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Design and Control of the Lower Part of Humanoid Biped Robot

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Abstract—**This manuscript describes the design methodology of a lower limb bipedal robot which was controlled to achieve a stable walking gait. The proposed design has 12 DOF to mimic human gait in the most daily living activities. The design process started by creating dynamically equivalent lower limb segments based on the human anthropometric data. A linear inverted pendulum model of human walking was developed to produce the trajectory of the robot center of mass (COM), and then generate the feet trajectories, as well as applying inverse kinematics model. An iterative optimization algorithm was used to find the angular correction. The system was simulated on MATLAB/SIMULINK simulation environment and the results were satisfactory.**

Keywords-bio-inspired robotics; humanoid; gait; walking pattern; trajectories; linear inverted pendulum

I. INTRODUCTION

A humanoid robot is used to mimic human activities and replacing human beings in carrying out some tasks which are either dangerous or effort-consuming [1]. Humanoid robots – like humans- have a torso, two arms, a head and two legs [2]. The attempts for developing humanoid robots goes back to the middle ages when Al Jazari [3], an engineer from the old Islamic world, designed and assembled a number of automata including the first humanoid robot. Other attempts followed Leonardo Da-Vinci designed humanoid automaton [4]. In the modern history, the first full-scale anthropometric robot was Wabot-1 which was able to communicate with a person in Japanese and measure distances using receptors and artificial eyes [5], additionally it was able to walk, grip and transport objects. Over the last decades, Over the last few decades, Honda developed several biped robots with many capabilities such as Asimo which can walk, run, ascend stairs [6].

Various control strategies have been evolved to mimic human walking and generate walking patterns like zero moment point (ZMP) based control to assure robot stability [7], linear inverted pendulum model [8], and cart-table model which generates the ZMP trajectory based on the given center of mass (COM) trajectory [9]. Since the basic control algorithms are concerned with offline walking pattern generation, there were other corrective online methods developed using stabilizers to overcome environment obstacles [10].

In this manuscript the design methodology to develop a humanoid lower limb robot will be demonstrated, focusing on the control scheme, inverse kinematics, COM trajectory correction and feet trajectory generation. This paper is organized as follows Section II introduces the configuration and model construction of the bipedal humanoid robot. Section III presents the control scheme that is used. Simulation and discussion is shown in section IV and finally the concluding remarks are drawn in section V.

II. BIPEDAL HUMANOID ROBOT

A. Robot Configuration

The proposed robot consists of a torso, two legs and two feet with 12 degrees of freedom, 3 in each hip, 1 in each knee and 2 in each ankle joints as shown in Fig. 1. A dynamically equivalent body model was used to provide a legit approximation and a guideline for finding the optimal design of the robot. This dynamically equivalent is a simplified model of the proposed robot design with the same masses and inertia parameters.

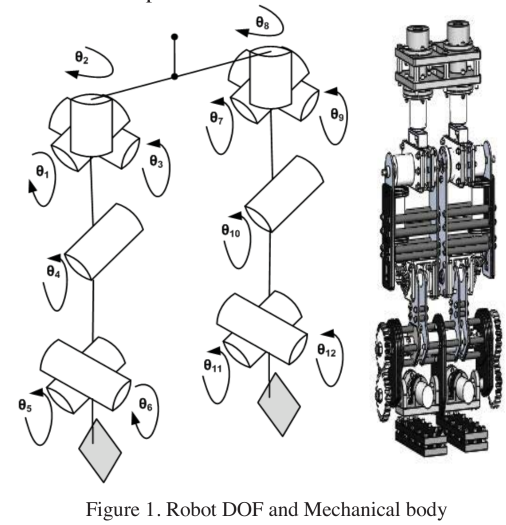


Figure 1. Robot DOF and Mechanical body

It was considered that the robot segments should be identical to anthropometric data as in [11]. The lower part has a share of almost half of the whole robot height, thigh and crus have the same length, the only exception to human anthropometric data are feet sizes, whose dimensions depend on the control scheme results and are therefore excluded.

