Human Gait Modelling Considerations of Biped Locomotion for Lower Limb Exoskeleton Designs

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Abstract: The number of links in human’s gait model is dependent on factors such as the number of degree of freedoms and the total of actuated joints used in the design. This paper discusses on the modeling consideration of the human gait that related to the design the biped locomotion. Seven types of models are discussed in this paper which suited various biped locomotion design arrangements.

Key-Words: exoskeleton, biped robot, Zero Moment Point (ZMP), human gait model

1 Introduction

Biped robotics has been developed by many research groups quite actively around the world. The prototypes have been proposed to increase able-bodied users’ physical performance or to support human motion for physical performances [1]. The research in advanced biped robotics are also useful for studies in rehabilitation field which include the development of exoskeleton that can help patients to improve their movements.

An exoskeleton is defined as an electromechanical device in overall or a frame that worn by a human operator. It is designed to increase the physical performance of the wearer which is the wearer’s own movements [1][2]. This device is programmed to walk naturally to provide intimacy to human. However, the human gait is a complex dynamic activity. Therefore, for control purposes, human’s gait need to be modelled accurately to achieve the natural gait of biped robot like human being.

Since the human’s gait is composed of dynamic motions of three planes which are sagittal, frontal and transverse as shown in Fig. 1, the complete biped gait robot modeling can only success if the gait is analyzed in two or more planes [3]. It is hard for human’s gait pattern to be applied to the biped robot model because it has complicated mechanical structure. Therefore, the human model for the gait analysis needs to be as simple as possible.

The sagittal plane analysis drives the biped robot gait pattern similar to the human natural gait pattern. The dynamics elements on the transverse plane drive the gait pattern of the biped robot on the frontal plane. The gait pattern of the biped robot on the frontal plane is drive so that the calculated Zero Moment Point (ZMP) of the biped robot converges into the desired ZMP.

Fig. 1: Reference sagittal, frontal and transverse planes of the human body in the standard anatomical position [4]

2 Human Gait Model Patterns

Most of walking dynamics take place on the sagittal plane [5]. This paper reviews the current literature and discusses the design of the biped gait models that related to the controller design of the lower limb exoskeleton. The biped gait patterns are divided into seven categories which are two-link model, compass-like, three-link model, five-link, seven-link gait models, linear inverted pendulum model and table-cart model. The patterns will be
discussed from most simple model up to the most complex.

2.1 Two-link gait model

Garcia et al. proposed simple and uncontrolled two-link model that can walks down a shallow slope, powered by gravity only [6]. It has only mass at the hip and feet as shown in Fig. 2. The mass of the hip is larger than the mass of the feet. Therefore, the motion of a swinging foot does not give affection to the motion of the hip. This links moves on a rigid ramp of slope $\gamma$.

\[ M(\theta)\ddot{\theta} + N(\theta, \dot{\theta})\dot{\theta} + \frac{1}{2} g(\theta) = 0 \]

where, $M(\theta)$, $N(\theta, \dot{\theta})$ and $g(\theta)$ depend on $\mu$ and $\beta$ only and not on $m$, $m_h$, $a$ and $b$ which can be shown as follows:

\[ M(\theta) = \begin{bmatrix} \beta^2 & -(1+\beta)bcos2\alpha \\ -(1+\beta)bcos2\alpha & (1+\beta)^2(\mu+1) + 1 \end{bmatrix} \]

\[ N(\theta) = \begin{bmatrix} 0 & (1+\beta)b\dot{\theta}_s\sin(\theta_s - \theta_n) \\ -(\mu+1)(1+\beta) + 1)gsin\theta_n \end{bmatrix} \]

2.2 Compass-like gait model

Compass-like gait model has a difference with the two-link model although it has same number of links. In this case, the biped robot is kinematically equivalent to a double pendulum which consists two kneeless legs; each has a point mass, and a third point mass at the hip joint as shown in Fig. 3. This gait biped model is not considering the feet. This model also known as compass gait model because the locomotion produced within this model is analogous to the movement of a pair of compasses [7].

