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Dynamic structure of variability in joint angles and center of mass position during user-driven treadmill walking

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ABSTRACT

Background: Overground locomotion exhibits greater movement variability and less dynamic stability compared to typical fixed-speed treadmill walking. To minimize the differences between treadmill and overground locomotion, researchers are developing user-driven treadmill systems that adjust the speed of the treadmill belts in real-time based on how fast the subject is trying to walk.

Research question: Does dynamic structure of variability, quantified by the Lyapunov exponent (LyE), of joint angles and center of mass (COM) position differ between a fixed-speed treadmill (FTM) and user-driven treadmill (UTM) for healthy subjects?

Methods: Eleven healthy, adult subjects walked on a user-driven treadmill that updated its speed in real-time based on the subjects' propulsive forces, location, step length, and step time, and at a matched speed on a typical, fixed-speed treadmill for 1-minute. The LyE for flexion/extension joint angles and center of mass position were calculated.

Results: Subjects exhibited higher LyE values of joint angles on the UTM compared to the FTM indicating that walking on the UTM may be more similar to overground locomotion. No change in COM LyE was observed between treadmill conditions indicating that subjects' balance was not significantly altered by this new training paradigm.

Significance: The user-driven treadmill may be a more valuable rehabilitation tool for improving gait than fixed-speed treadmill training, as it may increase the effectiveness of transitioning learned behaviors to overground compared to fixed-speed treadmills.

1. Introduction

Treadmills are a regularly used rehabilitation tool because they allow for a controlled environment where kinematic and kinetic data can be more easily collected [5]. Theoretically, the motor training learned on the treadmill would be applicable to improving overground locomotion. However, treadmills at fixed speed do not perfectly simulate an individual's overground locomotor patterns and have limited transfer of learned treadmill behaviors to overground [6]. Differences in kinematic and spatiotemporal parameters have been observed between treadmill and overground walking [7,8]. Additionally, overground locomotion exhibits greater movement variability and lesser local dynamic stability of triaxial accelerations and kinematics than typical treadmill walking [8,9].

Dynamic structure of variability, in the context of this study, refers to stride-to-stride differences in joint angle and center of mass (COM) position trajectories [10]. Dynamic structure of variability is characterized by the stability of an attractor rather than mechanical stability. However, high variability has been correlated with decreased motor control [11], while some variability is necessary and inherent in healthy locomotion, allowing for adaptability to everyday perturbations [11]. One way to quantify dynamic variability in clinical populations is the Lyapunov Exponent (LyE) [12], which quantifies how a trajectory diverges in a specific dimension of phase space. Greater LyE reflects faster divergence and greater dynamic instability.

To minimize the differences between treadmill and overground locomotion, researchers are developing user-driven treadmill systems that adjust the treadmill belts' speed in real-time based on how fast the subject is trying to walk [13]. We have designed a novel treadmill controller that combines force, position, and spatiotemporal

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Table 1
Subject characteristics.

Subject	Age (years)	Gender	Height (m)	Weight (lbs.)	Avg. SS speed (m/s)	Avg. fast speed (m/s)
1	20	M	1.77	159	1.10	1.60
2	22	F	1.60	154	1.10	1.25
3	32	F	1.75	134	1.28	1.35
4	20	F	1.52	99	0.86	1.60
5	22	F	1.68	146	1.85	2.20
6	22	F	1.57	141	1.50	1.90
7	24	M	1.83	188	1.46	1.93
8	34	F	1.80	166	1.32	2.02
9	21	M	1.78	156	1.43	1.87
10	20	F	1.57	118	1.27	1.47
11	20	F	1.68	145	1.30	1.68

parameters.

The objective of this study was to determine how healthy subjects' dynamic structure of variability, quantified by the LyE, of joint angles and COM position changed on a fixed-speed treadmill (FTM) and user-driven treadmill (UTM). We hypothesized the UTM would exhibit larger LyE values than the FTM.

2. Methods

2.1. Participants

Eleven healthy adults (age 23.4 ± 4.9 years, 3 males) with no history of musculoskeletal disorders were recruited (Table 1). All individuals completed a physical activity readiness questionnaire and were excluded if negative responses were provided. All participants signed an informed consent approved by the University of Delaware Institutional Review Board.

2.2. Procedures

Twenty-five single reflective markers, 19 markers on shells, and an 8-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) were used while recording kinematic and kinetic data (100 Hz and 2000 Hz, respectively). All subjects walked on an instrumented split-belt treadmill (Bertec Corp., Columbus, OH) in fixed-speed and user-driven modes. The UTM control system used is unique because it updates the treadmill belts' speed in real-time based on propulsive forces, location on the treadmill, step length, and step time [16]. The speed of the treadmill belts on the UTM was tied such that, at any time, the speed of the left belt was equal to the right belt. Subjects were instructed to walk at their self-selected (SS) and fastest comfortable (fast) walking speeds for 1 min. After completing UTM trials, subjects walked at the average walking speed on the FTM to control for speed. The change in UTM speed was limited to a maximum acceleration of 0.2 m/s^2.

