Studying Balance on an Active Balance Board with Controllable Stiffness and Time-delay

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INTRODUCTION

Understanding how humans balance on unstable surfaces is critical for the development of methods to prevent falls and improve stability. A mathematical model of a human on a balance board was presented in Chagdes et al. [1]. Model simulations revealed two mechanisms of instability: a static instability resulting in “tipping” and a dynamic instability leading to limit cycle oscillations (LCOs). LCOs were also detected in balance-compromised populations standing on solid ground [2]. Muscular stiffness and neuromuscular time-delay were both important factors contributing to instability. However, while commercial balance boards manipulate torsional stiffness to explore one instability, time-delay is not utilized as a parameter.

First, we explore the relationship between upright stability and the adjustable board parameters with a model of a human on the active balance board. Simulations revealed both types of instability. Second, we design and fabricate an active balance board with controllable rotational board stiffness and board feedback time-delay. Initial testing of this active balance board is completed with a population of healthy college-aged adults, which also revealed both types of instability.

METHODS

The model of human posture on a balance board from Chagdes et al. [1] was adapted by combining the 1-DOF inverted pendulum human model with a 1-DOF inverted pendulum balance board model with tunable rotational stiffness and time-delay (Figure 1, Equation 1).

$$[I(\theta)]\begin{Bmatrix}\ddot{\theta}\\ \ddot{\phi}\end{Bmatrix}+[C(\theta,\dot{\theta},\dot{\phi})]\begin{Bmatrix}\dot{\theta}\\ \dot{\phi}\end{Bmatrix}+[K(\theta,\phi)]\begin{Bmatrix}\theta\\ \phi\end{Bmatrix}=\begin{Bmatrix}M_{ankle}\\ M_{board}\end{Bmatrix} \qquad (1)$$

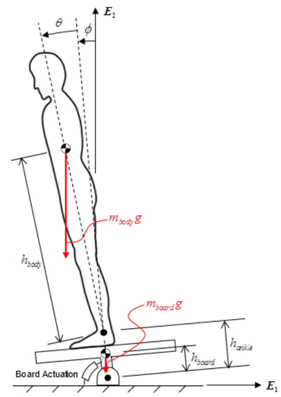

Figure 1: Diagram of a person on the balance board showing all external forces

A bifurcation analysis was completed by observing the variable space of equilibrium positions (θ^*, ϕ^*) in the parameter space of τ, K_{board}, $K_{\tau,board}$, and τ_{board} with all other parameters held constant. All values shown are ratios of $K^{cr} = m_{body} g h_{body}$. Equilibrium position and their stability were calculated using DDE-BIFTOOL MATLAB package and verified through 45 second time series realizations using the MATLAB (The MathWorks, Inc.) function dde23 [3].

A balance board with controllable stiffness and feedback time-delay was fabricated (Figure 2). For the initial testing, thirteen college-aged students (19.9 ± 1.7 yrs.; 65.4 ± 10.1 kg; 171.8 ± 9.1 cm) with no known balance issues participated in the study. The experimental procedure was approved by the local Institutional Review Board.

Participants stood with feet shoulder-width apart and ankles in line with the board’s axis-of-rotation. The goal was to stay upright on the board and keep the board horizontal for each trial. Each participant performed 24 trials that were 45 seconds long, with a 60 second break between each.

Figure 2: a) Active balance board with safety platform, b) primary mechanism of balance board, c) person standing in position on balance board.

RESULTS AND DISCUSSION

Simulations of the model led to a stability plot (Figure 3). The vertical axis represents the board feedback time-delay, and the horizontal axis represents the active board stiffness, normalized by an individual's mass and the height of the center of mass. This plot shows the parameter combinations which lead to upright stability (grey), as well as the two types of instabilities. The blue line denotes a supercritical pitchfork bifurcation, which occurs when the stiffness is not large enough to maintain upright stance, leading to tipping forward or backward. The red line identifies a supercritical Hopf bifurcation which presents itself via LCOs of the person on the board.

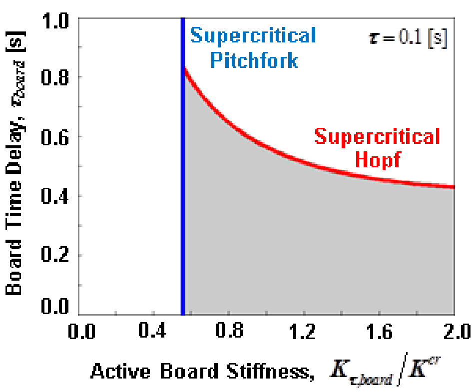

Figure 3: Stability plot showing stable (grey) and unstable (white) regions of upright stance on a 1-DOF balance board.

From human experiments, we identified the tipping point as well as the point when LCOs began for each participant, and then averaged the results to create a stability plot (Figure 4).

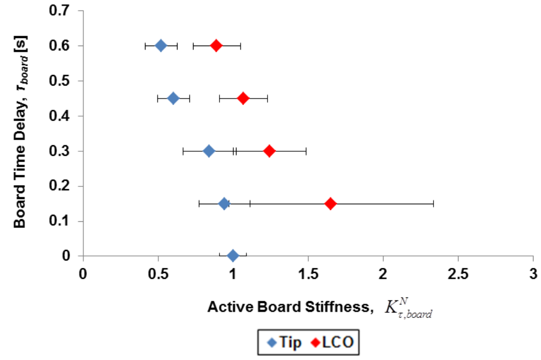

Figure 4: Average stability plot for all participants. The blue dots represent the tipping instability, and the red dots show the point at which limit cycle oscillations occur. The error bars represent the 95% confidence intervals for each of the points.

CONCLUSIONS

We developed an active balance board capable of identifying two distinct mechanisms of postural instability previously predicted with theoretical modeling and simulations. We expect that this active balance board will allow for the early identification of increased fall-risk populations. In addition, having multiple variable parameters potentially allows for the creation of individualized balance training plans which will improve training efficacy.

REFERENCES

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