We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Asymmetrical Bipedal Modeling for Biomechanical Sit-to-Stand Movement

Asif Mahmood Mughal and Kamran Iqbal
University of Arkansas at Little Rock
 USA

1. Introduction

Human bipedal model are symmetrical as well as asymmetrical depending upon nature of movement, task and orientation of the body. A bipedal model with a full symmetry of limbs is redundant due to the physiological equilibrium. Asymmetrical models are applicable to both healthy subjects and stroke patients for sit-to-stand (STS) maneuver. Healthy subjects usually donot behave with an exact symmetry on both extremities for STS due to seating position, sitting posture, seat and age related variables. On the other hand stroke patients with paraplegic limbs exhibit complete asymmetrical behavior in the right and left limbs, with one side of limbs moving significantly slower than the other side. Several researchers provided many computational solutions to model human bipedal design. Anderson and Pandy (2001) studied the bipedal modeling and neuro-musculoskeletal system with 3D modeling and combined it with optimization theory to simulate the dynamics of motor task. They also further elaborated this model with 23 degrees of freedom for mechanical linkages actuated by 54 muscles. In this study, they simulated results for repeated gait cycles and computed the minimal metabolic energy per unit traveled by using SD/Fast. Few other researchers also developed bipedal models such as Jalics et al. (1996) presented a 2D bipedal model with 5 links as 7 segments for locomotion control, and, Spong et al. (2006) presented a model for almost linear bipedal robot. In order to avoid redundancies, a 3-link model was more successful with no constraints or nonzero open loop eigenvalues as discussed by Iqbal and Pai (2000). This model does not provide analysis of right and left extremities especially for stroke patients and was developed for the sagittal plane movement simulation, postural stability and balance recovery after perturbation. The particular biomechanical model consists of a foot segment or the base of support (BoS), lower leg, upper leg, and a head arm and trunk (HAT). The assembly of three links represents a triple inverted pendulum model, which is intrinsically unstable and consistently needs control effort in the shape of joint torques to maintain a stable posture. Roberts and McCollum (1996) presented a Hamiltonian based mathematical model of human body similar to Hemami and Jaswa's (1978) inverted pendulum model. The 4 link rigid body model was further developed by Barin (1989) with a head link and this rigid body model is now being taught in biomechanics courses. Several text books have provided the detail explanation of this model with free body diagram, Lagrangian approach and estimation of these different variables among several age groups.

Recently 2 segment and 4 segment models were also used for postural stability with PID controllers by Iqbal and Roy (2004). Main contributions towards biomechanical studies are computational modeling schemes for simulation purposes and experimental validations. Analytical models are complex in nature and computationally expensive. But, these models can be used for variety of analysis, controller design and experimental studies where computational models lack in general.

In this chapter, we will discuss a conceptual bipedal model with symmetrical angles in sagittal and frontal planes. Asymmetry exists in the model due to asymmetrical connection of feet to the ground, and asymmetrical references to the ground for translational and rotational variables. With only one foot connecting to the ground, and other free foot makes a unconstrained model which is simple to use but less realistic. We present two modeling schemes in this chapter namely unconstrained model, and constrained model. This bipedal model consists of two feet, two lower limbs (shanks), two upper limbs (thighs), a pelvic junction, and a head-arm-torso (HAT) segment in both 2D and 3D spaces. The constrained models have both feet connected to the ground; which produces holonomic constraints to maintain a physical balance between two legs in x , y and z axes. For each model, Maple environment generates nonlinear ODEs in the state space formulation, which can be transferred to Matlab for simulation purposes. We prove the stability of these models with Lyapunov's indirect method, and also provide simulation results for regulated STS maneuver. We simulate these models for human STS transfer with synthesized reference trajectories, and optimal feedback controller design. Our results of angular profiles, feedback torques and some physiological variables indicate the usefulness of these modeling schemes for the study of biomechanical movements.

2. Conceptual Bipedal Model

The general structure of a bipedal model includes 2 foot segments, 2 lower legs (shanks), 2 upper legs (thighs) connected with pelvis through a 2-DoF joint. Pelvic segment is connected with a segment consist of head, arm, and trunk (HAT). Both feet are on x -axis, and each segment length is along y -axis. In sitting position thighs are along z -axis, and along y -axis at standing position as shown in Fig 1. There are 7 joints in the systems connecting in yz or sagittal plane with x as axis of rotation representing joint angles θ_1 - θ_6 and θ_9 . Hip-pelvic and pelvic-HAT joints can also move the limbs in xy or frontal plane with z - axis of rotation, and these angles will be modeled with Euler angle representations shown as ϕ_7 , ϕ_8 and ϕ_{10} in Fig 1. These joints are represented as either revolute or universal joints in Maple's DynaFlexPro environment; Mughal and Iqbal (2007) discussed these joint types in details. A revolute joint connects two bodies with a fixed reference frame and allows a single relative rotation of the two frames; all other relative rotations and translations are prevented by this joint type. With this joint type an input torque can be specified as a variable, which will appear in dynamic equations. A universal joint allows two relative rotations, about orthogonal axes, of the two connected frames; all other relative motions of two frames are prevented by this joint type. It provides two rotational variables in dynamic equations for two orthogonal axes but a drawback is that input torques cannot be specified directly for these rotational variables.

Fig. 1. Bipedal rigid body model, with sagittal plane angles θ_1 - θ_6 and θ_9 , frontal plane angles φ_7 - φ_8 , φ_{10} . The sagittal plane angles are shown in standing posture along x-axis and frontal plane angles are shown in sitting posture along z-axis. A small arrow in angle points towards its placement.

3. Unconstrained Bipedal Model

In this scheme, we joined right foot as a weld joint to the ground and left foot is a free foot without any joint. An 8-segmented biomechanical bipedal model in DynaFlexPro-ModelBuilder (GUI) environment is shown in Fig 2. J1 and J2 are the revolute joints from feet to lower limbs (Shank), J3 and J4 are the revolute joints from lower limbs to upper limbs (Thigh) representing sagittal plane angles θ_1 to θ_4 in Fig 1. These joints allow motion in yz plane or through axis of rotation along x-axis and are represented as x_1 - x_4 variables in the system of equations with T1-T4 torque drivers (not shown in the figure). J5 is an universal

joint with two angular movements in yz plane with rotation along x-axis with sagittal plane angle θ_5 (x_5) and in xy plane with rotation along z-axis as frontal plane angle ϕ_7 (x_7). There is no built-in torque driver in the universal joint, so there is an “Applied Moment” driver T57 at this joint to supply torques with two components T5 and T7 in x-and z directions respectively. There is a universal joint J6 on the left upper limb and pelvis segment which represents sagittal plane angle θ_6 (x_6), frontal plane angle ϕ_8 (x_8) and a torque driver (applied moments) T68 with two components T6 and T8 for their respective angles. Similarly, pelvis-HAT joint J7 is also a universal joint with applied moment driver T910 supplying torques to sagittal plane θ_9 (x_9) and frontal plane ϕ_{10} (x_{10}) joint angles. This scheme has only one path for rotational variables to the ground i.e. R-tree and same path for translational variables to the ground i.e. T-tree.

