ARTICLE IN PRESS

Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Predicting foot placement for balance through a simple model with swing leg dynamics

Lei Zhang [a,b], Chenglong Fu [a,*]

[a] Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[b] Beijing Key Lab of Precision/Ultra-Precision Manufacturing Equipments and Control, Tsinghua University, Beijing 100084, China

A R T I C L E I N F O

Article history:
Accepted 4 July 2018
Available online xxxx

Keywords:
Push recovery
Swing dynamics
Capturability
Biped system
Step strategy

A B S T R A C T

Stepping is one important strategy to restore balance against external perturbations. Although current literature have proposed models to predict the recovery foot placement, swing leg actuation is rarely taken into account. In this paper, we combine the capturability-based analysis with swing leg dynamics and seek to contribute to the following problem: *for a biped system recovering balance from external perturbations, how to choose a step position and duration in minimizing swing actuation cost?* We expand the linear inverted pendulum model with an actuated linear pendulum mounted on the pelvis, the addition of which is proposed to describe the swing leg dynamics. The closed-form expression of swing actuation with constraints is derived from the explicit formulations of the pelvis and swing foot motion. We calculate the optimal step position and duration to minimize swing cost under various perturbations. Results show that the optimal step duration keeps constant, while the optimal step position is linearly proportional to the magnitude of perturbations. Such findings match well with experimental data from ten subjects delivered with waist-perturbations. These current results demonstrate that our proposed model with swing dynamics suggests an effective alternative to predict recovery foot placement of biped systems following unexpected perturbations.

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1. Introduction

Avoiding falls is a primary issue in legged locomotion. Not only may it damage a legged system or robot, a fall will disturb its surroundings as well. It is desirable that bipedal systems can restore balance from perturbation rapidly and efficiently. Previous research has presented various strategies to recover balance (Muhammad et al., 2010), but one promising method is to take a step to avoid a fall, especially for a large-magnitude push (Pai, 2006; Fu, 2014).

Dynamic stability in bipedal locomotion and prediction models have been proposed to predict recovery steps (Hof et al., 2005; Pratt et al., 2012; Wu et al., 2007; Pai and Patton, 1997; Millard et al., 2009, 2012). On basis of the well-known Linear Inverted Pendulum Model (LIPM) (Kajita et al., 2001), which is often used to approximate the biped dynamics, Pratt et al. (2006) presented a notion of the capture point, the point on the ground where the robot can step to achieve a full stop; capture region is the set of capture points. Koolen et al. (2012) introduced the capturability framework and presented a capturability-based algorithm to control a humanoid robot M2V2 (Pratt et al., 2012). Furthermore, a recovery step is developed to execute a desired bipedal locomotion for both stationary standing and steady-state walking (Zaytsev, 2015). Although a number of studies have demonstrated the predicted recovery step positions, the action of stepping by swing leg actuation was usually simplified as vague boundaries of step duration, which do not precisely reflect physical facts about the real hardware.

Swing leg actuation is one important aspect closely related to push recovery (Fu et al., 2012). Wisse et al. (2005) argued that the robot would never fall forward if it moves its swing leg fast enough in front of the support leg. Such an infinite swing ability is untrue in the real biped system. One alternative method to assume limited swing actuation is a constant minimum step duration over all perturbed situations (Koolen et al., 2012; Zaytsev et al., 2015). It is mutually independent with the maximum step length constraint for simplifications. Formally, these two types of physical limits contained in prediction models indicate that reaching the maximum step length with the minimum step duration is allowed under various external perturbations. Yet this is usually contradictory because it requires higher driving power to swing

* Corresponding author.
E-mail address: fucl@sustc.edu.cn (C. Fu).

https://doi.org/10.1016/j.jbiomech.2018.07.006
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Please cite this article in press as: Zhang, L., Fu, C. Predicting foot placement for balance through a simple model with swing leg dynamics. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.07.006

leg, which probably beyond the actuation ability. Moreover, experimental results have shown that different magnitudes of external perturbations produce the diversity of influences on recovery steps (Hsiao and Robinovitch, 1999; Pai et al., 1998). Therefore, this method with a constant minimum step duration may lead to a significant difference between the theoretical and practical balance performance of biped systems. More explicit considerations on swing leg, instead of vague estimations on step duration, are critical for predictions of step recovery.

