Support for the Existence of Open-loop and Closed-loop Regions in Balance Control

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Summary

In this paper, we give evidence to support the claim that there are two regions in balance control characterized by open-loop and closed-loop behavior. Subjects were equipped with a skin-stretch feedback device (SSD) at the fingertip to provide sensory augmentation [1]. It was found that skin-stretch feedback based on sway angular velocity improved postural stability with respect to several parameters, including a significant decrease in $z_{\lambda_2,AP}$ and a tendency ($p = 0.07$) of $z_{\lambda_2,Rad}$ to decrease, which corresponded to a smaller open-loop region. Thus, it would seem that $z_{\lambda_2,AP}$ could potentially be used to decompose the state-space into the open-loop $\{x|x \leq z_{\lambda_2}\}$ and closed-loop $\{x|x > z_{\lambda_2}\}$ regions.

Introduction

The underlying mechanisms of human standing balance are not well understood. In order to assess the progress of patients undergoing balance rehabilitation, it becomes necessary to quantify balance. To this end, researchers have introduced various techniques and parameters to characterize postural sway from the perspectives of statistical mechanics, controls, and more recently, a unifying theory called the free-energy principle [2]. This work uses two of these techniques and the results of a balance rehabilitation experiment, which involves the SSD at the fingertip and an entropy minimizing controller, in order to strengthen the claim that the open-loop and closed-loop regions exist.

Methods

Subjects (3 female, 12 male, mean age: 25.6 ± 3.33) were equipped with the SSD and a belt with an IMU to track body angular velocity. Center of pressure (COP) data was collected for AP, ML, and radial directions using a force plate. Based on the free-energy principle, balance is regulated by minimizing the entropy of postural sway sampled from the postural sway probability density. Invariant Density Analysis (IDA) was used to calculate this probability density and quantify balance [3]. Stabilogram Diffusion Analysis (SDA) was used to validate the results of IDA [4].

SDA examines how the COP diffuses over time during standing balance. It was found that the postural control system could be divided into two major regions: a short-term region closer to the equilibrium, in which the COP is allowed to drift away from the equilibrium, and a long-term region outside of the previous region, in which the COP is forced toward the equilibrium. Collins and De Luca claimed that these two regions involved open-loop and closed-loop dynamics, respectively [4].

IDA introduces a reduced-order finite Markov chain model to analyze the stochastic structure of postural sway and thereby provide insight into the long-term behavior of the system. This Markov chain model defines the states of the system by partitioning the zero-mean COP data using concentric circles and describes the evolution of the states using a transition matrix P. It was found that the COP distribution converges to a unique steady-state distribution π, called an invariant density [3]. The eigenvector λ_2 corresponding to the second largest eigenvalue of P, henceforth known as the second eigenvector, is of interest in this work. The zero crossing z_{λ_2} of the second eigenvector has been shown to yield information regarding the dynamics of a finite state-space ergodic Markov chain by decomposing the state-space into two almost invariant sets [5].

Results and Discussion

Subjects using the SSD had improved balance with respect to several parameters from IDA and SDA. Most importantly, they had a significantly earlier zero crossing z_{λ_2} in the AP direction (Figure 1) and a significantly smaller open-loop region (Figure 2) in the AP direction.

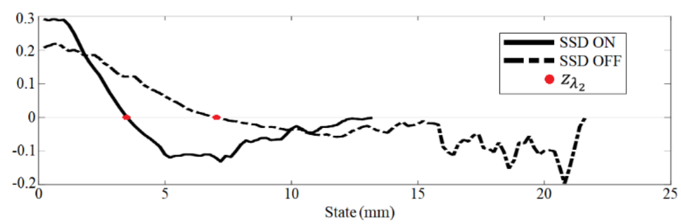

Figure 1: Second eigenvector for AP direction.

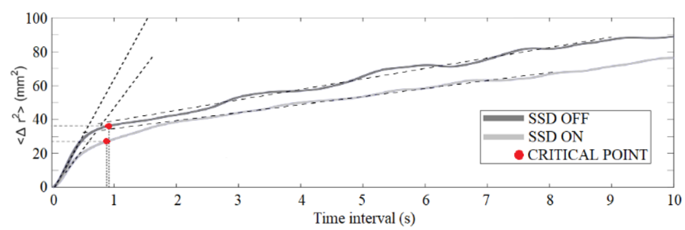

Figure 2: Linear Stabilogram Diffusion plot for AP direction.

This suggests that the zero crossing may correspond to the state-space location of the boundary between the two almost invariant open-loop and closed-loop regions.

Conclusions

This work supports the claim that there are two regions in balance control characterized by open-loop and closed-loop behaviour. Future simulation-based research will investigate hitting time and the existence of the critical point.

References

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