III. CONTROL SCHEME

In this section the controller scheme is presented, starting by implementing the COM trajectory generation algorithm, followed by feet trajectory generation based on foot placement. Finally, inverse kinematics is applied and angular displacements are optimized using an iterative approach.

A. Walking Pattern Generation Algorithm

The linear inverted pendulum (LIP) model simplifies the body COM as a single point of mass lying at the end of an unstable inverted pendulum. An algorithm was developed on MATLAB based on Shuuji Kajita [12] work to generate walking pattern using the LIP model. The flowchart of this algorithm is shown in Fig. 2.

B. Feet Trajectory Generation

In foot placement trajectory algorithm, feet trajectory is calculated to determine the location of each foot vs. time. A cubic spline function is used to offers smooth foot transition and impact avoidance. Cubic spline coefficients matrix is shown in eq. (6).

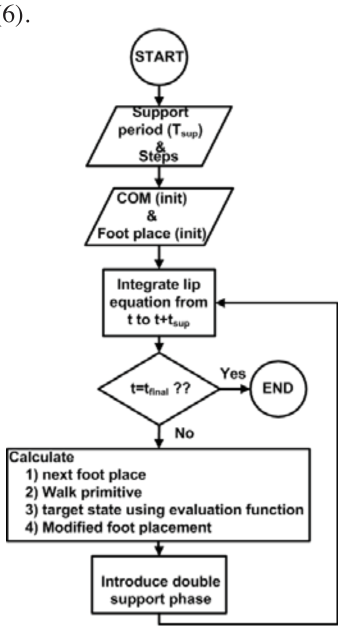


Figure 2. MATLAB algorithm flow chart

The foot vertical displacement is assumed to be a fraction of the robot COM height as follows

$$Z_{max} = Z_c \times C \tag{1}$$

where Z_{max} is the maximum foot displacement, Z_c is the robot COM height and C is a constant which is less than unity. The initial coordinates of the stance foot is as follows:

$$X_{init} = \begin{bmatrix} x_{init} \\ y_{init} \\ z_{init} \end{bmatrix} \tag{2}$$

$$X_{init} = F_P(i-1) \tag{3}$$

where X_{init} is the initial coordinate's vector of right foot, F_P is the foot placement, i is the foot placement number, since i represents the number of the current foot placement which is the stance foot. The next foot placement is defined as the final destination X_{final} as shown in eq. (4)

$$X_{final} = F_P(i+1) \tag{4}$$

Initial velocity $\dot{\boldsymbol{X}}_{init}$ and final one $\dot{\boldsymbol{X}}_{final}$ are set to zero

Let

$$T = \begin{bmatrix} 1 & t_o & {t_o}^2 & {t_o}^3 \\ 1 & t_f & {t_f}^2 & {t_f}^3 \\ 0 & 1 & 2t_o & 3{t_o}^2 \\ 0 & 1 & 2t_f & 3{t_f}^2 \end{bmatrix} \tag{5}$$

where initial time is set to zero and final time is equal to the single support phase period. The coefficients of the cubic spline are calculated using the pseudo-inverse function in Matlab as in eq. (6)

$$A = T^{-1} \begin{bmatrix} {X_{init}}^T \\ {X_{final}}^T \\ {\dot{X}_{init}}^T \\ {\dot{X}_{final}}^T \end{bmatrix} \tag{6}$$

C. Inverse Kinematics

Inverse kinematics equations are derived and approximations are made for easier computations [12] [13].

