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

MECHANICAL ENGINEERING
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RESEARCH SUMMARY

- We give evidence to support the claim that there are two regions in balance control characterized by open-loop and closed-loop behavior.
- Skin-stretch feedback based on postural sway 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.
- $z_{\lambda_2,AP}$ 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

Previous studies:

- The underlying mechanisms of human standing balance are not well understood.
- 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 [1].

This study:

- This work uses two of these techniques (Stabilogram Diffusion Analysis and Invariant Density Analysis) and the results of a balance rehabilitation experiment, which involves a skin-stretch feedback device (SSD) at the fingertip and an entropy minimizing controller, in order to strengthen the claim that two regions, characterized by open and closed-loop behavior, exist.

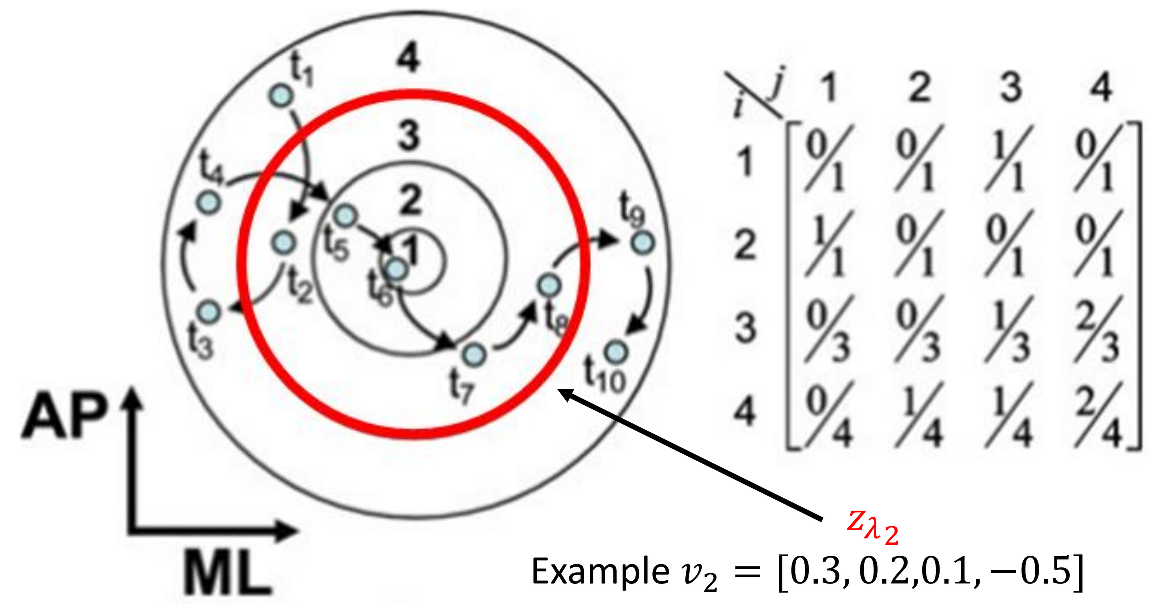
BACKGROUND

Stabilogram Diffusion Analysis (SDA) [2]

- SDA models the COP as a particle which diffuses over time during standing balance.
- Previous research found that the postural control system could be divided, by a critical point, into two major regions in time [2]:
  - Short-term: persistent behavior
  - Long-term: anti-persistent behavior
- They claimed that these two regions involved open-loop and closed-loop dynamics, respectively.

Invariant Density Analysis (IDA) [3]

- 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 shown 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, as 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 [4].

METHODS

Experimental Information

- 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 sway 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) is used to calculate this probability density and quantify balance. Stabilogram Diffusion Analysis (SDA) is used to validate the results of IDA.
- The device and setup are given in Figure 1 [5].

