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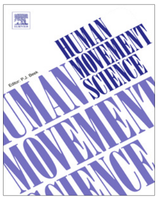

Full Length Article

Reconstruction of human swing leg motion with passive biarticular muscle models ☆

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ABSTRACT

Template models, which are utilized to demonstrate general aspects in human locomotion, mostly investigate stance leg operation. The goal of this paper is presenting a new conceptual walking model benefiting from swing leg dynamics. Considering a double pendulum equipped with combinations of biarticular springs for the swing leg beside spring-mass (SLIP) model for the stance leg, a novel SLIP-based model, is proposed to explain human-like leg behavior in walking. The action of biarticular muscles in swing leg motion helps represent human walking features, like leg retraction, ground reaction force and generating symmetric walking patterns, in simulations. In order to stabilize the motion by the proposed passive structure, swing leg biarticular muscle parameters such as lever arm ratios, stiffnesses and rest lengths need to be properly adjusted. Comparison of simulation results with human experiments shows the ability of the proposed model in replicating kinematic and kinetic behavior of both stance and swing legs as well as biarticular thigh muscle force of the swing leg. This substantiates the important functional role of biarticular muscles in leg swing.

1. Introduction

Template models such as the inverted pendulum (IP) (Cavagna, Saibene, & Margaria, 1963; Cavagna & Margaria, 1966) and the spring-mass model (SLIP, spring-loaded inverted pendulum) (Blickhan, 1989) can help understand principles inherent in human locomotion (Full & Koditschek, 1999) and demonstrate them in robotic counterparts. Many studies on these two basic models concentrate on the description of ground reaction forces (GRF) and center of mass (CoM) trajectories and neglect the effects of swing leg dynamics when the leg is massless (Alexander, 1976; Geyer, Seyfarth, & Blickhan, 2006; Hemami & Golliday, 1977; Seyfarth, Geyer, Guenther, & Blickhan, 2002; Wisse, Atkeson, & Kloimwieder, 2006). In the swing phase of walking, beside ground clearance, the main function of the swing leg is providing an appropriate foot placement, i.e. achieving a suitable leg configuration, a desired angle of attack, and leg retraction. Although the swing leg's mass also affects

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whole body motion, in most studies this effect is ignored and the swing leg movement is simplified to provide an appropriate angle of attack and the focus is on stance leg, CoM movement and GRF (Kuo, 2007; Knuesel, Geyer, & Seyfarth, 2005).

In Mochon and McMahon (1980), Mochon et al. presented a model comprising a stiff stance leg and a segmented swing leg. They showed that the passive model with 2-segmented swing leg can better represent features (e.g., swing time course) of human walking compared with single pendulum. However, the vertical GRF of the model is different from experiments because the modelling constraints (e.g., stiff stance leg). Equipping the IP model with an elastic spring in the stance leg, the SLIP model could mimic GRF and COM movement and non-instantaneousness double support of human locomotion (Geyer et al., 2006). Still, swing leg movement is a missing part in SLIP model and many of its extensions (e.g., to 3d SLIP (Seipel & Holmes, 2005) or with extended foot (Maykranz & Seyfarth, 2014)). In OĆonnor et al. (2009), a new SLIP-based model with additional mass in both legs, curved feet and hip rotational spring was introduced. In this study, OĆonnor investigated different parameters' effects on stability of different types of gaits while integrating feedback (reflex) and feedforward control (CPG). Nevertheless, it has not yet been attempted to focus on human-like swing leg control and effects of segmented leg on overall motion dynamics while maitining simplicity in modelling by employing conceptual models.

In this paper, we combine a segmented swing leg with the spring-loaded inverted pendulum model for the stance leg to represent the swing phase of human-like walking (Fig. 1a). Such a new simple model can potentially explain significant features of human walking which could so far be described in complex models including detailed leg muscles like (Geyer & Herr, 2010). Therefore, we can achieve a target behavior inspired from human walking, and simplicity in modeling and control. We can also apply simple control methods developed using this model to robots and prostheses (see (Sharbafi et al., 2016) for implementing the controller on BioBiped robot).

Judging from human leg muscle activities in the swing leg movement, biarticular hip muscles rectus femoris (RF) and hamstrings (HA) seem to be the main contributors in the swing phase of walking (Nilsson, Thorstensson, & Halbertsma, 1985). By modeling these two muscles with biarticular springs, we aim at a better mechanical understanding of their activities in producing stable gait. In addition, such a passive mechanism may also replicate strong correlation observed between RF and HA in human swing leg movement (Prilutsky, Gregor, & Ryan, 1998), as a consequence of body mechanics.

The goal of this study is to identify the role of elastic biarticular thigh muscles (represented as springs) on swing leg dynamics, the appropriate spring parameters and morphology such that the model can mimic human swing leg motion in walking. With the proposed model, we investigate the role of HA and RF, by comparing the leg's behavior with and without muscles. Human walking data are used (Lipfert et al., 2010) to determine the initial conditions of the swing phase (at lift-off) and for comparison with simulation results. The influences of muscle lever arm ratio, muscle stiffness and muscle rest lengths on the COM motion and swing leg behavior are demonstrated. It is observed that with passive elastic biarticular muscles, walking motion characteristics, like swing leg retraction and symmetric stance leg behavior around mid-stance are obtainable.

2. Methods

2.1. Model

In this section, we describe the walking model shown in Fig. 1. It is assumed that the segments of the swing leg have a distributed mass while the stance leg is massless. The model properties are adapted to anthropometric data (Winter et al., 2005) and are summarized in Table 2. Human walking is characterized by alternating double support and single support phases, and the CoM is approximately at the hip (Maus, Lipfert, Gross, Rummel, & Seyfarth, 2010). In the model, during double support phase, the whole mass is represented by a point mass at the hip; in the single support phase, the mass at the hip is body mass reduced by the mass of the swing leg segments. Since the focus of this study is on swing leg dynamics, double support is not playing a significant role in our analyses. However, for completing the walking step, the bipedal SLIP model is used to describe the double support and we implement a switching between springy leg and two segmented leg, as described in Appendix A.

First, we describe the hybrid "**DPS**" model including double pendulum (**DP**) for the swing leg and SLIP for the stance leg (Fig. 1). Later, we add biarticular springs (muscles) to the two segmented swing leg, as shown in Fig. 1. Considering $q = [l; \theta; \varphi; \sigma]$ as depicted in this figure, we write Lagrange equations that give the dynamical system equations for the single support phase of motion[1],

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = BF \tag{1}$$

in which D and C are the inertia and the Coriolis matrices, respectively. G is the gravity vector and B is a constant matrix that maps the force vector F to the generalized forces. Hence, defining the state vector $x = [q; \dot{q}]$ gives the following relation for the continuous mode of the robot motion:

$$\dot{x} = \begin{bmatrix} \dot{q} \\ D^{-1}(q)[-C(q,\dot{q})\dot{q} - G(q) + BF] \end{bmatrix} \tag{2}$$

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[1] Sign ";" concatenates the matrices vertically; i.e. $[a; b : [a^T b^T]^T$, where super index T means transpose.