Employing the governing equation method, the swing stage equation of this model is similar to a frictionless double pendulum as shown below:

\[ D(\theta)\ddot{\theta} + C(\theta)\dot{\theta} + G(\theta) = B(\theta)u \]

2.3 Three-link biped model

A planar biped model consists of a torso, hips and two equal length legs. The legs do not have any ankles and knees as shown in Fig. 4.

\[ \begin{bmatrix} \beta(1-cos\phi) & 0 \\ 0 & \beta(1-cos\phi) \end{bmatrix} \begin{bmatrix} \dot{\theta}_s \\ \dot{\theta}_n \end{bmatrix} + \begin{bmatrix} -\beta\sin\phi(\dot{\theta}^2 - 2\dot{\phi}) \\ -\dot{\beta}\dot{\theta}\sin\phi \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]

where, $\beta = \frac{m}{m}$ and $\theta$, $\phi$ are functions of time $t$. 

Fig. 2: Two-link Gait Model [6]

Fig. 3: Compass-like Gait Model [7]

Fig. 4: Three-link Gait Model [8]
where, 

\[ D = \begin{bmatrix} \frac{1}{4}m + M_t + M_1 + M_2 & -\frac{1}{2}m r^2 \cos(\theta_1 - \theta_2) & M \rho_1 \cos(\theta_1 - \theta_2) \\ -\frac{1}{2}m r^2 \cos(\theta_1 - \theta_2) & \frac{1}{4}m r^2 & 0 \\ M \rho_1 \cos(\theta_1 - \theta_2) & 0 & M_1 l^2 \end{bmatrix} \]

\[ C = \begin{bmatrix} 0 & -\frac{1}{2}m r^2 \sin(\theta_1 - \theta_2) \dot{\theta}_2 & M \rho_1 \sin(\theta_1 - \theta_2) \dot{\theta}_2 \\ \frac{1}{2}m r^2 \sin(\theta_1 - \theta_2) \dot{\theta}_2 & 0 & 0 \\ -M \rho_1 \sin(\theta_1 - \theta_2) \dot{\theta}_2 & 0 & 0 \end{bmatrix} \]

and 

\[ G = \begin{bmatrix} -\frac{1}{2}g(2M_t + 3m + 2M_2) r \sin(\theta_1) \\ -\frac{1}{2}gmr \sin(\theta_2) \\ -gM_2 r \sin(\theta_2) \end{bmatrix} \]

### 2.4 Five-link biped model

The five-link biped model is shown in Fig. 5. For this case, the feet are not considered in the biped model. The biped robot consists of five links which are a torso and two legs. It also has two pelvises at the hip, two knees between the thighs and the shanks, and two ankles at the tips of the two limbs. All of the joints can only rotate on the sagittal plane. The mass of a link is assumed concentrated at a single point on the link.

![Fig. 5: Five-link biped model at sagittal plane](image)

By using Lagrange’s Equation, the equation of motion for the swing phase of this model is shown below:

\[ D(\theta) \ddot{\theta} + H(\theta, \dot{\theta}) \dot{\theta} + G(\theta) = T \]  

(4)

where, \( D(\theta) \) is a 5x5 positive definite and symmetric inertia matrix, \( H(\theta, \dot{\theta}) \) is the 5x5 matrix related to centrifugal and coriolis terms, and \( G(\theta) \) is a 5x1 matrix of gravity terms. \( \theta, \dot{\theta}, \ddot{\theta} \) and \( T \) are 5x1 vectors of generalized coordinates, velocities, accelerations and torques.

### 2.5 Seven-link biped model

In seven-link biped model case, the biped is actuated at each joint of right and left hip, knee and ankle of right and left legs [9]. It is quite the same like five-link biped model but there are two links added as the feet for this model. Therefore, the feet are considered in this biped model as shown in Fig. 6. The mass of links are assumed concentrated at a single point on the link. This model is applied to BLEEX system developed by Ghan et. al. [10].

![Fig. 6: Seven-link biped model](image)

The equation of motion for the swing phase of this model using Lagrange’s Equation can be shown as follow:

\[ D(\theta) \ddot{\theta} + H(\theta, \dot{\theta}) \dot{\theta} + G(\theta) = T \]

(5)

where, \( D(\theta) \) is 7x7 positive definite and symmetric inertia matrix, \( H(\theta, \dot{\theta}) \) is a 7x7 matrix related to centrifugal and coriolis terms, and \( G(\theta) \) is a 7x1 matrix of gravity terms. \( \theta, \dot{\theta}, \ddot{\theta} \) and \( T \) are the 7x1 vectors of generalized coordinates, velocities, accelerations and torques.

Using this model, Park and Choi [11] has demonstrated that trajectory with optimized mass centers can be minimizes the energy consumption in the locomotion of a biped robot. Braun and Goldfarb [9] proposed a closed-loop control approach for biped walking control that enables dynamic walking in a fully actuated biped robot. They also designed and constructed a seven-link biped robot for fully actuated, non-kinematic walking approach implementation [12].