- The COM is assumed to be at a constant distance from the pelvis center of mass, and this distance is to be updated continuously through several iterations to obtain optimum results
- The ZMP is assumed to be at a specific point in the foot sole, in this case right in the center

Geometric solution is used to solve the inverse kinematics for joint angles shown in Fig.1. The base frame is at the center of feet soles.

$$T_r = \begin{bmatrix} 1 & 0 & 0 & -X_{cr} \\ 0 & 1 & 0 & -Y_{cr} \\ 0 & 0 & 1 & -Z_{cr} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

where T_r is the transformation matrix, X_{cr}, Y_{cr} and Z_{cr} are the x, y and z coordinates of right foot relative to global frame

$$\begin{bmatrix} x_p \\ y_p \\ z_p \\ 1 \end{bmatrix} = T_r * \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} \tag{8}$$

x_p, y_p and z_p are the x, y and z coordinates of pelvis com relative to base frame, p_x, p_y and p_z are the x, y and z coordinates of pelvis com relative to global frame. Using trigonometric method, the inverse kinematics equations for the right leg are deduced as in eqs. (9) to (12)

$$\theta_3 = \theta_6 = \tan^{-1}\left(\frac{y - {pel_l}/_2}{z - F_h - {pel_h}/_2}\right) \tag{9}$$

pel_l is the pelvis length, F_h is the foot height, pel_h is the pelvis height

$$\theta_5 = \sin^{-1}\left(\frac{u_{leg}\sin(\theta_2)}{\sqrt{x^2 + (\frac{z - F_h - \frac{pel_h}{2}}{\cos\theta_6})^2}}\right) + \tan^{-1}\left(\frac{\frac{z - F_h - \frac{pel_h}{2}}{\cos\theta_6}}{x}\right) \tag{10}$$

where u_{leg} is thigh length, l_{leg} is crus length,

$$\theta_4 = \cos^{-1}\left(\frac{x^2+\left(\frac{z-F_h-\frac{pel_h}{2}}{\cos(\theta_6)}\right)^2-u_{leg}^2-l_{leg}^2}{2*u_{leg}*l_{leg}}\right) \tag{11}$$

$$\theta_1 = 270^{\circ} - \theta_5 - \theta_4 \tag{12}$$

Same for the left leg as shown in eqs (13) to (17)

$$T_{r2} = \begin{bmatrix} 1 & 0 & 0 & -X_{cl} \\ 0 & 1 & 0 & -Y_{cl} \\ 0 & 0 & 1 & -Z_{cl} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

here T_{r2} is the transformation matrix, X_{cl}, Y_{cl} and Z_{cl} are the x, y and z coordinates of left foot relative to global frame.

$$\theta_9 = \theta_{12} = \tan^{-1}\left(\frac{-y-{pel_l}/_2}{z-F_h-{pel_h}/_2}\right) \tag{14}$$

$$\theta_{10} = \cos^{-1}\left(\frac{x^2+\left(\frac{z-F_h-\frac{pel_h}{2}}{\cos(\theta_9)}\right)^2-u_{leg}^2-l_{leg}^2}{2*u_{leg}*l_{leg}}\right) \tag{15}$$

$$\theta_{11} = \sin^{-1}\left(\frac{u_{leg}\sin(\theta_8)}{\sqrt{x^2+(\frac{z-F_h-\frac{pel_h}{2}}{\cos\theta_9})^2}}\right) + \tan^{-1}\left(\frac{\frac{z-F_h-\frac{pel_h}{2}}{\cos\theta_9}}{x}\right) \tag{16}$$

$$\theta_7 = 270 - \theta_{10} - \theta_{11} \tag{17}$$

where, θ_2 and θ_8 are determined if the robot is to turn, otherwise they are set to zero