2.3. Analysis

Continuous hip, knee, and ankle flexion/extension angles and COM position were determined using Visual3D. Kinematic data were filtered at 60 Hz. The continuous trials were run through a custom MATLAB code utilizing the Wolf algorithm [17] to calculate the maximum LyE [18]. The time delay (τ) and embedding dimensions (m) were determined for each subject and trial. The time delay was selected by shifting the time series to find the first local minima of average mutual information. The embedding dimension was the dimension where the percentage of false nearest neighbors was less than 1%. The time delays and embedding dimensions used ranged between 3–50 ms and 4–10, respectively (Median values: Hip $\tau = 17$, m = 5; Knee $\tau = 11$, m = 6; Ankle $\tau = 6$, m = 10; COM $\tau = 20$, m = 5). In the context of gait analysis, the LyE quantifies the within-cycle and between-cycle fluctuations (Fig. 1). The Wolf algorithm was selected because of its sensitivity to smaller data sets [19]. It has been successfully demonstrated that a 1-minute trial is sufficient for accurate calculation of the LyE [19].

Separate 2 × 2 (speed by treadmill condition) repeated measures ANOVAs were run to determine the effect of walking speed and treadmill condition. Tukey's post-hoc analysis was run to determine the

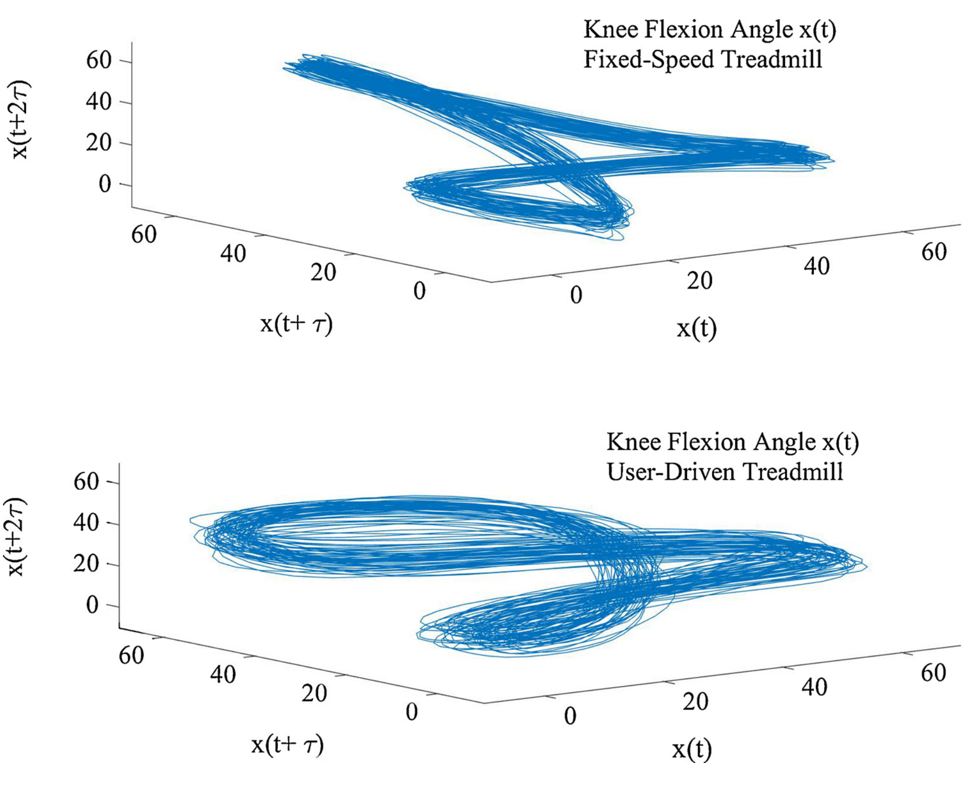

Fig. 1. Reconstructed attractors for (A) fixed-speed treadmill (FTM) and (B) user-driven treadmill (UTM) knee flexion/extension angle, x (t), of subject 2 at SS speed, shown in three dimensions for visualization purposes. The attractor shown is reconstructed in multiple dimensions using the measured knee flexion angle and time delayed copies of itself. Greater disorganization, as seen on the UTM, is indicative of greater divergence and greater positive LyE.