Fig. 2. Free foot rigid body model in Maple's GUI with T-Tree and R-Tree through joints

This model also does not move from its position for a normal gait due to the restriction of a weld joint. The system has 10 degrees of freedom and it is modeled using 10 generalized coordinates coupled by 0 algebraic constraints.

3.1 Mathematical Modeling for Free Foot Model

Let $\vec{x}(t)$ be the vector of joint angles and $\vec{\tau}(t)$ be the vector of joint torques.

$$\begin{aligned}\vec{x}(t) = \vec{x} &= [x_1 \quad x_2 \quad \cdots \quad x_{10}]^T \\ \vec{\tau}(t) = \vec{\tau} &= [\tau_1 \quad \tau_2 \quad \cdots \quad \tau_{10}]^T\end{aligned}\quad (1)$$

This modeling scheme generates equations of the following form

$$M(\vec{x}, \dot{\vec{x}}) \cdot \ddot{\vec{x}} = F(\vec{x}, \dot{\vec{x}}, \vec{\tau}) \quad (2)$$

Where $M = M(\vec{x}, \dot{\vec{x}})$ is a 10×10 inertia matrix, $F = F(\vec{x}, \dot{\vec{x}}, \vec{\tau})$ is a 10×1 vector which contains external load, quadratic velocity terms and torques. The system of equations can also be represented as

$$\ddot{\vec{x}} = M^{-1} \cdot F = f(\vec{x}, \dot{\vec{x}}, \vec{\tau}) = f \quad (3)$$

Eq (3) represents the system in 10×1 nonlinear state-space formulations with 10 nonlinear functions. This system can be linearized for controller design and analysis as

$$\begin{aligned}\begin{bmatrix} \ddot{\vec{x}} \\ \dot{\vec{x}} \\ \vec{x} \end{bmatrix} &= [A] \cdot \begin{bmatrix} \dot{\vec{x}} \\ \vec{x} \end{bmatrix} + [B] \cdot \vec{\tau} \\ A &= \begin{bmatrix} A_1 & A_2 \\ 0 & I \end{bmatrix}, B = \begin{bmatrix} B \\ 0 \end{bmatrix}\end{aligned}\quad (4)$$

where A_1 , A_2 and B_1 matrices are all 10×10 matrices given as

$$[A_1]_{ij} = \left. \frac{\partial f_i}{\partial \dot{x}_j} \right|_{\vec{x}=\vec{x}_e, \vec{\tau}=\vec{u}_e} \quad [A_2]_{ij} = \left. \frac{\partial f_i}{\partial x_j} \right|_{\vec{x}=\vec{x}_e, \vec{\tau}=\vec{u}_e} \quad [B]_{ij} = \left. \frac{\partial f_i}{\partial \tau_j} \right|_{\vec{x}=\vec{x}_e, \vec{\tau}=\vec{u}_e} \quad i, j=1..10 \quad (5)$$

Linearization points i.e. standing posture joint angles x_e and joint torques u_e give the equilibrium position where $\ddot{x} = 0$ in Eq (5). It is important to note that here we are using $\vec{x} = \Delta \vec{x}$, where $\Delta x_i = x_i - x_{ei}$ and $\vec{\tau} = \Delta \vec{\tau}$ where $\Delta \tau_i = \tau_i - u_{ei}$ for linearization at equilibrium point. In this model, all joint angles are local or relative between two respective bodies, gravity is in negative y-axis and height in positive y-axis, so all joint angles are zero at standing posture due to collinear body frames. However, we solve for u_e at these angles to obtain $\ddot{x} = 0$. This model produces pairs of eigenvalues in right and left half planes and thus is an unstable model, which requires a controller design to stabilize this system.

$$\vec{\tau}(t) = -K \cdot \begin{bmatrix} \dot{\vec{x}} \\ \vec{x} \end{bmatrix} + \vec{u}_e \quad (6)$$

This torque input can be used with nonlinear model for stable postural movement; however, this torque to the nonlinear model requires additional feedforward torque component $u_e = [0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 93.478 \ 0 \ 0 \ 0]^T$ to stabilize the system at $\ddot{x} = 0$.

3.2 Simulation and Results

We simulate the unconstrained model with linear quadratic regulator (LQR) based controller design. We use the physical values from de Leva (1996) for this simulation. Fig 3 shows the angular profiles of free foot model with desired reference trajectories synthesized by Mughal and Iqbal (2008a) for STS movement. Angular profiles of knee and hip-pelvis sagittal angles follow the reference trajectories very closely and symmetrically, and these are only profiles starting from non-zero initial conditions. Ankle and pelvic-HAT sagittal angle also follow reference trajectories and settle within 2 secs. However, frontal angles took

longer time to settle and hip-pelvic frontal angles show difference from reference trajectories.

Fig. 3. Movement profiles of joint angles in radians (solid blue lines) and their reference trajectories (dashed red lines) R=Right, L=Left, A=Ankle angle, K=Knee angle, P= Pelvic-Hip joint angle, H=HAT-Pelvic joint angle, S=Sagittal plane, F= Frontal plane

Fig. 4. Movement of a left foot positions in x, y and z direction (m) for a free foot model

Figure 4. shows the movement of a left foot with in a free foot model with LQR design to control joint angles only. The movement of left foot is very small but still it is moving significantly which is not very realistic for ordinary STS movement.

4. Constrained Bipedal Model

The model discussed in Sec 3 is without any geometric restrictions on physical body or in other words without any algebraic constraints. Although free foot is more related to stroke patients than a healthy subject, yet its movement can also violates some physiological constraints in healthy subjects. This model doesn't provide any control over the position of left (free) foot which is not a very applicable controlled bipedal model. Connecting each foot to the ground as a weld joint will generate irresolvable holonomic constraints in bipedal case due to lesser DOF in the system, so we now model with a 6-DoF joint for a left foot.

Fig. 5. Bipedal model with a weld joint in right foot and a 6-DOF joint in left foot with different R & T tree for state variables.

Model shown in Fig 5 is similar in joint angle and torque definition but differ in T-tree and R-tree and 6-DOF joint for left foot. We join one foot with ground as weld joint and other as a 6-DOF joint, which introduces more variables of translation in the model. Adopting the different T-tree (reference of translational variables to the grounds) and R-tree (reference of rotational variables to the ground) for the model will result in three translational variables of left foot position to appear in the state equations. Fig 5a shows the bipedal model with R tree and Fig 5b shows the T-tree of the same model. This configuration and the additional three variables will results in three holonomic (algebraic) constraints in the system. This

scheme is better than free foot scheme because of holonomic constraints which are the part of a physiological human model. This model does not move from its position for a gait cycle due to the restriction of a weld joint. The system has 10 degrees of freedom and it is modeled using 13 generalized coordinates coupled by 3 algebraic constraints.

4.1 Mathematical Representation

Let $\vec{z}(t) = [\vec{p}(t) \quad \vec{x}(t)]$ be the vector of left foot position variable $\vec{p}(t)$ and joint angles $\vec{x}(t)$, and $\vec{\tau}(t)$ be the vector of joint torques, where

$$\begin{aligned}\vec{p}(t) &= \vec{p} = [p_1 \quad p_2 \quad p_3]^T \\ \vec{x}(t) &= \vec{x} = [x_1 \quad x_2 \quad \cdots \quad x_{10}]^T \\ \vec{\tau}(t) &= \vec{\tau} = [\tau_1 \quad \tau_2 \quad \cdots \quad \tau_{10}]^T\end{aligned}\quad (7)$$

This modeling scheme also generate equations of the following form

$$M(\vec{z}, \dot{\vec{z}}) \cdot \ddot{\vec{z}} = F(\vec{z}, \dot{\vec{z}}, \vec{\tau}) \quad (8)$$

Where $M = M(\vec{z}, \dot{\vec{z}})$ is a 13×13 inertia matrix, $F = F(\vec{z}, \dot{\vec{z}}, \vec{\tau})$ is a 13×1 vector which contains external load, quadratic velocity terms and torques. The system of equations can also be represented as

$$\ddot{\vec{z}} = M^{-1} \cdot F = f(\vec{z}, \dot{\vec{z}}, \vec{\tau}) = f \quad (9)$$

Eq (9) represents the system in 13×1 nonlinear state-space formulations with 13 nonlinear functions. This system can be linearized for controller design and other analysis as

$$\begin{bmatrix} \ddot{\vec{z}} \\ \dot{\vec{z}} \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ 0 & I \end{bmatrix} \cdot \begin{bmatrix} \dot{\vec{z}} \\ \vec{z} \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} \cdot \vec{\tau} \quad (10)$$

Where A_1 , A_2 are 13×13 matrices and B_1 is a 13×10 matrix as

$$[A_1]_{ij} = \left. \frac{\partial f_i}{\partial \dot{z}_j} \right|_{z=z_e, \tau=u_e} \quad [A_2]_{ij} = \left. \frac{\partial f_i}{\partial z_j} \right|_{z=z_e, \tau=u_e} \quad [B]_{ij} = \left. \frac{\partial f_i}{\partial \tau_j} \right|_{z=z_e, \tau=u_e} \quad i, j=1..10 \quad (11)$$

We linearize the model at standing posture i.e. joint angles z_e and joint torques u_e are the equilibrium position where $\ddot{\vec{z}} = 0$ from Eq (10). In this model, all joint angles are local or relative between two respective bodies, gravity is in negative y-axis and height in positive y-axis, so all joint angles are zero at standing posture due to collinear body frames. However, we solve for u_e at these angles to obtain $\ddot{\vec{z}} = 0$. This model produces pair of eigenvalues in right and left plane and thus an unstable model, which requires a controller design to stabilize this system.

4.2 Holonomic Constraints

Holonomic constraints are represented as closed forms of nonlinear algebraic functions and in bipedal model; these constraints represent the closed form of distance between the two ankle joints in x, y, z- directions. In this model, there are three holonomic constraints for position variables and three for velocity variables, which are also Scleronomous constraints

i.e. doesn't depend on time explicitly. The position constraints for this bipedal system are represented as

$$\begin{aligned} -p_1 + C_1(\vec{x}) &= 0 \\ -p_2 + C_2(\vec{x}) &= 0 \\ -p_3 + C_3(\vec{x}) &= 0 \end{aligned} \quad (12)$$

Vector form representation of position and velocity constraints are given as

$$\begin{aligned} -\vec{p} + \vec{C}_p(\vec{x}) &= 0 \\ -\dot{\vec{p}} + \vec{C}_v(\vec{x}) &= 0 \end{aligned} \quad (13)$$

First and third constraints represent that the distance between feet should be equal to pelvic length in x and z directions respectively, because of one weld joint, and no frontal movement in ankle and knee joints. Second constraints maintain that the length of both legs should be equal in y-direction for any movement. Velocity constraints are the time derivatives of position constraints. These constraints are useful because these require to be satisfied during any movement profile to maintain the physiological distance between right and left feet. On the other hand it also adds zero eigenvalues in open loop system equal to number of position and velocity constraints. Also, this system requires a special controller which doesn't violate the constraint surface(equations) during the movement.

4.3 Decoupling of Linearized System

A linear system given in Eq(10) represents a 26th order system with 3 left foot position and velocity variables, 10 joints angles and velocities and 10 input torques to the joints. The order of state variables are given in Eq (7) and it has 20 pairs of nonzero eigenvalues in left and right half planes and six zero eigenvalues due to six holonomic (position and velocity) constraints in the system. It is challenging to find a controller design which doesn't violate the constraints during movement simulation. Iqbal et al. (1994) discussed the decoupling of constraints for bipedal model with only frontal plane angles, De Sapia and Khatib (2005) presented a decoupled controller design for holonomic constrained systems and furthermore, Hemami and Wyman (2007) discussed in details about decoupled design schemes for rigid bodies. We decouple the constrained system from unconstrained system to find the better control strategy for required task. Eq (13) shows us that in constraints equations left foot position and velocity variables occurs explicitly, while joint angle variables are used as nonlinear functions. So, we change the order of state variables for decoupling as

$$\begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \vec{x} \\ \dot{\vec{x}} \end{bmatrix} = [R_{26}] \cdot \begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \vec{x} \\ \dot{\vec{x}} \end{bmatrix} \quad (14)$$

Where R_{26} is a rotation matrix and linearized system will take a form as follows

$$\begin{bmatrix} \ddot{\vec{p}} \\ \ddot{\vec{p}} \\ \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = \begin{bmatrix} A_p & A_{px} \\ A_{xp} & A \end{bmatrix} \cdot \begin{bmatrix} \dot{\vec{p}} \\ \dot{\vec{p}} \\ \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} + \begin{bmatrix} B_p \\ B \end{bmatrix} \cdot \vec{\tau} \quad (15)$$

Now, we decouple the constrained (translational) system from unconstrained (rotational) system, which is to separate the $\vec{p}$, $\dot{\vec{p}}$ from $\vec{x}$, $\dot{\vec{x}}$ variables. As $A_{xp} = 0$, and 20×6 matrix so we can decouple the systems as

$$\begin{bmatrix} \ddot{\vec{p}} \\ \ddot{\vec{p}} \end{bmatrix} = A_p \cdot \begin{bmatrix} \dot{\vec{p}} \\ \dot{\vec{p}} \end{bmatrix} + B_p \cdot \vec{\tau} \quad (16)$$

$$A_p = \begin{bmatrix} 0 & 0 \\ I_3 & 0 \end{bmatrix} \quad B_p = \begin{bmatrix} B_2 \\ 0 \end{bmatrix}$$

and

$$\begin{bmatrix} \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = A \cdot \begin{bmatrix} \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} + B \cdot \vec{\tau} \quad (17)$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ I & 0 \end{bmatrix} \quad B = \begin{bmatrix} B_3 \\ 0 \end{bmatrix}$$

Where A_p and B_p are 6×6 and 6×10 matrices respectively with structures given in Eq (16). Similarly, A and B are 20×20 and 20×10 matrices respectively with structures given in Eq (17). A_{px} is a nonzero matrix which represents linearized form of constraints and will impose restriction on controller design. The joint torque vector is computed from a decoupled optimal controller design scheme. We discussed this scheme in Mughal and Iqbal (2009) with details of decoupling conditions to satisfy the holonomic constraints.

$$\vec{\tau}(t) = -K \cdot \begin{bmatrix} \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} - K_p \cdot \begin{bmatrix} \dot{\vec{p}} \\ \dot{\vec{p}} \end{bmatrix} + u_e \quad (18)$$

This torque input can be used with nonlinear model for stable STS movement

4.4 Simulation and Results

We simulate the nonlinear model given by Eq(8) with decoupled optimal controller design of Eq(18). We simulate the nonlinear model with reference trajectories at all joint angles and their respective velocities as well as left foot position and velocity variables. An error $e(t)$ computed from output of nonlinear model with respect to desired (reference) response is an input to the feedback controllers as given in Eq (17). We use synthesized reference trajectories for angles and translational variables for entire STS movement as discussed in detail by Mughal and Iqbal (2008a). The output of this controller in addition to static torques u_e drives the nonlinear model, and stabilizes it from sitting to standing posture. Fig. 6 shows the profiles of ankle, knee hip-pelvic and pelvic-HAT joint angles. Blue solid lines represent the angular profiles and red dashed lines represent the reference trajectories in this simulation. It is clear that angular profiles follow the reference trajectories especially knee angles which has different position at sitting and standing positions. Fig. 7 shows the movement profiles of left foot translational variables, and it is evident that only joint torque controller can regulate the foot position effectively. Holonomic constraints from Eq(13)

generates the reference trajectories for left foot translational variables from angular reference trajectories, which shows almost negligible movement in foot during entire STS task. There is no separate control law for the foot position control and it is totally dependent upon joint angles. This shows that holonomic constraints not only maintain physiological balance in the model but also useful for the movement coordination between joint angles and foot position. Fig. 7 also shows that three position based holonomic constraints from Eq(12) are not violated, which ensure the physiological balance during the movement. This model is more realistic from unconstrained model for STS movement of healthy subjects and stroke patients due to imposed physiological (holonomic) constraints. It still has one weld or 0-DoF joint which doesn't allow any movement in the right foot, but other foot is tracked as 6-DoF joint and its translational movement is indirectly regulated.

Fig. 6. Movement profiles joint angles in radians (solid blue lines) and their reference trajectories (dashed red lines). R=Right, L=Left, A=Ankle angle, K=Knee angle, P= Pelvic-Hip joint angle, H=HAT-Pelvic joint angle, S=Sagittal plane, F= Frontal plane

Fig. 7. Movement of a left foot position (m) in x,y,z directions (blue solid lines) with reference trajectories (red dashed lines) and constraints violation during movement

5. Symmetrical Angular Tree Model

Asymmetrical model with both R-tree and T-tree from different foot cannot produce symmetrical torques, which are required to study for healthy subjects. Now, we propose a design with symmetry along R-tree or for joint angles and their respective torques, and asymmetry is only caused by T-tree and feet connection to the ground.

5.1 Twist Joint and Modeling Equations

Weld joint is not an ideal joint and though it restricts motion, yet an additional number of constraints don't allow us to work in this scheme. Now, we model a right foot with a revolute joint representing twist with y-axis as axis of rotation, which allow moving one end of foot in y direction connecting toes (other end) to the ground. Generating R-tree and T-tree with twist will bring twist variables in state equations with only 5 constraints but this model is redundant as compare to number of degrees in the system and not very different to previous model in Sec 4. So, we model a twist-joint right foot and a free left foot with a T-tree from it instead of pelvic joint.

Fig. 8. Bipedal Model with a 6-DoF left foot and a twist joint in a right foot

Fig 8 shows a model with different R-tree and T-tree from ground to each frame in the model. This create a model with a symmetry as well as asymmetry with 5 reactions as five holonomic constraints with 16 generalized (position) coordinates in the system. The structure of state space formulation remains the same, whereas left foot translational variables and pelvic rotation variables ζ_p, η_p, ξ_p . appear in the formulation. This model has similar structure of model with 13 generalized coordinates discussed in Sec 4 with three additional pelvic rotational variables. A general structure of nonlinear model is given as

$$\begin{bmatrix} \ddot{\vec{p}} \\ \ddot{\vec{x}} \\ \ddot{\vec{r}}_p \\ \ddot{\vec{p}} \\ \ddot{\vec{x}} \\ \ddot{\vec{r}}_p \end{bmatrix} = f(\vec{p}, \vec{x}, \vec{r}_p, \vec{p}, \vec{x}, \vec{r}_p, \vec{\tau}) \tag{19}$$

Where $\vec{p}$ is a vector of left translational foot position variables for p_1 , p_2 , and p_3 in x , y , and z direction respectively similar to Eq (7) and Eq(16) and $\vec{r}_p$ is a vector of pelvic angles.

$$\vec{r}_p = \begin{bmatrix} \zeta_p \\ \eta_p \\ \xi_p \end{bmatrix} \quad (20)$$

Linearizing Eq (19) at standing posture and after rotation given in Eq (21) yields a linear state space formulation given in Eq (22).

$$\begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \ddot{\vec{p}} \\ \vec{r}_p \\ \dot{\vec{r}}_p \\ \ddot{\vec{r}}_p \\ \vec{x} \\ \dot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} \rightarrow \begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \ddot{\vec{p}} \\ \vec{r}_p \\ \dot{\vec{r}}_p \\ \ddot{\vec{r}}_p \\ \vec{x} \\ \dot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} \ddot{\vec{p}} \\ \ddot{\vec{p}} \\ \ddot{\vec{r}}_p \\ \ddot{\vec{r}}_p \\ \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = \begin{bmatrix} A_p & A_{pr} & A_{px} \\ A_{rp} & A_r & A_{rx} \\ A_{xp} & A_{xr} & A_x \end{bmatrix} \cdot \begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \\ \vec{r}_p \\ \dot{\vec{r}}_p \\ \vec{x} \\ \dot{\vec{x}} \end{bmatrix} + \begin{bmatrix} B_p \\ B_r \\ B \end{bmatrix} \cdot \vec{\tau} \quad (22)$$

Now we obtained three decoupled linearized system, one translation of left foot, one for pelvic rotational joints and the one for joint angles in sagittal and frontal plane. Both A_p and A_r represents the 6th order linearized system matrices for foot translational and pelvic rotational system respectively given as

$$\begin{bmatrix} \ddot{\vec{p}} \\ \ddot{\vec{p}} \end{bmatrix} = A_p \cdot \begin{bmatrix} \vec{p} \\ \dot{\vec{p}} \end{bmatrix} + B_p \cdot \vec{\tau} \quad (23)$$

$$\begin{bmatrix} \ddot{\vec{r}}_p \\ \ddot{\vec{r}}_p \end{bmatrix} = A_r \cdot \begin{bmatrix} \vec{r}_p \\ \dot{\vec{r}}_p \end{bmatrix} + B_r \cdot \vec{\tau} \quad (24)$$

The other system is for only joint angle both in sagittal and frontal plane with similar structure and variables given in Eq(17) given as

$$\begin{bmatrix} \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ 0 & I \end{bmatrix} \cdot \begin{bmatrix} \vec{x} \\ \dot{\vec{x}} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \cdot \vec{\tau} \quad (25)$$

This modeling scheme has 5 holonomic constraints and this decoupling separates the joint variables from other variables and doesnot decouple all holonomic constraints in one subsystem so that the other subsystem is free of holonomic constraints. A full system is 32nd order with only 10 zero eigenvalues, and the system in Eq (23) has 6 zeros eigenvalues and these are due to three position constraints between feet. The pelvic rotational system in Eq (24) has only two zero eigenvalues due to pelvic angular constraints. The system in Eq (25) has also two zero eigenvalues one due to a symmetrical angular constraints in right and left

limbs. Controller design becomes difficult due to holonomic constraints and symmetry because both of these add singularities to the system. This controller gain matrices in Eq(26) are obtained by satisfying stability requirements of linear decoupled models and holonomic constraints.

$$\bar{\tau}(t) = -K \cdot \begin{bmatrix} \dot{\vec{x}} \\ \vec{x} \end{bmatrix} - K_p \cdot \begin{bmatrix} \dot{\vec{p}} \\ \vec{p} \end{bmatrix} + -K_r \cdot \begin{bmatrix} \dot{\vec{r}}_p \\ \vec{r}_p \end{bmatrix} + u_e \quad (26)$$

5.2 Simulation and Results

We simulate the nonlinear system given in Eq (19) with a decoupled controller designs for three linear models and further into sagittal and frontal plane by using hybrid physiological cost optimization method. We use decoupled optimal controller design scheme which is complex in nature due to many analytical necessary conditions from algebraic constraints. We discussed these schemes in detail in Mughal and Iqbal (2008b), for decoupling conditions, hybrid physiological cost optimization and reference torques u_e . In this chapter we only focus on bipedal modeling with different possibilities without discussing the details of controller design scheme. Fig. 9 shows the angular profiles for sagittal and frontal angles for nonlinear model Eq(19) with feedback optimal controller design given by Eq(26). The magnitude of frontal plane angles shown in Fig. 9 are less as compare to results in Fig. 6 but still not following the desired response as sagittal angles do. We have three more variables of pelvic angle in state space and Fig. 10 shows the profiles of 3 left foot variables p_1 , p_2 , and p_3 and three pelvis angular variables (due to R-Tree) ζ_p, η_p and ξ_p . First three position holonomic constraints provides reference trajectories for a left foot position and we selected an arbitrary reference profiles for pelvic joint variables. These variables shows the movement which are more closely related to frontal plane angles. This overall scheme shows improved profiles due to more control over the STS movement with more variables for cost optimizations, and a twist joint. There are some differences in the right and left ankle trajectories and overall angles in sagittal plane are symmetrical in response.

Fig. 9. Profiles of joint angles in radians with three decoupled controller designs, a twist joint in right foot and a free left foot

Fig. 10. Profiles of left foot (m) and pelvic joint state variables (radians) given by Eq (6.14) with reference profiles (dashed red lines)

Figure 11. shows the profiles of CoM movement and head movement in x, y and z axis. x-CoM and x-head positions settles at $\frac{1}{2}$ distance between the feet, y-CoM settles at length reaching midway in pelvic height and y-head settles at total body height, initially it goes little down and this shows that the head for a small time goes down and then raises up in

order to perform STS movement. Whereas, both z-CoM and z-head settles to 0 at steady state, that is a person in sitting or standing posture with a right foot on origin and a left feet on x-axis. Left foot position profiles in Fig 10 also explain the movement of CoM and HP during the movement which are not significantly large in magnitude but does affect the movement profiles. Similarly pelvic rotation angles specifically ζ_p , and ξ_p also account for their profiles during this task with small amount of torque components in the system. These physiological results of kinematic variables of CoM position and head position show the relevancy and applicability of this modeling scheme for STS maneuver.

Fig. 11. CoM and HP profiles (m) during STS maneuver for system given by Eq (6.10)

6. Symmetrical Translational-Tree and Rotational-Tree Model

Creating a symmetrical model has many limitations and constraints due to the redundancy in the bipedal design. If we join both feet as weld joint and try to work with any T-tree or R-tree configuration, this model has many constraints and at stable standing (equilibrium) position, model has singularities and so unsolvable. Using the same scheme discussed in Section 3 and 4, and joining both as the weld (0-DOF) joint, instead of a free or 6-DOF left foot, generates 6 algebraic constraints with 10 generalized coordinates and with 4 general degree of freedom, this model is redundant and a singular linear matrix is unsolvable at standing posture. Now, we introduce another scheme in order to obtain computable symmetrical model. Feet as weld joints has no degree of freedom and it generates only reaction variables and in other words in a close chain system, there are either 3 or 6 reaction variables depending upon R-tree or T-tree configuration. With both weld feet in this scheme generates 12 holonomic constraints with 16 generalized coordinates and this system cannot be linearized at standing posture. The reason for asymmetrical torques at both right and left side comes from an engineering model, which starts solving for torques starting from right ankle and reaches to left ankle at the end. We now introduce a model with symmetrical R-

tree and T-tree with aysmmtrical joint beteen ground and feet. In this case we try to reduce asymmetry due to engineering modeling schemes by allowing more variables in the system.

6.1. Feet Joints and Pelvic Variables

Now, we model a right foot with a revolute joint representing tilt with z-axis as axis of rotation, and a left foot as a revolute joint representing twist with y-axis as axis of rotation. This twist and tilt allows to move a feet in z and y direction and generates less constraints.

Fig. 12. 3D bipedal model with tilt and twist in both feet, and R-tree and T-tree from pelvis center and 6 additional state variables.

Generating R-tree and T-tree with twist and tilt will bring either twist or tilt variables in state equations with only 5 constraints but this model is still asymmetrical and redundant as compare to number of degrees in the system. Twist and tilt allows more movement and produces fewer constraints but for developing a symmetrical model, we need to generate symmetrical behavior for right and left ankle, knee and hip-pelvic behavior with similar configuration of R-tree and T-tree. Removing R-tree and T-tree from tilt and twist joints of both right and left feet respectively, and adding pelvis position variables for translational and rotational degrees generates a symmetrical model as shown in Fig. 12. Both R-tree and T-tree join pelvis with the ground and follow the path symmetrical for left and right limbs

till ankle joints. There are tilt and twist joints at right and left foot respectively and these joint variables does not appear in state equation because no T-tree and R-tree in these places. Allowing T-tree from pelvis generates three translational DoF in state equation as x_p, y_p, z_p for position of pelvis in x, y , and z directions. Similarly, R-tree through pelvis generates three rotational DoF to the state equation as ζ_p, η_p, ξ_p angular variables. There are 10 angular variables in sagittal and frontal planes and the system has 16 generalized (position) DoF with 10 constraints. There are also 10 reaction variables of 3 Ground Reaction Forces (GRF) and 2 Moments in each foot. In a right foot with a tilt joint, reaction moments are in y and x direction, whereas in left foot reaction moments in x and z direction for twist in the foot.

6.2 Modeling Equations and Decoupling

This above modeling scheme has 16 generalized coordinates for position variables and state space system is as follows

$$\begin{bmatrix} \ddot{x}_p \\ \ddot{y}_p \\ \ddot{z}_p \\ \ddot{\bar{x}} \\ \ddot{\zeta}_p \\ \ddot{\eta}_p \\ \ddot{\xi}_p \end{bmatrix} = f(x_p, y_p, z_p, \bar{x}, \zeta_p, \eta_p, \xi_p, \dot{x}_p, \dot{y}_p, \dot{z}_p, \dot{\bar{x}}, \dot{\zeta}_p, \dot{\eta}_p, \dot{\xi}_p, \bar{\tau}) \quad (27)$$

Eq (27) shows three translational coordinates x_p, y_p, z_p , and three angular coordinates ζ_p, η_p, ξ_p of pelvis with their respective derivatives for velocities and accelerations. There is a vector $\bar{x}$ for 10 joint angular coordinates with 7 in sagittal plane and three in frontal plane with exactly same configuration as discussed in previous sections. A torque vector $\bar{\tau}$ represents 10 joint torques for their respective joint angles in sagittal and frontal plane. At sitting position y_p is at combined foot and shank length and at standing posture y_p is at foot, shank and thigh length. Similarly, at sitting position z_p is at negative of thigh length along negative z -axis and zero at standing posture, whereas x_p remains at zero for sitting and standing posture. Rotational angles with respect to ground are at zeros at sitting and standing positions for pelvic center. For sake the of simplicity we represent three translational coordinates as $\vec{d}_p$ vector and three angular coordinates as $\vec{r}_p$ for pelvis as follows

$$\vec{d}_p = \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} \quad (28)$$

$$\vec{r}_p = \begin{bmatrix} \zeta_p \\ \eta_p \\ \xi_p \end{bmatrix} \quad (29)$$

We linearize this model at standing posture to obtain a state space formulation as follows

$$\begin{bmatrix} \ddot{\vec{d}}_p \\ \ddot{\vec{x}} \\ \ddot{\vec{r}}_p \\ \ddot{\vec{d}}_p \\ \ddot{\vec{x}} \\ \ddot{\vec{r}}_p \end{bmatrix} = [A] \cdot \begin{bmatrix} \dot{\vec{d}}_p \\ \dot{\vec{x}} \\ \dot{\vec{r}}_p \\ \dot{\vec{d}}_p \\ \dot{\vec{x}} \\ \dot{\vec{r}}_p \end{bmatrix} + [B] \cdot \ddot{\tau} \quad (30)$$

A and B are 32x32 and 10x32 order state space matrices by linearizing Eq(27) at standing posture. Now we rotate the state space formulation for decoupling the system into joint angles and pelvic translation variables as shown in Eq (31)

$$\begin{bmatrix} \dot{\vec{d}}_p \\ \dot{\vec{x}} \\ \dot{\vec{r}}_p \\ \dot{\vec{d}}_p \\ \dot{\vec{x}} \\ \dot{\vec{r}}_p \end{bmatrix} \rightarrow \begin{bmatrix} \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \\ \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \\ \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} \quad (31)$$

$$\begin{bmatrix} \ddot{\vec{d}}_p \\ \ddot{\vec{r}}_p \\ \ddot{\vec{d}}_p \\ \ddot{\vec{r}}_p \\ \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = \begin{bmatrix} A_p & A_{xp} \\ A_{px} & A_x \end{bmatrix} \cdot \begin{bmatrix} \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \\ \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \\ \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} + \begin{bmatrix} B_p \\ B \end{bmatrix} \cdot \ddot{\tau} \quad (32)$$

Now we obtained two linearized system, one for pelvic variables as

$$\begin{bmatrix} \ddot{\vec{d}}_p \\ \ddot{\vec{r}}_p \\ \ddot{\vec{d}}_p \\ \ddot{\vec{r}}_p \end{bmatrix} = \begin{bmatrix} A_d & A_{dr} \\ A_{rd} & A_r \end{bmatrix} \cdot \begin{bmatrix} \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \\ \dot{\vec{d}}_p \\ \dot{\vec{r}}_p \end{bmatrix} + B_p \cdot \ddot{\tau} \quad (33)$$

$$\begin{bmatrix} \ddot{\vec{x}} \\ \ddot{\vec{x}} \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ 0 & I \end{bmatrix} \cdot \begin{bmatrix} \dot{\vec{x}} \\ \dot{\vec{x}} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \cdot \ddot{\tau} \quad (34)$$

Eq (33) has a 12th order decoupled system for $\vec{d}_p$ and $\vec{r}_p$ coordinates and Eq (34) is same as Eq (17) decoupled system. It is difficult to have an optimal controller design for a full 32 order system because A matrix has 20 zero eigenvalues pairs due to 10 generalized holonomic constraints or in total 20 position and velocity constraints for a state space system. For a decoupled optimal controller design, this scheme must follow the analytical necessary conditions to satisfy the holonomic constraints. It is important to note that this system has many constraints and this is not possible to decouple a entire constrained

systems from unconstrained system. A linear controller design has two gain matrices for each model given in Eq(33) and Eq (34).

$$\bar{\tau}(t) = -K \cdot \begin{bmatrix} \dot{\bar{x}} \\ \bar{x} \end{bmatrix} - K_{dr} \cdot \begin{bmatrix} \dot{\bar{d}}_p \\ \dot{\bar{r}}_p \\ \dot{\bar{d}}_p \\ \dot{\bar{r}}_p \end{bmatrix} + u_e \quad (35)$$

6.3 Simulation for Linear System

We now simulate a system in Eq (30) with controller design given by Eq(35). There is further decoupling of angular components into frontal and sagittal planes to get a better design scheme. Fig. (13) shows the response of state variable vectors in simulated with a linear plant of Eq (30). Sagittal angular profiles behaves as desired as right and left knee angles change from $-\pi/2$ to 0 and right and left hip-pelvic sagittal angles changes from $\pi/2$ to 0 in STS maneuver. Right and left ankle angles and pelvic-Hat sagittal angle also settles at zero starting from the same value. Right and left hip-pelvic frontal angles are not affected by the controller and remain at very low zero value, and pelvic-HAT frontal angle settles at 0.008 rads. For pelvis DoF x_p , y_p , η_p and ξ_p are also not affected by the controller and remains at starting values. Change are observable in z_p and ζ_p profiles, where, z_p settles at 0.25.