D. Angular Correction

The angular profile trajectories' correction is used to generate the exact desired COM trajectory. The flow chart of the algorithm is shown in Fig. 3. The COM location is checked using the following eqs (18) to (24)

$$\begin{bmatrix} x_{ur} \\ y_{ur} \\ z_{ur} \end{bmatrix} = \begin{bmatrix} (\frac{u_{leg}}{2}) \times \cos(\theta_3) \times \cos(\theta_1 - \frac{\pi}{2}) \\ -\left(\frac{pel_l}{2}\right) - (\frac{u_{leg}}{2}) \times \sin(\theta_1 - \frac{\pi}{2}) \times \sin(\theta_3) \\ -\left(\frac{u_{leg}}{2}\right) \times \cos(\theta_3) \times \sin\left(\theta_1 - \frac{\pi}{2}\right) - \frac{pel_h}{2} \end{bmatrix} \tag{18}$$

where x_{ur}, y_{ur} and z_{ur} are the right thigh com x, y and z coordinates

$$\begin{bmatrix} x_{lr} \\ y_{lr} \\ z_{lr} \end{bmatrix} = \begin{bmatrix} (u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_4)) \times \cos(\theta_3) \times \cos(\theta_1 - \frac{\pi}{2}) \\ -\left(\frac{pel_l}{2}\right) - (u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_4)) \times \sin(\theta_4 - \frac{\pi}{2}) \times \sin(\theta_3) \\ -\left(u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_4)\right) \times \cos(\theta_3) \times \sin\left(\theta_1 - \frac{\pi}{2}\right) - \frac{pel_h}{2} \end{bmatrix} \tag{19}$$

where x_{lr}, y_{lr} and z_{lr} are the right crus com x, y and z coordinates

$$\begin{bmatrix} x_{fr} \\ y_{fr} \\ z_{fr} \end{bmatrix} = \begin{bmatrix} (u_{leg} + l_{leg} \times \cos(\theta_4)) \times \cos(\theta_3) \times \cos(\theta_1 - \frac{\pi}{2}) \\ -\frac{pel_l}{2} - (u_{leg} + l_{leg} \times \cos(\theta_4)) \times \sin(\theta_1 - \frac{\pi}{2}) \times \sin(\theta_3) \\ -\left(u_{leg} + l_{leg} \times \cos(\theta_4)\right) \times \cos(\theta_3) \times \sin\left(\theta_1 - \frac{\pi}{2}\right) - \frac{pel_h}{2} - \frac{F_h}{2} \end{bmatrix} \tag{20}$$

where x_{fr}, y_{fr} and z_{fr} are the right foot com x, y and z coordinates

$$\begin{bmatrix} x_{ul} \\ y_{ul} \\ z_{ul} \end{bmatrix} = \begin{bmatrix} (\frac{u_{leg}}{2}) \times \cos(\theta_9) \times \cos(\theta_7 - \frac{\pi}{2}) \\ \frac{pel_l}{2} + (\frac{u_{leg}}{2}) \times \sin(\theta_7 - \frac{\pi}{2}) \times \sin(\theta_9) \\ -\left(\frac{u_{leg}}{2}\right) \times \cos(\theta_9) \times \sin\left(\theta_7 - \frac{\pi}{2}\right) - \frac{pel_h}{2} \end{bmatrix} \tag{21}$$

where x_{ul}, y_{ul} and z_{ul} are the left thigh com x, y and z coordinates

$$\begin{bmatrix} x_{ll} \\ y_{ll} \\ z_{ll} \end{bmatrix} = \begin{bmatrix} (u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_{10})) \times \cos(\theta_9) \times \cos(\theta_7 - \frac{\pi}{2}) \\ \frac{pel_l}{2} + (u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_{10})) \times \sin(\theta_7 - \frac{\pi}{2}) \times \sin(\theta_9) \\ -\left(u_{leg} + \frac{l_{leg}}{2} \times \cos(\theta_{10})\right) \times \cos(\theta_9) \times \sin\left(\theta_7 - \frac{\pi}{2}\right) - \frac{pel_h}{2} \end{bmatrix} \tag{22}$$

