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Dynamic stability of a human standing on a balance board

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ABSTRACT

The neuromuscular system used to stabilize upright posture in humans is a nonlinear dynamical system with time delays. The analysis of this system is important for improving balance and for early diagnosis of neuromuscular disease. In this work, we study the dynamic coupling between the neuromuscular system and a balance board—an unstable platform often used to improve balance in young athletes, and older or neurologically impaired patients. Using a simple inverted pendulum model of human posture on a balance board, we describe a surprisingly broad range of divergent and oscillatory CoP/CoM responses associated with instabilities of the upright equilibrium. The analysis predicts that a variety of sudden changes in the stability of upright postural equilibrium occurs with slow continuous deterioration in balance board stiffness, neuromuscular gain, and time delay associated with the changes in proprioceptive/vestibular/visual-neuromuscular feedback. The analysis also provides deeper insight into changes in the control of posture that enable stable upright posture on otherwise unstable platforms.

1. Introduction

Research into the instability mechanisms of upright standing posture is of great relevance for the improved rehabilitation and fall-prevention among the elderly (Kannus et al., 2005), athletes (Emery et al., 2005), persons suffering from neuromuscular diseases such as Parkinson's (Ashburn et al., 2001; Blaszczyk et al., 2007; Stolze et al., 2004) and multiple sclerosis (Corradini et al., 1997), and people impaired due to stroke (Kannus et al., 2005) or cancer treatment (Winters-Stone et al., 2011). In daily life, individuals maintain upright posture in dynamically evolving environments where the balance system must interact with an external dynamical system. Therefore, it is important to examine the stability of upright posture under various environmental conditions, especially those that are likely to cause instability. A balance board—an inherently unstable platform that pivots about a fulcrum with its center of mass located above the pivot—provides a simple environmental manipulation which results in instability. This manipulation is especially important because the balance board has been used to prevent injury in young athletes (Aaltonen et al., 2007; Emery and Meeuwisse, 2010) and to improve stability in balance-compromised populations (e.g. de Bruin et al., 2009; Godard et al., 2004; Hinman, 2002; Nordt et al., 1999). Although balance boards are present in many clinics, the mechanisms behind balance improvements are not yet clear (Zech et al., 2010). For example, improved balance after training on an unstable surface can stem from a variety of factors including an improved ability to rapidly process and act on sensory information, adopting more appropriate levels of muscle stiffness, or strength increases which allow more joint torque to be produced so that body perturbations can be more effectively attenuated.

From a dynamical systems point of view a human attempting to balance upright on an unstable balance board represents the coupling of two dynamical systems, the human balance system with neuromuscular feedback supported on the balance board (an inverted pendulum). The coupling of these two dynamical systems, with time delay and nonlinearities, creates an ideal setting for the emergence of complex postural behavior and unanticipated interactions between the individual, task, and the external dynamical system. Thus, applying a dynamical systems perspective should provide important insights into the study of stability on a balance board. Recently such an approach has been applied to the study of upright sitting posture on an unstable surface (Cholewicki et al., 2000; Reeves et al., 2006; Tanaka et al., 2010). However, to the best of our knowledge mathematical models and their nonlinear dynamic analysis of *standing* postural balance on balance boards are not available.

In order to understand the dynamic stability of a human standing upright on an unstable balance board we present a simple mathematical model that couples the standard inverted pendulum posture (Asai et al., 2009; Barauskas and Krusinskiene, 2007; Corradini et al., 1997; Fukuoka et al., 2001; Hur et al., 2010; Iqbal and Roy, 2004; Ishida et al., 1997; Johansson et al., 1988;

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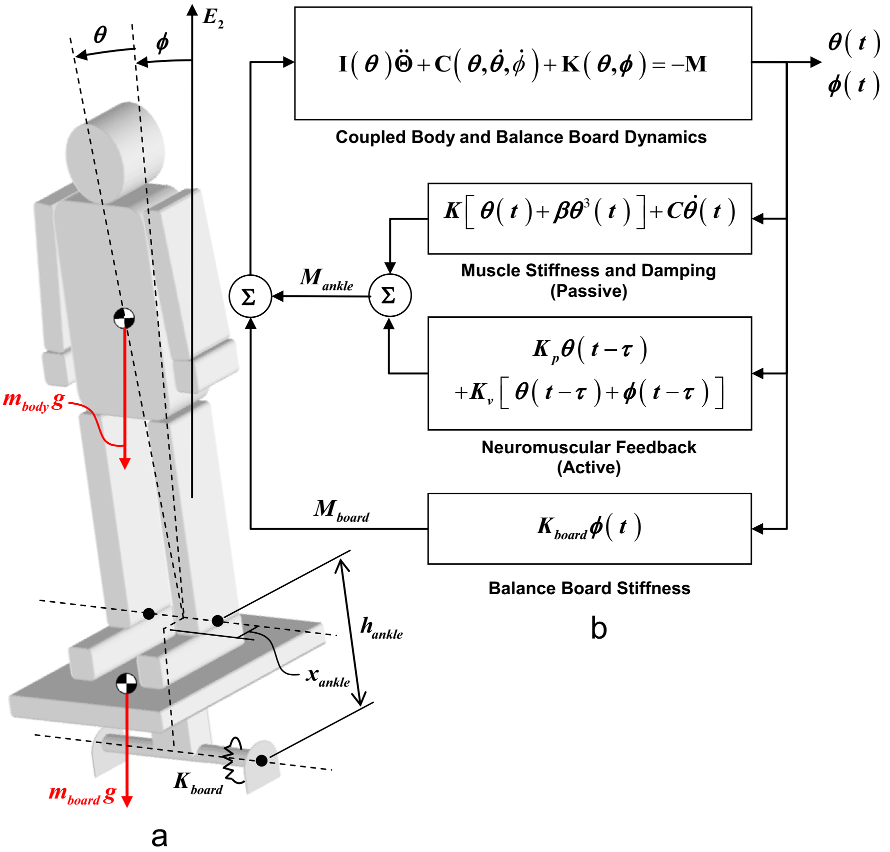

Fig. 1. (a) Diagram of posture on a 1-DOF balance board with forces and correcting moments along with system geometric parameters, and (b) a block diagram of the postural control system on a 1-DOF balance board.