The purpose of this paper is to take swing leg dynamics to analyze recovery foot placement under perturbations. We propose a new template model, called Linear Inverted Pendulum plus Swing Leg (LIPSL). This model depicts the constraints of swing motion and predictions of foot placement, which are subject to these constraints. Using LIPSL and optimization formulations, we aim to examine the optimal step position and duration when given various perturbation levels. To achieve the truthful data of foot placement for push recovery, we conduct human experiments with waist-pull perturbations and collect data from TEN subjects. Combined with capturability-based analysis, the resulting step predictions are compared with human experimental results. As a result, it shows that the predicted results match well with the experimental results.

2. Methods

2.1. The biped model LIPSL

2.1.1. Model hypotheses

We consider here the motion of LIPSL in the sagittal plane and on a level ground. The biped model composes of a pelvis with massive mass M, two point feet with small mass m and two telescopic legs (see Fig. 1). It is assumed that $M \gg m$. The *support leg* behaves as a LIPM and the body mass maintains a constant height z_0 above the ground. The *swing leg* behaves as a moving linear pendulum mounted on the pelvis. A swing torque τ is applied between two legs to actuate the swing foot. A stepping cycle consists of a single support phase and an instantaneous double support phase, which

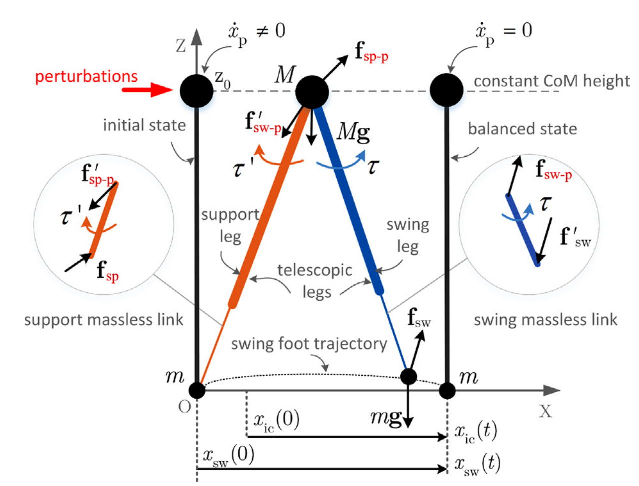

Fig. 1. Biped walking model. Schematic representation of LIPSL. The proposed model comprises a pelvis with the main mass of a body, two feet with small masses, and two massless links. The support part of a body is the same as LIPM, and the swing part is modeled as a linear pendulum, in which swing foot is driven by a swing actuator located between two legs. Starting from a standstill posture of the biped system, a step is triggered in reaction to external perturbations until the instantaneous capture point is caught by swing foot. The position of the instantaneous capture point is according to a function over time expressed as Eq. (14). Note that once swing foot touches down, it immediately transforms into new support leg and last support leg turns into new swing leg for the next step.

means that once the swing foot touches down, the swing leg transforms into the support one instantaneously. During the swing phase, the swing foot keeps a nearly zero distance from the ground and the swing-foot scuffing is ignored for simplicity (Kuo, 2002; Srinivasan and Ruina, 2006; Hasaneini et al., 2014).