Fig. 13. Movement profiles pelvic variables and joint angles for linear symmetrical model R=Right, L=Left, A=Ankle angle, K=Knee angle, P= Pelvic-Hip joint angle, H=HAT-Pelvic joint angle, S=Sagittal plane, F= Frontal plane

Fig. 14. CoM and HP profiles (m) for a linearized 32nd order model for STS maneuver

Figure 14. shows the CoM and HP profiles for this simulation of STS maneuver and it shows changes in x-axis for both profiles. Because of tilt in the right foot, CoM position and head frame in x-direction settles at slightly different values. Settlement of z-CoM at 0.05 instead of 0, is due to z_p settling at nonzero value. However, y and z axis profiles of head position shows the physiological correctness of STS maneuver, which can also be verified from knee and hip-pelvic sagittal angular profiles. Besides physiologically correct STS maneuver due to angular profiles and movement of head, this model has lot of limitations as many variables doesn't take any affect due to controller design. y_p doesn't move from sitting position, frontal angles doesn't show properly regulated performance. Due to 20 zero eigenvalues in 32nd order system and the rank of controllability matrix is only 4, which shows that the controller design doesn't regulate the states. An advantage of decoupling of a system is that it increase rank of decoupled system as compare to full order system. Symmetrical distribution of left and right side limbs for torques or gain scheduling may require either very high gains or some other design scheme to control the nonlinear plant.

7. Stability Analysis of Nonlinear System

The nonlinear unconstrained system or a nonlinear constrained system are stable with feedback controller design The nonlinear system for both constrained and unconstrained system is given as (36) representing either of Eq(3), Eq(9), Eq(19) or Eq(27).

$$\ddot{\vec{x}} = M^{-1} \cdot F = f(\vec{x}, \dot{\vec{x}}, \vec{\tau}) = f \quad (36)$$

After linearization this can be represented as Eq (37) same as either of Eq(4), Eq(10), Eq(22) or Eq(30).

$$\Delta \dot{x} = A\Delta x + B\Delta u$$

$$A = \left. \frac{\partial f}{\partial x} \right|_{x=x_e, u=u_e} \quad B = \left. \frac{\partial f}{\partial u} \right|_{x=x_e, u=u_e} \quad (37)$$

$$A\Delta x + B\Delta u = 0 \rightarrow x \rightarrow x_e, u \rightarrow u_e \quad (38)$$

The nonlinear representation after Taylor's series approximation is given as

$$\dot{x} = Ax + Bu + g(x) \quad (39)$$

We adopt Lyapunov's Indirect Method to check for the stability of nonlinear system. According to this method, a stability point is tested for the stability of origin i.e. in the small neighborhood of equilibrium point a nonlinear system is approximated as linearized system provided the following condition holds.

$$\lim_{\|x\| \rightarrow 0} \frac{\|g(x_e, u_e)\|}{\|x\|} = 0 \quad (40)$$

$g(x)$ can be determined as a difference between output of linearized system in MATLAB and a nonlinear system, and this term given by Eq(40) is zero. This leaves the stability to be determined by A and B matrices. In this bipedal model, eigenvalues of A matrix for an open loop system are in pair in right and left half planes, and thus a unstable system. If all the eigenvalues are in left half plane then this system is an asymptotically stable system. The controller designs for unconstrained system and constrained system with either LQR, H_2 or H_∞ optimization stabilizes the system and places all the eigenvalues in left half plane. However, in the case of decoupled controller design, this should also meet the additional criterion to satisfy the holonomic constarints.

8. Conclusion

A free foot model provides a simple model with no holonomic constraints. Designing control design schemes is relatively easy. Simulation results in Fig.3 and Fig. 4 display well controlled results settled within 2 seconds at steady state values. The left foot moves up to 3 cm in z direction which is also due to the more frontal angles movement. The free foot model does not impose restrictions on the left (free) foot to be on ground or any physiological constraints to be satisfied. In this case, the free foot model does not provide more physiological relevancy even though there is a well-behaved head position profiles for STS maneuvers. The second model with three holonomic constraints has more physiological relevance due to three holonomic constraints on the left foot position. These holonomic constraints maintain the distance between two feet in x , y , and z directions and due to these there are six eigenvalues of the system at zero. Decoupling the constrained system from the unconstrained system provides more flexibility on controller design. However, this scheme generates higher torques due to high controller gains to satisfy the holonomic constraints during simulation. Symmetrical systems with holonomic constraints are redundant with lots of singularities, which make system more complex, and an optimal controller design becomes a difficult task. On the other hand asymmetrical systems have singularities only

due to holonomic constraints and an optimal controller design scheme for a nonlinear model is easily achievable.

In sec 5, we allow a twist joint instead of a weld joint which provides a model similar to the model in sec 4, with additional variables of pelvic joints. This also increases the size of the system to the 32nd order from the 26th order system with total of 5 holonomic (position) constraints and 10 joint torques. A twist in left joint allows with symmetrical R-tree to both feet from the pelvic joint, but does not provide symmetrical torque. Allowing for a symmetrical T-tree produces a model with no holonomic constraints like a free foot model which does not serve the purpose very well. A tilt in the right foot also provides a similar system but with a twist joint we achieved better results and thus provided this design scheme. It also explores the possibility of active torque components to this modeling framework, which requires the adaptation of fewer active components for better angular profiles. A weld joint or 0-DoF joint may not be a good assumption for STS which also adds more constraints to the system. On the other hand a twist or tilt joint provides better assumption with one less holonomic constraint to the system. A full symmetrical model discussed in Sec 6 has 20 singularities for a 32nd order system and decoupling allows improving the controllability of the system by improving rank of decoupled controllability matrices. Linear decoupled controller designs which fulfill all the necessary conditions for a large nonlinear system in Eq (30) is not very easily achievable. In this study we provide results of linear systems which show the applicability of symmetrical design with tilt and twist joints in the right and left feet respectively. Allowing both weld joints or both tilt and both twist joints result in overall singular system which is not available for further analysis and controller design.