where x_{ll}, y_{ll} and z_{ll} are the left crus com x, y and z coordinates

$$\begin{bmatrix} x_{fl} \\ y_{fl} \\ z_{fl} \end{bmatrix} = \begin{bmatrix} (u_{leg} + l_{leg} \times \cos(\theta_{10})) \times \cos(\theta_9) \times \cos(\theta_7 - \frac{\pi}{2}) \\ \frac{pel_l}{2} + (u_{leg} + l_{leg} \times \cos(\theta_{10})) \times \sin(\theta_7 - \frac{\pi}{2}) \times \sin(\theta_9) \\ -\left(u_{leg} + l_{leg} \times \cos(\theta_{10})\right) \times \cos(\theta_9) \times \sin\left(\theta_7 - \frac{\pi}{2}\right) - \frac{pel_h}{2} - \frac{F_h}{2} \end{bmatrix} \tag{23}$$

where x_{fl}, y_{fl} and z_{fl} are the left foot com x, y and z coordinates

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} (U_{leg_{mass}} \times (x_{ur} + x_{ul}) + L_{leg_{mass}} \times (x_{lr} + x_{ll}) + Foot_{mass} \times (x_{fr} + x_{fl}))/M \\ (U_{leg_{mass}} \times (y_{ur} + y_{ul}) + L_{leg_{mass}} \times (y_{lr} + y_{ll}) + Foot_{mass} \times (y_{fr} + y_{fl}))/M \\ (U_{leg_{mass}} \times (z_{ur} + z_{ul}) + L_{leg_{mass}} \times (z_{lr} + z_{ll}) + Foot_{mass} \times (z_{fr} + z_{fl}))/M \end{bmatrix} \tag{24}$$

where M is the total robot mass, $U_{leg_{mass}}$ is thigh mass, $L_{leg_{mass}}$ is crus mass, $Foot_{mass}$ is foot mass, X, Y and Z are the Instantaneous COM x, y and z coordinates of robot relative to local reference frame. The instantaneous Robot COM is to be defined relative to the global frame as the following.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{25}$$

Once the actual COM is calculated, the inverse kinematics module is used iteratively to correct the angles, till the COM location error is below the threshold.

IV. Results and Discussion

The Simulation was carried out using MATLAB/SIMULINK where Z_c is 0.278 m, T_{sup} is 0.5 seconds. Furthermore, the ranges of joint angles were kept within human naturally walking boundaries [13]. The knee joint angle is restricted to be always greater than zero and less than 150 degrees as shown in Fig 5 (d) and (j). The abduction and adduction joint angle is assumed to fall between -50 and 60 degrees as shown in Fig 5 (c) and (i). Moreover, the extension and flexion joint angle value is assumed to fall between 60 and 150 degrees as shown in Fig

5 (a) and (g). Finally, the ankle joint angle is restricted to be between 0 degrees and 120 degrees as shown in Fig 5 (e) and (k). In the following results the robot do not turn so hip joint angles associated with θ_2 and θ_8 were set to zero as shown in Fig 6 (b) and (h). Figure 4 shows the desired and actual trajectory of the fixed certain step input. The actual and desired trajectories are almost coincident on each other with a Root mean square error (RMSE) of about 0.5 mm and a mean absolute error (MAE) of about 0.3 mm.