2.1.2. Dynamic equations

The equations of motion for the swing foot during the swing phase can be expressed as

$$m\ddot{\mathbf{r}}_{sw} = m\mathbf{g} + \mathbf{f}_{sw} \tag{1}$$

where $\mathbf{r}_{sw} = (x_{sw}, z_{sw})^{T}$ is the position of the swing foot in XOZ coordinates (see Fig. 1), $\mathbf{f}_{sw} = (f_{sw,x}, f_{sw,z})^{T}$ is the force from the swing massless link (part of swing leg not including swing foot) acting on the swing point foot and $\mathbf{g} = (0, -g)^{T}$ is the gravitational acceleration vector.

A moment balance around the pelvis for the swing massless link shows that

$$(\mathbf{r}_{sw} - \mathbf{r}_p) \times \mathbf{f}'_{sw} + \tau = 0 \tag{2}$$

where $\mathbf{r}_p = (x_p, z_p)$ is the pelvis position of body and $\mathbf{f}'_{sw} = -\mathbf{f}_{sw}$.

According to our model hypotheses, $\ddot{z}_{sw} = 0$ and $z_{sw} = 0$ hold true for the swing foot. Using Eq. (1), we have $f_{sw,x} = m\ddot{x}_{sw}$ and $f_{sw,z} = mg$. These can be substituted into Eq. (2) to obtain

$$\ddot{x}_{sw} = \omega_0^2(x_p - x_{sw}) + \frac{\tau}{mz_0} \tag{3}$$

where $\omega_0 = \sqrt{\frac{g}{z_0}}$ is the reciprocal of the time constant for LIPSL.

The equations of motion for the pelvis during the single support phase can be expressed as

$$M\ddot{\mathbf{r}}_p = M\mathbf{g} + \mathbf{f}_{sp\text{-}p} + \mathbf{f}'_{sw\text{-}p} \tag{4}$$

where $\mathbf{f}_{sp\text{-}p}$ is the force from support leg acting on pelvis. Note that a force balance for the swing massless link presents $\mathbf{f}_{sw\text{-}p} = -\mathbf{f}'_{sw}$ (see Fig. 1), then we have $\mathbf{f}'_{sw\text{-}p} = -\mathbf{f}_{sw\text{-}p} = \mathbf{f}'_{sw}$.

Similarly, a moment balance around the support foot for the massless support leg link is

$$(\mathbf{r}_p - \mathbf{r}_{sp}) \times \mathbf{f}'_{sp\text{-}p} + \tau' = 0 \tag{5}$$

where $\mathbf{r}_{sp} = \mathbf{0}$ because the position of the support foot fixed on the ground lies in the origin of coordinate. Due to the law of interaction, we have $\tau' = -\tau$ and $\mathbf{f}'_{sp\text{-}p} = -\mathbf{f}_{sp\text{-}p}$. Additionally, a force balance for the support massless link shows that $\mathbf{f}'_{sp\text{-}p} = -\mathbf{f}_{sp}$; $\mathbf{f}_{sp}$ is from support foot (ankle).

Since the pelvis always stays at the constant height z_0, we have $\ddot{z}_p = 0$. Hence, with the integration of Eqs. (3)–(5), the pelvis position in forward direction can be written as

$$\ddot{x}_p = -\frac{m}{M}\ddot{x}_{sw} + \left(1 + \frac{m}{M}\right)\omega_0^2 x_p + \frac{\tau}{Mz_0}. \tag{6}$$

Compared with the motion of center of mass (CoM) in the classic LIPM, Eq. (6) contains two other terms τ and $\ddot{x}_{sw}$. Due to $M \gg m$ and $\frac{\tau}{M}$ is usually small because of lightweight swing leg, the motion of support leg can be approximately decoupled from that of swing leg so that those terms related to swing leg can be ignored. Then, Eq. (6) becomes

$$\ddot{x}_p \approx \omega_0^2 x_p. \tag{7}$$

This is the same as the CoM motion of the classic LIPM. The explicit formulation is

$$x_p(t) \approx x_p(0)\cosh\omega_0 t + \frac{\dot{x}_p(0)}{\omega_0}\sinh\omega_0 t \tag{8}$$

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