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Effect of sensory-motor latencies and active muscular stiffness on stability for an ankle-hip model of balance on a balance board

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A B S T R A C T

To achieve human upright posture (UP) and avoid falls, the central nervous system processes visual, vestibular, and proprioceptive information to activate the appropriate muscles to accelerate or decelerate the body's center of mass. In this process, sensory-motor (SM) latencies and muscular deficits, even in healthy older adults, may cause falls. This condition is worse for people with chronic neuromuscular deficits (stroke survivors, patients with multiple sclerosis or Parkinson's disease). One therapeutic approach is to recover or improve quiet UP by utilizing a balance board (BB) (a rotating surface with a tunable stiffness and time delay), where a patient attempts to maintain UP while task difficulty is manipulated. While BBs are commonly used, it is unclear how UP is maintained or how changes in system parameters such as SM latencies and BB time delay affect UP stability. To understand these questions, it is important that mathematical models be developed with enough degrees-of-freedom to capture the many responses evoked during the maintenance of UP on a BB. This paper presents an ankle-hip model of balance on a BB, which is used to study the combined effect of SM latencies and active muscular stiffness of the ankle and hip joints, and the BB stiffness and time delay on UP stability. The analysis predicts that people with proprioceptive, visual, vestibular loss, or increased SM latencies may show either leaning postures or larger body-sway. The results show that the BB time delay and the visual and vestibular feedback have the largest impact on UP stability.

1. Introduction

The stabilization process of human upright posture (UP) requires the contribution of the visual, vestibular, proprioceptive, and muscular systems (Morasso and Schieppati, 1999; Engelborghs et al., 2000). This process is regulated by the central nervous system (CNS) and has inherent sensory-motor (SM) latencies (Peterka, 2002; Stepan, 2009). The body-angle information is estimated by the visual and vestibular (V&V) systems in the absolute reference frame (Tahboub, 2009) and by the proprioceptive system in a local reference frame (Chiba et al., 2016). The muscular system produces corrective forces that accelerate or decelerate the body's center of mass (CoM) for maintaining UP. This process can be difficult for older adults and people with chronic neuromuscular deficits (people with multiple sclerosis, Parkinson's disease, or stroke survivors), each being more likely to suffer falls and show reduced mobility and independence, fractures, and death (Rabadi et al., 2008). It is critical for these groups of people to adopt certain strategies to recover or improve balance to positively impact their quality of life. One method for developing such strategies is to train individuals on a balance board (BB) (a rotating surface with tunable stiffness and some with a tunable time delay). BBs provide simple manipulations that train individuals how to react to dynamically evolving environments, similar to external disturbances that are encountered during everyday life. Despite the use of BBs in therapeutic interventions, the mechanisms responsible for maintaining UP on a BB are not completely understood. Understanding these mechanisms is crucial for the improvement of therapeutic approaches and future designs of BBs. One technique used to investigate these mechanisms is by evaluating the underlying stability and inherent bifurcations through a mathematical model.

In the literature, there is only one model of upright stance on a balance board, a simple ankle strategy model (Chagdes et al., 2013; Cruise et al., 2017). The ankle strategy model is the simplest model of UP and assumes body-sway is controlled using a pure ankle strategy with negligible contributions from the knee and hip joints (Gage et al., 2004). This model has been used for about 30 years in different studies (Johansson et al., 1988; Peterka, 2000; Asai et al., 2009; Cruise et al., 2017) and found to be sufficient for modeling

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balance during quiet stance (Gage et al., 2004; Peterka, 2003). When recovering from disturbances it has been found that there are larger contributions from the hip (Pinter et al., 2008). Nashner and McCollum (1985) and Nashner et al. (1988) found that UP can be achieved by pure ankle or hip movements or by a sequential mixture of the two when exposed to support-surfaces translations. Pinter et al. (2008) and Johansson et al. (1988) reported that after a sagittal disturbance, a subject recovers his or her equilibrium through a combination of ankle and hip strategies. Moreover, impaired people suffering from stroke (Diener et al., 1984), Parkinson's disease (Horak et al., 1992), multiple sclerosis (Chua et al., 2014), spastic hemiplegia, or ataxia (Nashner and McCollum, 1985) tend to use the hip strategy more frequently. Because BBs provide simple manipulations of the balance environment, which are similar to mimic external disturbances on a rigid surface, models of UP on BBs should include hip contribution (Sasagawa et al., 2009; Suzuki et al., 2011, 2012).