### 2.5 Linear inverted pendulum model

Kajita and Tani [13] demonstrated a biped robot model which has a mass body and two
massless legs and it restricted to move in sagittal plane. This state is considered only one leg supports the body. Dynamical relationship between ZMP and the center of gravity (COG) have been used in this model. The biped legged system has similar dynamics with inverted pendulum which has supporting point that equivalent to the ZMP location as shown in Fig. 7. Using this model, Sugihara et al. [14] proposed the method that controls the whole body system’s COG in realtime through the ZMP manipulation.

Fig. 7: Inverted Pendulum and Biped Legged System [14]

Kajita et al. [15] analyzed the dynamics of a three-dimensional (3D) inverted pendulum which the motion is constrained to move along an arbitrarily plane for 3D walking control of robot. Hence, Dimensional Linear Inverted Pendulum was created. This model is successfully applied to Meltran V, a 12 DOF biped robot with telescopic legs [16]. Fig. 8 shows an inverted pendulum under constrained in 3D which consists a point mass and a massless telescopic leg.

Fig. 8: 3D Inverted Pendulum [15]

### 2.5 Table-cart model

Cart-table model is a walking biped robot model that simplified into a running cart of a mass \( m \) on a massless pedestal table and has position of \((x, z_c)\) that depicts the center of mass (COM) of the robot as shown in Fig. 8. The mass \( m \) is the total mass of the robot. COM motion avoids the table from tipping and ZMP at a prescribed desired location.

![Fig. 9: Table-cart Model [17]](image)

For this case, two sets of cart on table are needed for motion in \( x \) and \( y \) directions. This methods is traditionally appropriate representation to design a ZMP-based controller [17]. In this case, the torque \( \tau \) around the point \( p \) is given by:

\[
\tau = mg(x - px) - m\ddot{z}_c \tag{6}
\]

where, \( g \) is the acceleration due to gravity. With the zero moment condition of \( \tau = 0 \), the computed ZMP of the cart-table model is obtained as

\[
\begin{align*}
p_x &= x - \frac{z_c}{g} \ddot{x} \\
p_y &= y - \frac{z_c}{g} \ddot{y}
\end{align*} \tag{7}
\]

To control \( p_x \) and \( p_y \), the cart-table model in Fig. 6 was proposed by Kajita et al [17]. This method’s effectiveness has been proven by creating on-line stable walking motions using a ZMP trajectory reference. In [18], Suleiman et al. proposed a new nonlinear model to approximate the dynamic behaviour of walking motion of a robot. The nonlinear part of the nonlinear model is the cart-table model as shown in Fig. 6.

Most of the advanced robots with a humanlike morphology such as LOCH [19] and HRP-4C [18] use ZMP-based control method. The construction of these robots is not only focused on the ability to walk but also on tasks which are using robotic manipulation, machine vision, and artificial intelligence [20].
3 Conclusion
A table is constructed to summarize the differences between biped robot models that are discussed from Section 2. Table 1 show the differences between the robots which are based on mass point that considered in the models and derivation of equation techniques of the models.

Table 1: Differences of Human Gait Models

<table>
<thead>
<tr>
<th>Human Gait Model</th>
<th>Mass Point Availability</th>
<th>Consideration</th>
<th>Equation Derivation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-link Gait Model</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Three-link Gait Model</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Five-link Gait Model</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Seven-link Gait Model</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Linear Inverted Pendulum Model</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Cartesian Model</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

The table can assist researchers to choose the equivalent scheme for their developed system and obtaining the appropriate mathematical model of the system.

In this paper, several numbers of biped models commonly used in the biped gait’s analysis and control has been discussed. Researchers chose most suitable type of the biped model for their research based on their biped robot’s mechanical design. It is important to recognise the number of links and actuated joints of the robot when modelling the biped. Furthermore, the number of DOF takes part on choosing the right model type. A lower limb exoskeleton needs to have several numbers of DOF that similar to the human gait so that the exoskeleton can help the users specially patients to increasing their movement performances. For instance, a standalone exoskeleton called BLEEX [10] has seven DOF which each leg has three DOF at hip, one DOF at knee and 3DOF at the ankle. Therefore, it is appropriate for the Ghan et al. [10] to choose the seven-link type biped model because the model consist the feet part.

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References:


