Journal of Biomechanics 44 (2011) 2123–2128

Contents lists available at ScienceDirect

Journal of Biomechanics

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

A structurally optimal control model for predicting and analyzing human postural coordination

Vincent Bonnet [a,*], Sofiane Ramdani [b], Philippe Fraisse [a], Nacim Ramdani [a], Julien Lagarde [b], Benoit G. Bardy [b]

[a] LIRMM UMR 5506 CNRS, Montpellier 2 University, 161 rue Ada, Montpellier 34392, France
[b] Movement to Health, Montpellier 1 University, EuroMov, 700 av. du pic Saint Loup, Montpellier 34090, France

ARTICLE INFO

Article history:
Accepted 18 May 2011

Keywords:
Postural coordination
Feedback postural model
Optimal control

ABSTRACT

This paper proposes a closed-loop optimal control model predicting changes between in-phase and anti-phase postural coordination during standing and related supra-postural activities. The model allows the evaluation of the influence of body dynamics and balance constraints onto the adoption of postural coordination. This model minimizes the instantaneous norm of the joint torques with a controller in the head space, in contrast with classical linear optimal models used in the postural literature and defined in joint space. The balance constraint is addressed with an adaptive ankle torque saturation. Numerical simulations showed that the model was able to predict changes between in-phase and anti-phase postural coordination modes and other non-linear transient dynamics phenomena.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Human stance requires the control of different body segments in a synergetic way. Nashner and McCollum (1985) described two preferential postural strategies, i.e., the hip and the ankle strategies, using a popular experimental paradigm based on external postural perturbations. In the ankle strategy, the postural system response is characterized by a large activity and movement of the ankles, whereas the hip strategy corresponds to the coordinative activation of hips and ankles with larger movements of the hips. In this context, a classical modelling approach is to assume that humans perform goal-directed movements following certain optimal criteria (He et al., 1991; Kuo, 1995; Tian and He, 1997; Park et al., 2004; Torrence et al., 2008). Kuo (1995), for example, proposed an optimal control model which computes continuous joint feedback responses by explicitly minimizing the quadratic sum of the joint torques, under specific constraints. Most of these approaches used a linearized biomechanical model with an optimal controller defined in the joint space. Actually, the main goal of the Nashner and McCollum paradigm was to restore the joint angle to zero position (vertical position of the body).

Assuming that a minimization of an explicit criterion is required implies a knowledge by the central nervous system (CNS) of complex internal representations of human dynamics and its interaction with the environment. The existence of these internal models is the target of a vivid debate in motor control literature (Mehta and Schaal, 2002; Todorov, 2004). In addition, this concept is unclear as regarding telhe definition of descriptive variables and the existence of a mixed strategy (Horak and Nashner, 1986; Runge et al., 1999) merging into postural observations which are different from the original strategies.

Based on these observations, Bardy et al. (2002) proposed that it is not the participation of these different joints per se which determine the organization of the postural system, but rather their coordination. During a visual tracking task, the authors analyzed a collective variable to describe the non-linear postural couplings: the relative phase (Φ) between hips and ankles. In the princeps experiment, standing participants followed in the anteroposterior direction a sinusoidal target with the head. Two coordination modes were observed depending on the target frequency: an in-phase ($\Phi = 0^\circ$) mode for low frequencies and an anti-phase ($\Phi = 180^\circ$) mode for high frequencies. This experimentation allowed the observation of non-linear properties of the postural system, such as phase transition, multistability and hysteresis.

Attempts to model postural strategies available so far have used controllers defined in joint space (He et al., 1991; Kuo, 1995; Tian and He, 1997; Park et al., 2004; Torrence et al., 2008). For this reason, they cannot reproduce supra-postural performance such as looking, tracking, or reaching during standing. Only one model (Martin et al., 2006) using a constrained optimization process, based on the minimization of an energetic criterion, was recently proposed to investigate postural coordination (PC) dynamics. The main result

* Corresponding author.
E-mail address: vincent.bonnet@lirmm.fr (V. Bonnet).

0021-9290/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2011.05.027