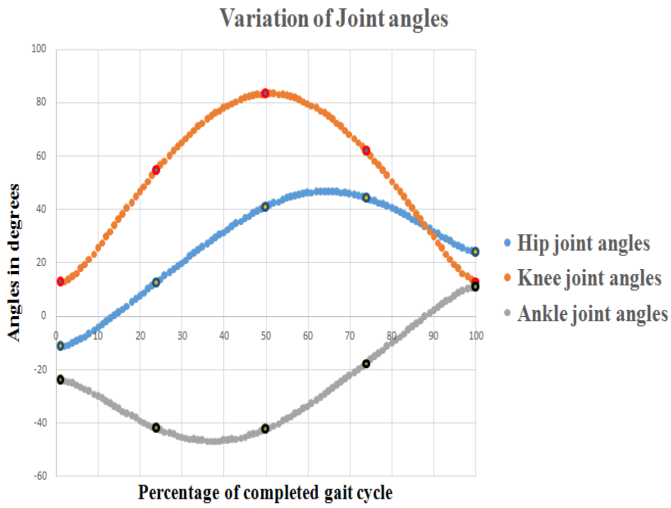

Figure 4: Variation of Joint Angles

V. 3D MODELLING AND SIMULATION

A 3D rendered concept design of the Bipedal Humanoid Robot similar in structure and design to a human has been created using CATIA V5 which can be seen in the figure 5 below.

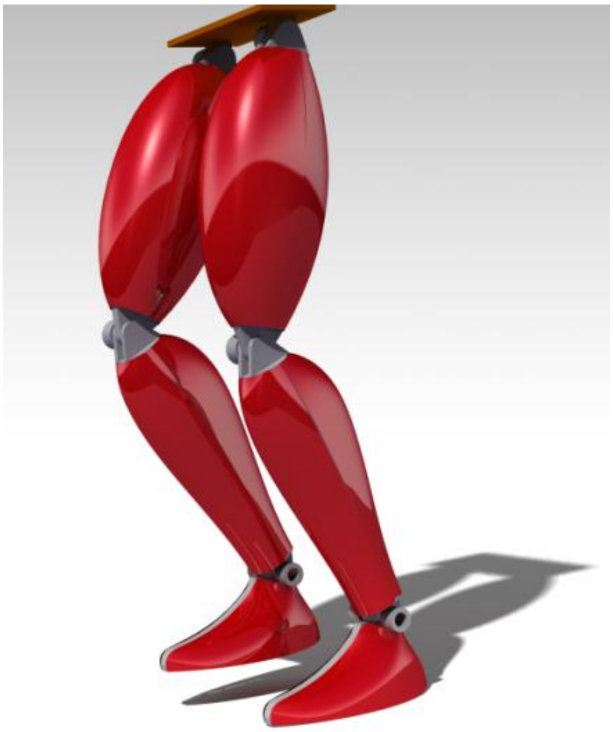

Figure 5: Concept Design of the Humanoid Biped Robot

The link lengths, height and other dimensions have been determined based on Forward Kinematics, end effector reach analysis and study of gait profiles. For the model, the thigh link length, L3 and the shin link length, L4 have been selected as 250 mm while the distance from ground to the ankle joint has been selected as 55 mm considering factors such as the total height of the biped and the step length of the foot. The overall shape of the links has been designed to represent a human leg and has been created using surfacing modeling

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techniques. Simulation of the model from the Pre Swing position to Terminal Swing can be seen in figure 6.

Figure 6: Pre Swing to Terminal Swing motion steps

As seen from the figure, the 5 positions reflect the positions of the foot on the gait profile at points representing percentages of 0, 24, 50, 74 and 100 on the gait profile respectively. Thus, the generated gait profile is sucessfully traced by the foot of the leg structure.

CONCLUSION

An effective yet simple foot gait pattern for robotic walking mechanism is cycloidal in nature. Analysis of human gait proved to be useful in optimization of the walking in the Biped and the generated pattern along with the phases can be seen in the model.

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