Age-Related Differences in Local Dynamic Stability During Step-Aerobic Training: A Nonlinear Analysis Using Lyapunov Exponent

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Summary

LyE and state-space analysis revealed age-related differences in local dynamic stability (LDS) during step-aerobic training (SAT). Young participants initially lost stability but later recovered, while middle-aged individuals showed increasing instability, particularly in the AP and ML directions. In the VT direction, young participants stabilized, whereas middle-aged individuals remained chaotic. Determinism analysis indicated young individuals shifted to a dissipative system, while middle-aged participants retained chaotic behavior. However, the lack of statistical significance in LyE suggests it may not be a standalone trainability measure, requiring further investigation.

Introduction

Time series analysis of human movement provides objective data for assessing exercise interventions[1]. Motor variability reflects adaptability and influences local dynamic stability (LDS)[2]. Step-aerobic training (SAT) enhances balance and mobility, but its impact on acceleration variability and LDS remains unexplored. While previous studies focus on gait stability, this study investigates the nonlinear structure of motor variability in SAT, its effects on LDS across age groups, and state-space reconstruction. Using Lyapunov exponent (LyE), the study evaluates motor behavior determinism and recovery from perturbations, addressing gaps in SAT kinematic analysis.

Methods

Lyapunov exponent (LyE) was used to assess local dynamic stability (LDS) and determine the deterministic nature of motor variability during step-aerobic training (SAT). Twelve young (26.5±4.1 years, BMI: 20.3±2.8 kg/m²) and eleven middle-aged (53.38 years, BMI: 24.45 kg/m²) participants completed an 8-week SAT program.

An IMU (100 Hz) mounted on the sacrum recorded acceleration. LyE was computed via state-space reconstruction, with embedding dimension and time delay determined using FNN and AMI. Pseudo-Periodic Surrogation (PPS) analysis validated motor behavior determinism.

Results and Discussion

LyE and state-space reconstruction revealed age-related differences in local dynamic stability (LDS) during step-aerobic training (SAT). Young participants initially lost stability in the AP direction but recovered by session 24, while middle-aged individuals showed increasing instability, especially in the AP and ML directions. In the VT direction, young participants stabilized, whereas middle-aged individuals remained chaotic (Table 1). Determinism analysis showed young individuals transitioned from chaotic to dissipative systems, while middle-aged participants maintained chaotic behavior. However, the lack of statistical significance in LyE ($p>0.05$) suggests it may not be a standalone indicator of LDS transitions, warranting further investigation.

Conclusions

Step-aerobic training (SAT) improves local dynamic stability (LDS) in young individuals, while middle-aged participants exhibit increasing instability. Determinism analysis highlights age-related differences in motor control adaptation. However, LyE alone lacks statistical significance, necessitating further research to identify complementary stability measures.

References

1. Montull, L., et al., *Assessing proprioception through time-variability properties of acceleration.* Frontiers in Physiology, 2023. **14**: p. 1112902.
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Table 1: the LyE measures in the anatomical axes (AP, ML, and VT) and the probability of the deterministic system presence in each session.

	AP Acc				ML Acc				VT Acc			
	LyE		Prob. Of Determinism		LyE		Prob of Determinism		LyE		Prob. Of Determinism	
	Young	Middle-aged	Young	Middle-aged	Young	Middle-aged	Young	Middle-aged	Young	Middle-aged	Young	Middle-aged
Session 1	-2.88	-2.33	54%	33%	2.98	2.80	42%	41%	2.50	3.92	48%	41%
Session 12	0.69	1.94	35%	50%	-6.21	1.21	55%	56%	2.47	1.26	45%	31%
Session 24	-4.82	13.31	47%	33%	-3.95	5.54	62%	25%	-1.30	2.93	72%	67%