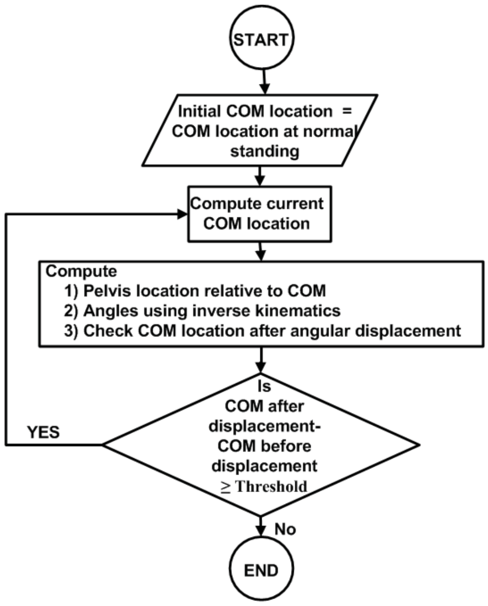


Figure 3. Angular correction algorithm flow chart

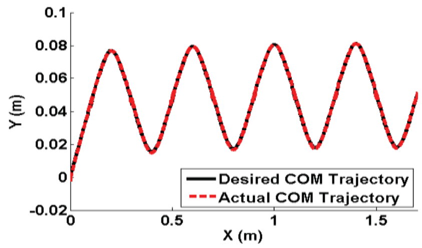
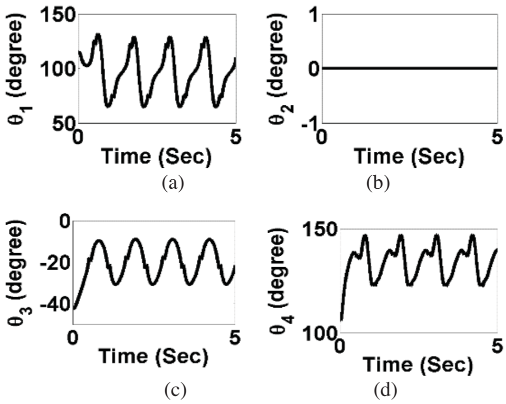


Figure 4. Desired vs Actual Com trajectory



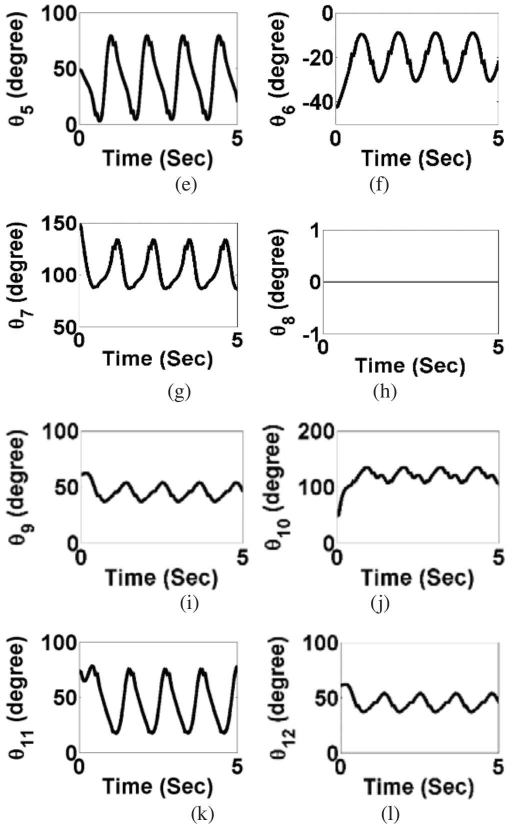


Figure 5. (a) Theta 1(right hip extension and flexion), (b) theta 2(right rotation), (c) theta 3(right abduction and adduction), (d) theta 4(right knee extensions and flexion), (e) theta 5(right ankle plantarflexion and dorsiflexion), (f) theta 6(right eversion and inversion), (g) theta 7(left hip extension and flexion), (h) theta 8(left rotation), (i) theta 9(left abduction and adduction), (j) theta 10(left knee extensions and flexion), (k) theta 11(left ankle plantarflexion and dorsiflexion), (l) theta 12(left eversion and inversion)

Figs. 6 and 7 are obtained when the certain fixed steps applied to the robot. In this case the RMSE error is 0.5 mm and MAE is 0.38 mm