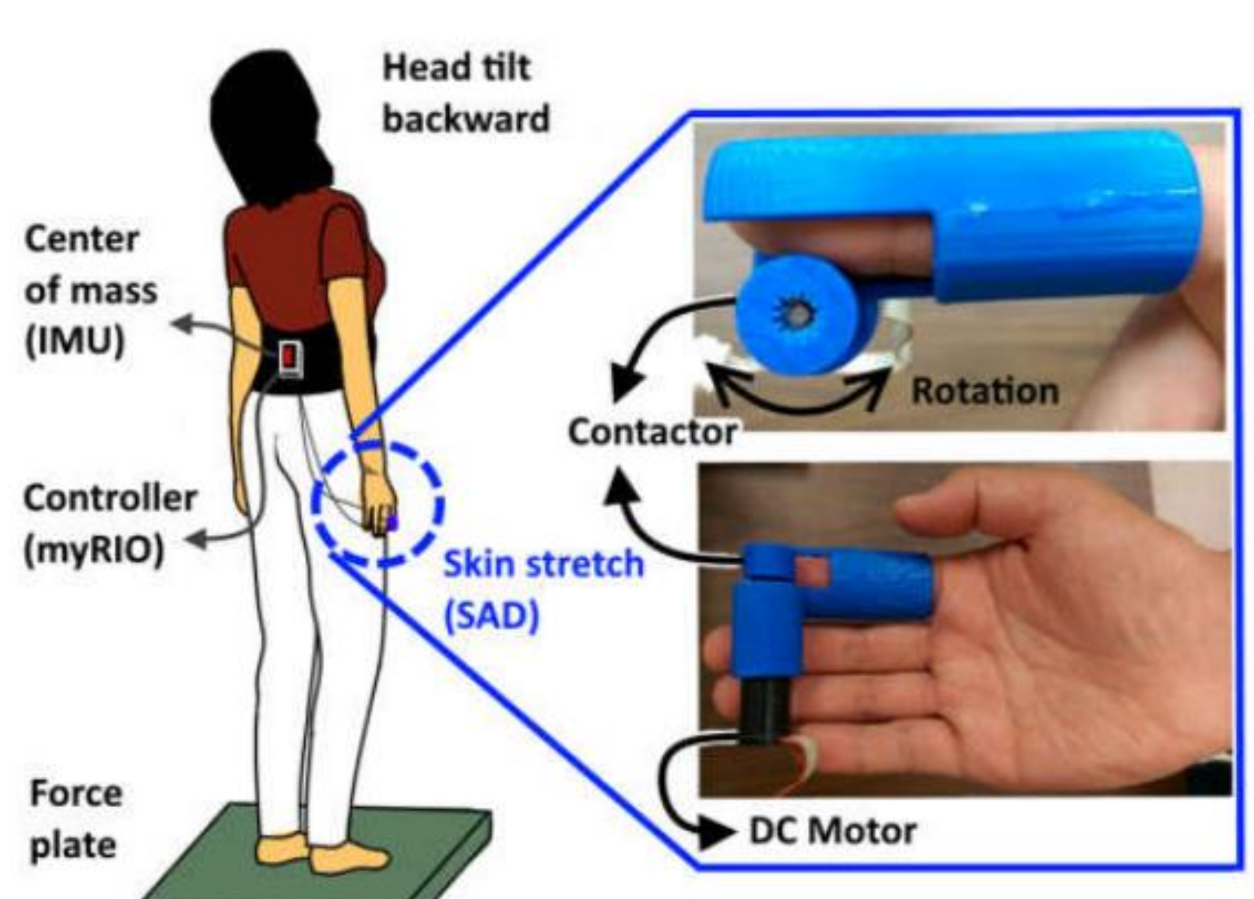


Figure 1: Experimental setup and SSD

RESULTS AND DISCUSSIONS

Results

- Subjects using the SSD had improved balance with respect to several parameters from IDA and SDA.
- Specifically, they had a significantly earlier zero crossing z_{λ_2} in the AP direction and significantly smaller open-loop region in the radial direction.
- Sample plots for the second eigenvector and for the Stabilogram diffusion plot are given in Figures 1 and 2, both for the AP direction.