Loram et al., 2005; Masani et al., 2003, 2006; Maurer and Peterka, 2005; Milton et al., 2009; Peterka, 2000, 2002, 2003; Ting et al., 2009; Verdaasdonk et al., 2004; Vette et al., 2010; Yao et al., 2001) to a one degree of freedom (1-DOF) balance board with torsional stiffness. We analyze the bifurcations and stability inherent in this simple coupled system with nonlinear muscle stiffness, large sway nonlinearities, and a time delay in neuromuscular feedback. Bifurcations have been studied within mathematical models of posture (Asai et al., 2009; Verdaasdonk et al., 2004; Yao et al., 2001), but they have not been studied for humans coupled to balance boards. We identify a variety of bifurcations (i.e. Hopf, pitchfork, and saddle-node) which suggests a possible control strategy that is used while maintaining posture on a balance board, as well as how that strategy may be adjusted as the neuromuscular system degrades.

2. Methods

2.1. Model of human posture on a 1-DOF balance board

Prior mathematical models of human posture on a rigid surface include proposed passive proportional-integral-derivative (PID) controllers (Asai et al., 2009; Barauskas and Krusinskiene, 2007; Johansson et al., 1988), active PID controllers with time delay (Masani et al., 2003, 2006; Peterka, 2000, 2003), combinations of passive and active PID controllers (Asai et al., 2009; Maurer and Peterka, 2005; Peterka, 2002, 2003; Vette et al., 2010), and complex controllers such as hysteresis (or bang–bang) controllers (Asai et al., 2009). Furthermore it has long been recognized that upright body sway may involve more than 1-DOF owing to the contribution of other joints (Gunther et al., 2009; Kuo and Zajac, 1993; Pinter et al., 2008; Sasagawa et al., 2009). Nonetheless, the 1-DOF model with PID control has been shown to reliably model the movement of the CoM (Maurer and Peterka, 2005). In what follows we present a mathematical model that couples this 1-DOF balance model with the dynamics of a 1-DOF balance board. While more advanced mathematical models for postural control may need to be developed to fully understand this system, our goal is to study the simplest coupled system model in terms of the inherent nonlinear dynamics as a proof-of-concept of the emergent phenomena inherent in such a coupled system.

For this purpose we model human posture on a balance board by coupling the 1-DOF inverted pendulum model to a 1-DOF inverted pendulum balance board controlled by ankle torque M_{ankle} and a torque between the balance board and the ground M_{board} (Fig. 1a), where the system dynamics are described by the coupled equations

$$\begin{bmatrix} I_{11}(\theta) & I_{12}(\theta) \\ I_{21}(\theta) & I_{22}(\theta) \end{bmatrix}\begin{Bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{Bmatrix}+\begin{Bmatrix} C_{11}(\theta,\dot{\theta},\dot{\phi}) \\ C_{21}(\theta,\dot{\theta},\dot{\phi}) \end{Bmatrix}+\begin{Bmatrix} K_{11}(\theta,\phi) \\ K_{21}(\theta,\phi) \end{Bmatrix}=-\begin{Bmatrix} M_{ankle} \\ M_{board} \end{Bmatrix}. \tag{1}$$

Details of terms in Eq. (1) can be seen in Appendix. The human body has a mass m_{body} whose center of mass (CoM) is assumed to be a constant distance of h_{body} from the ankle joint and the sway angle θ is measured relative to the balance board in the anterior-posterior (AP) direction (Fig. 1a). The sway angle of the balance board is ϕ in the AP direction. The ankle joint is assumed to be shifted a distance of x_{ankle} from the balance board's axis-of-rotation. The balance board and foot have a lumped mass m_{board} that is assumed to be centered at a constant distance of h_{board} from the balance board axis-of-rotation. The balance board also has a torsional spring connected at its hinge which applies a torque to the board as follows

$$M_{board}(t)=K_{board}\phi(t), \tag{2}$$

where K_{board} represents the torsional spring constant.

We model the corrective ankle torque applied by the neuromuscular system as the sum of a passive and an active torque. The passive torque arises from the stiffness and damping due to muscle stretching while the active torque is applied in response to the motion sensed by the neuromuscular system (Peterka, 2002). Because passive torque only acts as the ankle angle changes, the corrective passive torque can be modeled as the nonlinear controller,

$$M_{ankle,passive}(t)=K[\theta(t)+\beta\theta^3(t)]+C\dot{\theta}(t), \tag{3}$$

where K represents the linear muscle stiffness and β represents the extent of nonlinearity in force-extension/compression response of the muscle groups involved in postural control. Specifically, β is the ratio of passive cubic-nonlinear muscle stiffness to passive linear muscle stiffness, and C represents the linear muscle damping (Barauskas and Krusinskiene, 2007; Fukuoka et al., 2001; Maurer and Peterka, 2005; Peterka, 2002, 2003; Vette et al., 2010).