Evaluation of a Generalized Model of Human Postural Dynamics and Control in the Sagittal Plane*

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Abstract. A two-step identification method is used to evaluate a generalized model of human postural control in the sagittal plane. Postural dynamics are represented as a planar open-chain linkage system supported by a triangular foot. The control mechanism is modeled as a state feedback element in which the torque acting at a given link is an arbitrary function of the state variables - angles and angular velocities. To validate the approach, six normal subjects underwent two series of experiments. The first series were used to determine an appropriate model of the system dynamics. The second series were used to estimate the parameters of the feedback model. A computer simulation of the complete system shows that the model predictions closely match the observed responses. These results suggest that the proposed model provides a useful framework for analysis of postural control mechanisms.

1 Introduction

Maintenance of postural stability is accomplished in humans by a complex neural control mechanism (Herman et al. 1976). While the sensorimotor systems contributing to postural control have been studied for over a century (Romberg 1853), mathematical descriptions of these systems have begun to emerge only in the past decade (Hatze 1980a; McGhee et al. 1979). One of the earliest analytical studies of human postural control was performed by Nashner (1971, 1972). He developed a mathematical model of the vestibular system by representing the human body as a rigid link capable of rotating only about the ankle joint. Subsequently, Hemami and Goolliday (1977) derived the stability requirements of the single-link model using a linear state feedback control law. Camana et al. (1977) extended this work to a two-link structure. They evaluated the model for one subject by estimating the elements of the feedback gain matrix such that the model predictions were similar to the measured responses. More recent attempts to model postural control have involved the simulation of complex motions (Hemami and Jaswa 1978; Hatze 1981), and the use of nonlinear feedback laws (Hemami and Camana 1976; Hemami 1980).

While mathematical models of the type used by Camana et al. (1977) provide a promising framework for examining possible ways in which the postural control system may work, as yet there has been little direct application of modeling approach to experimental or clinical problems. One of the main obstacles has been the lack of computationally-manageable identification methods, which has prevented a large scale evaluation of the model. The lack of identification methods has also prevented incorporation of physiological findings into the model. As a result of these difficulties, some investigators have adopted more empirical approaches. One promising approach is presented by Nashner and his colleagues. Their approach is based on representation of postural movements in a position space described by ankle, hip, and vertical axes (Nashner and McCollum 1985). Recent studies have provided some experimental support for this scheme, suggesting that it may provide a useful framework for studying postural control (Horak and Nashner 1986).

The present paper describes a two-step identification procedure as a basis for analyzing sensory feedback in postural control. The procedure is based on a series of computationally-efficient analytical methods which result in a manageable framework for model validation. Finally, through a number of examples, it will be shown that strategy-oriented
hypotheses adopted by Nashner and his colleagues can be incorporated into the proposed model. It will also be shown that the proposed analytical approach is a generalization of the methods which are based on partitioning of the position space and therefore, offers a number of advantages over those methods.

2 Mathematical Model

The human postural control system receives information from proprioceptive, visual, vestibular, and perhaps other sensors, and it controls a musculoskeletal structure with over 200 deg of freedom powered by approximately 750 muscles. Figure 1 shows a simplified characterization of the system in the sagittal plane. The model has two major components— one representing the musculoskeletal dynamics in the sagittal plane, the other representing the sensors, the central nervous system, and the neural network.

2.1 Dynamics of the Musculoskeletal System

Human postural dynamics in the sagittal plane is represented as an open-chain N-link inverted pendulum placed atop a triangular foot. It is assumed that limb segments are one-dimensional with concentrated masses and that they rotate about simple pin joints with a torque actuator at each joint. The subject is instructed to fold his arms across his chest and to keep his feet together so that the left and right ankle joints rotate about the same axis. The human body standing under these conditions can be modeled as a system of rigid bodies connected together with N rotary joints and with a control torque vector, \( T' (N \times 1) \), acting at each joint. The general form of the motion equations for such a system is:

\[
J(\theta)\ddot{\theta} + A(\theta, \dot{\theta}) = BT',
\]

where \( J (N \times N) \) is the system inertia matrix; \( A (N \times 1) \) is the vector of torques resulting from all the forces; \( B (N \times N) \) is the distribution matrix; and \( \theta (N \times 1), \dot{\theta} (N \times 1), \) and \( \ddot{\theta} (N \times 1) \) are the vectors of inertial angles, angular velocities, and angular accelerations, respectively (Hollerbach 1980).

Figure 2 shows four variants of the system dynamics—a one-link model with a joint at the ankle, a two-link model with joints at the ankle and hip, a three-link model with joints at the ankle, knee, and hip, and a four-link model with joints at the ankle, knee, hip, and neck.

The solution to (1) can be approached from two distinct points of view. The first is known as the "motion analysis" problem, in which \( \theta, \dot{\theta}, \) and \( \ddot{\theta} \) are known and the joint torques, \( T' \), must be calculated. This problem is most efficiently solved using a recursive free-body approach based on Newton-Euler principles (Barin et al. 1984). The other is known as the "motion simulation" problem, in which \( T' \) is known and \( \theta, \dot{\theta}, \) and \( \ddot{\theta} \) are desired. A nonrecursive method based on defining the elements of \( J, A, \) and \( B \) provides a more efficient solution to this problem. In addition, the dynamic equations of a triangular foot provide a