Table 1: Zero crossing with respect to SSD condition

IDA	SSD OFF	SSD ON	p value
$z_{\lambda_2,AP}$ (mm)	6.63 (2.99)	5.84 (2.91)	**0.02**
$z_{\lambda_2,Rad}$ (mm)	7.84 (3.26)	6.95 (2.96)	0.07

Table 2: Open-loop region with respect to SSD condition

SDA	SSD OFF	SSD ON	p value
$\langle \Delta r^2 \rangle_{c,AP}$ (mm^2)	42.96 (45.40)	36.04 (33.54)	0.08
$\langle \Delta r^2 \rangle_{c,Rad}$ (mm^2)	55.69 (49.03)	46.58 (37.65)	**0.03**

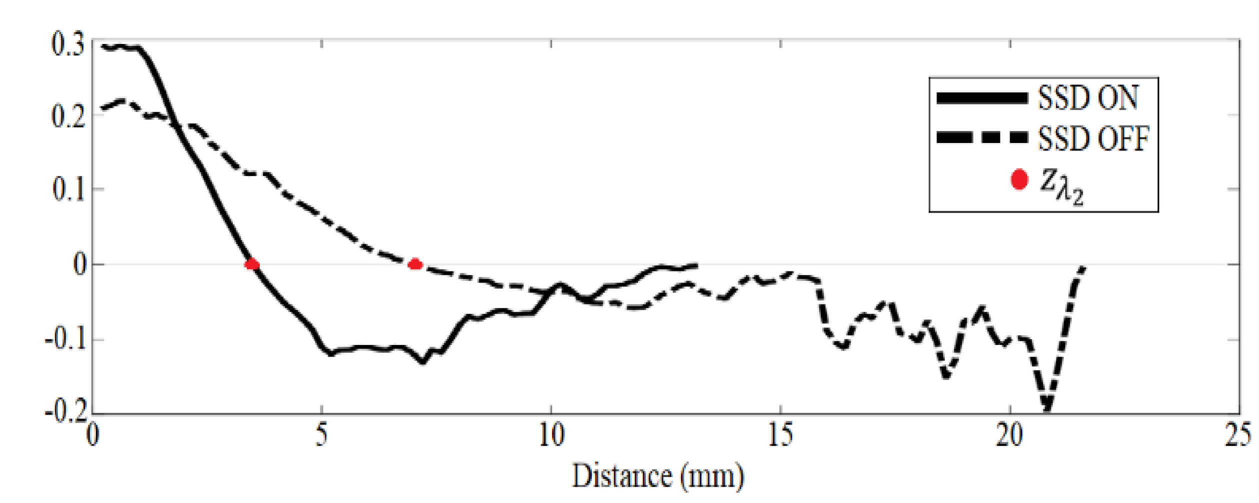


Figure 2: An example plot of second eigenvector for AP direction.

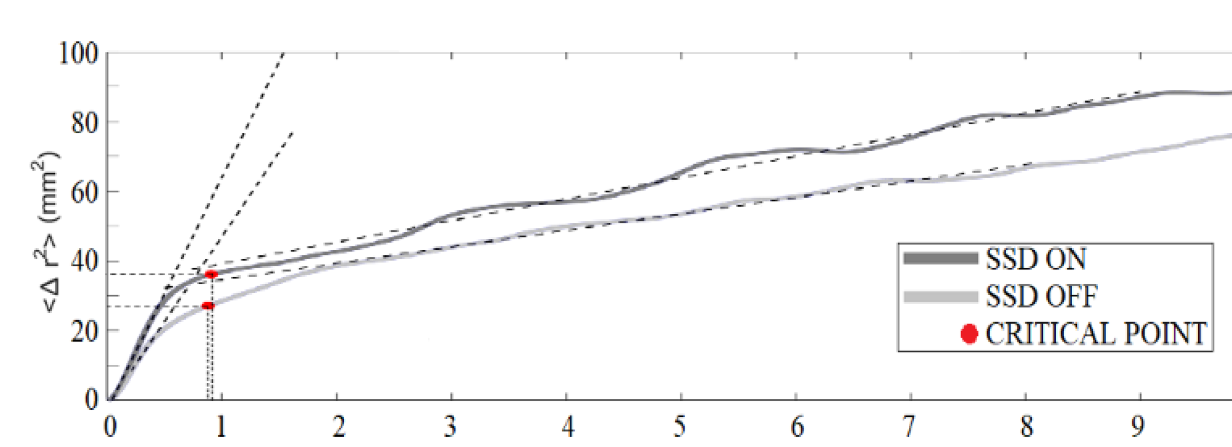


Figure 3: An example of linear Stabilogram diffusion plot for AP direction.

Discussion

- This simultaneous reduction in the zero crossing of the second eigenvector and in the radius of the supposed open-loop region supports 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 behavior.
- Future simulation-based research will investigate hitting time and the existence of the critical point.

References

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