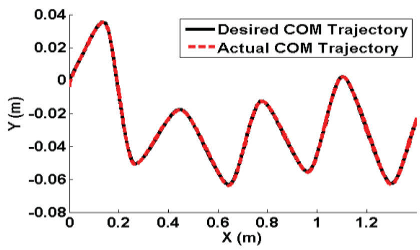
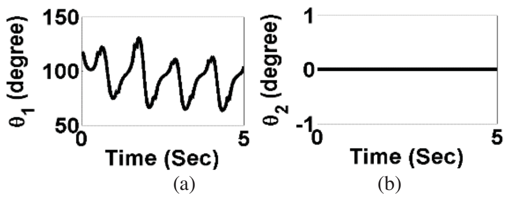


Figure 6. Desired vs Actual Com trajectory



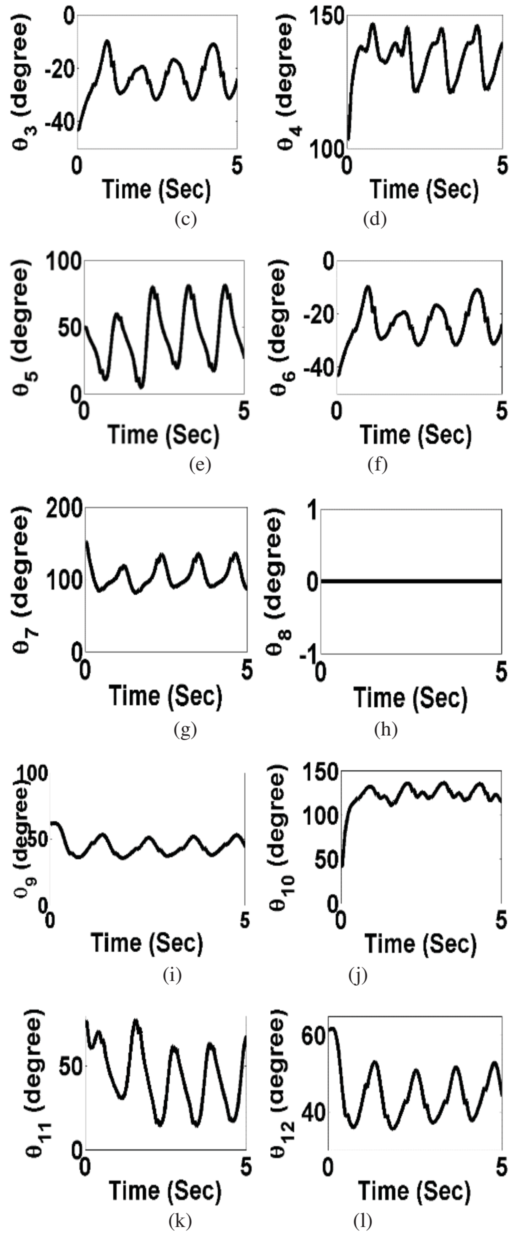


Figure 7. (a) Theta 1(right hip extension and flexion), (b) theta 2(right rotation), (c) theta 3(right abduction and adduction), (d) theta 4(right knee extensions and flexion), (e) theta 5(right ankle plantar flexion and dorsiflexion), (f) theta 6(right eversion and inversion), (g) theta 7(left hip extension and flexion), (h) theta 8(left rotation), (i) theta 9(left abduction and adduction), (j) theta 10(left knee extensions and flexion), (k) theta 11(left ankle plantar flexion and dorsiflexion), (l) theta 12(left eversion and inversion)

V. CONCLUSION

In this paper, the design methodology is proposed in terms of the control model, and how trajectories are generated, passing through trajectory correction and actual simulation of a dynamically equivalent humanoid robot gait, The trajectories generated were successfully optimized to be highly accurate and close to the ideal LIP model, as the simulation results showed that the maximum RMSE and MAE do not exceed 0.5mm and 0.38mm respectively, this methodology can be considered as a general methodology for appropriate design of any type of humanoid biped robots, and can lay the foundation for mechanical and hardware design based on the data extracted from the control scheme and dynamically equivalent body parameter manipulation.

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