In work performed by Chagdes et al. (2013), the upright stability of a mathematical model of UP on a traditional BB with tunable torsional stiffness was examined for a variations of human (i.e., neuromuscular feedback gain and time delay) and BB stiffness. A bifurcation analysis provided insight into a possible ankle strategy requiring the fine-tuning of feedback gains to maintaining upright stability when BB stiffness was decreased. The effect that neurological impairment has on maintaining UP on BBs was explored by simulating the model for a short (100 ms) and a long (300 ms) neuromuscular time delay; however, little is known about the transition between these two chosen delays. In an effort to develop a new device with better characterization of balance deficiencies, Cruise et al. (2017) introduced a tunable delay in BB feedback in a mathematical model. In this study, upright stability was examined for a continuous range of delays in BB feedback and BB torsional stiffness. It was found, through a bifurcation analysis performed on the model for a short (100 ms) and a long (200 ms) neuromuscular time delay, that this new device could characterize differences in the mathematical model with these two discrete values of time delay. While these studies developed simple mathematical models of UP on BBs, they neglected the importance of the hip joint. The objective of the study is to extend the ankle strategy model of balance on a BB to include hip contribution and to perform bifurcation analyses similar to those found in Chagdes et al. (2013) and Cruise et al. (2017). This paper presents a new model that includes ankle and hip joints and an analysis that considers time delays for ankle-hip joints and BB hinge at six discrete values for each time delay. Six combination cases of the parameters were tested: Proprioceptive feedback versus BB stiffness and visual-vestibular feedback versus BB stiffness, each with a time delay in BB feedback, ankle joint feedback, and hip joint feedback.

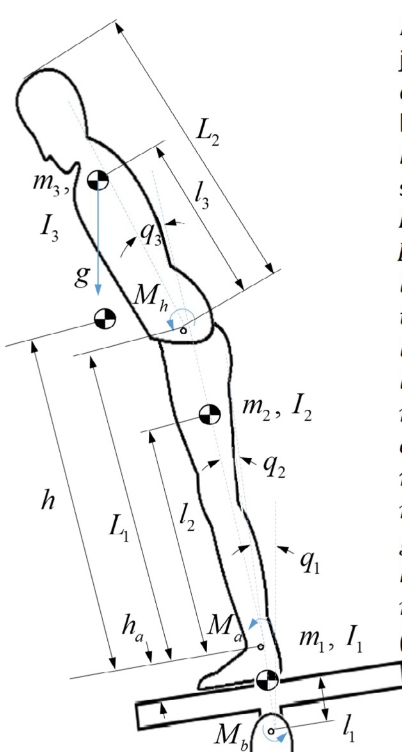
2. Methods

2.1. Model of the human-BB dynamic system

A three-link inverted pendulum representing an ankle-hip model of balance on a BB in the sagittal plane is shown in Fig. 1. The governing equation of motion is shown in Eq. (1).

$$\mathbf{D}(\mathbf{q}(t))\ddot{\mathbf{q}}(t) + \mathbf{C}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + \mathbf{G}(\mathbf{q}(t)) = \begin{bmatrix} M_b(t) \\ M_a(t) \\ M_h(t) \end{bmatrix}, \tag{1}$$

where $\mathbf{q}(t) = [q_1(t) \quad q_2(t) \quad q_a(t)]^T$, $\dot{\mathbf{q}}(t)$, and $\ddot{\mathbf{q}}(t)$ represent the joint angle, angular velocity, and angular acceleration vectors, respectively. Joint angles q_i are depicted in Fig. 1. $\mathbf{D}(\cdot)$, $\mathbf{C}(\cdot)$, and $\mathbf{G}(\cdot)$ denote the inertia matrix, the Coriolis term, and the gravity term, respectively. Details of the terms in Eq. (1) are given in Appendix A.



M_b, M_a, M_h: Torques at the board hinge, the ankle joint, and the hip joint respectively.
q_1, q_2, q_3: Angles of the board, the ankle and the hip.
h_a: Distance from the ankle's joint to the top side of the board.
L_1: Length of the legs.
L_2: Length of the trunk.
l_1: *Distance from the board's hinge to the CoM of the compound board-feet.*
l_2: *Distance from the ankle joint to the leg's CoM.*
l_3: *Distance from the hip joint to the HAT's CoM.*
m_1,I_1: *Mass and moment of inertia of the compound board-feet.*
m_2,I_2: *Mass and moment of inertia of the legs.*
m_3,I_3: *Mass and moment of inertia of the HAT.*
g: Gravitational acceleration.
h: Height of the total body's CoM.
$m = m_2 + m_3$: *Total mass of the human body (excluding feet).*

Fig. 1. Diagram of a human balancing on a BB. The system is represented by a triple inverted pendulum (BB, legs and HAT) swinging in the sagittal plane and driven by torques at the BB's hinge, the ankle joint, and hip joint.

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