In future research, other controller design schemes which solve this system may result in more effective designs. Also, additional controllers to optimize twist and tilt will provide an additional measure to achieve specific results. Effects of twist and tilt joints can also be useful to study instead of weld joint (0-DoF) at the left foot (model in sec 3 and 4) without pelvic joint variables. There are several other schemes which have potential for analysis and controller design, like a full symmetrical model with nonlinear controller design. More controller inputs other than only joint torques such as control over twist and tilt joints or control of pelvis frame with external controller design may result in better understanding of the symmetrical model. This modeling scheme with physiological cost optimization (Mughal and Iqbal 2008c), will also produce a better design of the STS maneuver. These schemes provide an overall mathematical and analytical framework with optimal controller design to further study the human voluntary movement (like STS) for specific and required applications. There are myriads of possibilities and including all of these in a one model will result in much large and complex system, which may also be a redundant for a simple voluntary movement task.

9. References

- Anderson, F. C. & Pandy, M. G. (2001). Dynamic Optimization of Human Walking, *Journal of biomechanical Engineering*, Vol. 123, (October 2001).
- Barin, K. (1989). Evaluation of a generalized model of human postural dynamics and control in the sagittal plane, *Biological Cybernetics* Vol. 61, (1989) pp 37-50.
- De Sapio, V. & Khatib, O. (2005). Operation space control of multi-body systems with explicit holonomic constraints, *Proceedings of the 2005 IEEE International conference on robotics and automation*, Barcelona Spain, April (2005).
- Hemami, H. & Jaswa V. C. (1978). On the three link model of the dynamics of standing up and sitting down, *IEEE transaction on Systems Man and Cybernetics*, Vol. 8, (1978) pp115-120.
- Hemami, H. & Wyman B. (2007). Rigid Body Dynamics, Constraints, and Inverses, *Journal of Applied Mechanics*, Vol. 4, (Jan 2007), pp47-56.
- Iqbal, K. & Pai Y. (2000). Predicted region of stability for balance recovery: motion at the knee joint can improve termination of forward movement, *Journal of Biomechanics*, Vol. 33, (2000), pp1619-1627.
- Iqbal, K. & Roy, (2004). A. Stabilizing PID Controllers for an inverted pendulum-based biomechanical model with position, velocity, and force feedback, *ASME Transactions on Biomechanical Engineering*, Vol. 126, (2004), pp838-843.
- Iqbal, K., Kallel, H. and Hemami, H., (1994). Linear decoupling controllers for constrained dynamic systems, *International Journal of Control*, Vol. 60, (October 1994), pp607-616.
- Jalics; L, Hemami, H. & Clymer B. (1996). A Control Strategy for Adaptive Bipedal Locomotion, *Proceedings of the 1996 IEEE International Conference on Robotics and Automation* Minneapolis, MN, (April 1996).
- de Leva, P., (1996), Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters, *Journal of Biomechanics*, Vol. 29, (1996), pp. 1223-1230.
- Mughal A. & Iqbal K. (2008a). Synthesis of Angular Profiles for Bipedal Sit-to-Stand Movement, *40th IEEE Southeastern Symposium on System Theory*, New Orleans, LA, USA, (March 17-18, 2008).
- Mughal A. & Iqbal K. (2008b). Biomechanical bipedal model with asymmetrical reference trajectories for sit-to-stand task, *2nd International conference on Electrical Engineering*, Lahore, Pakistan, (25-26 March 08).
- Mughal A. & Iqbal K. (2008c). Physiological cost optimization for bipedal modeling with optimal controller design, *International Conference on Computational & Experimental Engineering and Sciences*, Vol. 235, pp 1-6, Honolulu, HI, USA, (17-22 March 2008).
- Mughal A. & Iqbal K. (2009). Controller Design by Decoupling of Angular Planes for Bipedal Sit-to Stand Movement, *11th Intl. IASTED Conf. on Control and Application*, Cambridge, UK, (13-15 July 09).
- Mughal, A & Iqbal, K. (2007). Human bipedal biomechanical modeling with DynaFlexPro, *SAE transactions on Digital Human Modeling for Design and Engineering*, Seattle, WA, USA, (June 12-14, 2007).
- Roberts, P & McCollum, G. (1996). Dynamics of sit-to-stand movement, *Biological Cybernetics*, Vol. 74, (1996).
- Spong, M, Hutchinson, S. & Vidyasagar, M. (2006). *Robot Modeling and Control*, John Wiley and sons Inc. (2006).

IntechOpen

IntechOpen

Modelling Simulation and Optimization

Edited by Gregorio Romero Rey and Luisa Martinez Muneta

ISBN 978-953-307-048-3

Hard cover, 708 pages

Publisher InTech

Published online 01, February, 2010

Published in print edition February, 2010

Computer-Aided Design and system analysis aim to find mathematical models that allow emulating the behaviour of components and facilities. The high competitiveness in industry, the little time available for product development and the high cost in terms of time and money of producing the initial prototypes means that the computer-aided design and analysis of products are taking on major importance. On the other hand, in most areas of engineering the components of a system are interconnected and belong to different domains of physics (mechanics, electrics, hydraulics, thermal...). When developing a complete multidisciplinary system, it needs to integrate a design procedure to ensure that it will be successfully achieved. Engineering systems require an analysis of their dynamic behaviour (evolution over time or path of their different variables). The purpose of modelling and simulating dynamic systems is to generate a set of algebraic and differential equations or a mathematical model. In order to perform rapid product optimisation iterations, the models must be formulated and evaluated in the most efficient way. Automated environments contribute to this. One of the pioneers of simulation technology in medicine defines simulation as a technique, not a technology, that replaces real experiences with guided experiences reproducing important aspects of the real world in a fully interactive fashion [iii]. In the following chapters the reader will be introduced to the world of simulation in topics of current interest such as medicine, military purposes and their use in industry for diverse applications that range from the use of networks to combining thermal, chemical or electrical aspects, among others. We hope that after reading the different sections of this book we will have succeeded in bringing across what the scientific community is doing in the field of simulation and that it will be to your interest and liking. Lastly, we would like to thank all the authors for their excellent contributions in the different areas of simulation.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Asif Mahmood Mughal and Kamran Iqbal (2010). Asymmetrical Bipedal Modeling for Biomechanical Sit-to-Stand Movement, *Modelling Simulation and Optimization*, Gregorio Romero Rey and Luisa Martinez Muneta (Ed.), ISBN: 978-953-307-048-3, InTech, Available from: <http://www.intechopen.com/books/modelling-simulation-and-optimization/asymmetrical-bipedal-modeling-for-biomechanical-sit-to-stand-movement>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China

www.intechopen.com

51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

IntechOpen

IntechOpen

© 2010 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License](https://creativecommons.org/licenses/by-nc-sa/3.0/), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.

IntechOpen

IntechOpen