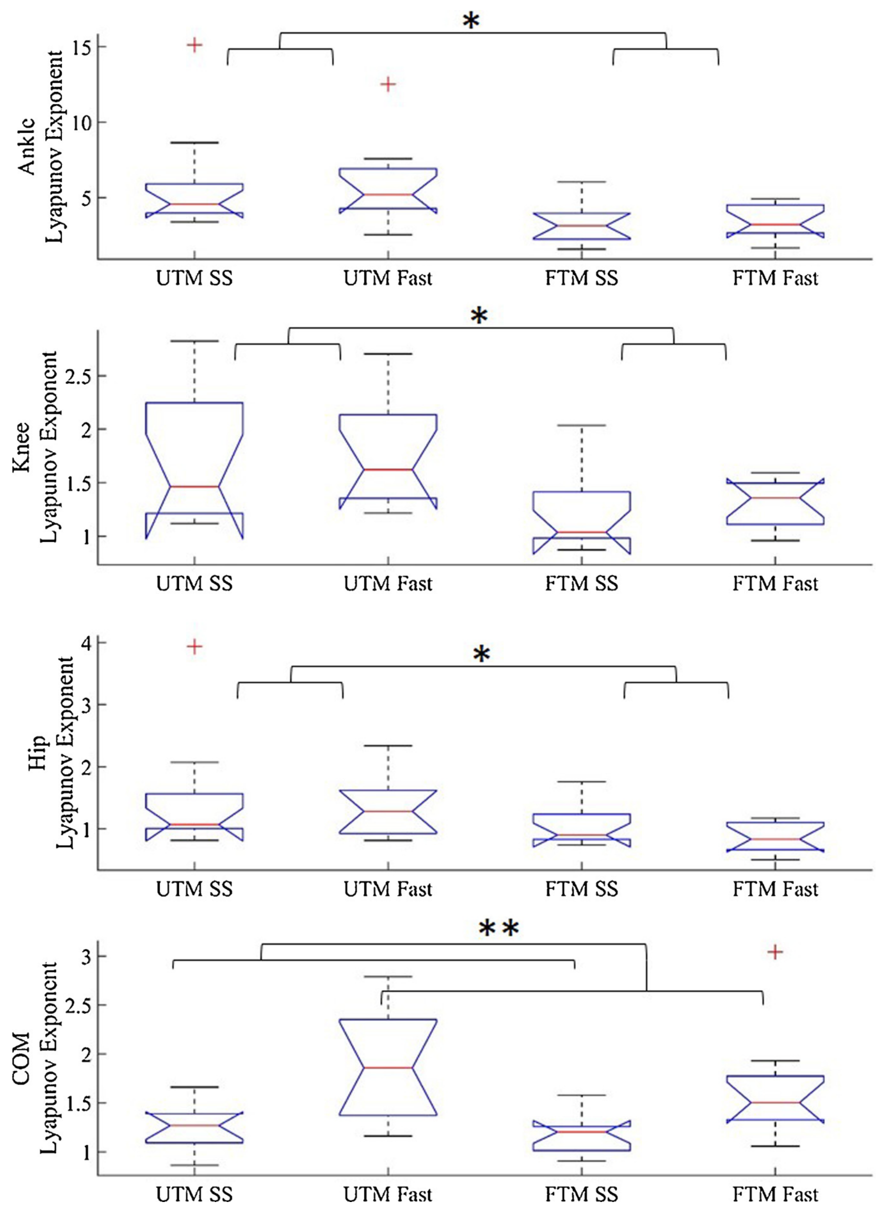

Fig. 2. Boxplot displaying LyE values for ankle, knee, and hip sagittal plane angles. * indicates significant difference between treadmill control ($p < 0.05$). ** indicates significant difference between speeds ($p < 0.05$).

interaction between speed and treadmill condition. Cohen's d effect size was calculated for pairwise comparisons to determine the strength of the differences observed, with $d > 0.8$ defining a large effect size.

3. Results

The LyE was larger on the UTM compared to the FTM for ankle ($p < 0.01$, $\eta^2 = 0.55$, 88% power), knee ($p < 0.01$, $\eta^2 = 0.61$, 95% power), and hip ($p = 0.01$, $\eta^2 = 0.50$, 81% power) angles (Fig. 2). There was no difference in LyE between FTM and UTM for COM ($p > 0.05$, $d = 0.23$). A main effect of speed was observed for the COM, with fast speed showing a greater LyE across treadmill types ($p = 0.001$, $\eta^2 = 0.71$, 99% power). No interaction effects were observed for the four tested variables.

4. Discussion

In healthy adults, we observed increased LyE on the UTM compared to FTM, complementing previous work and suggesting the UTM may be more similar to overground gait. Greater LyE is indicative of faster divergence and greater dynamic instability. The increased LyE of joint angles observed on the UTM compared to FTM suggests the UTM may be more comparable to overground walking. Since speed was controlled, the change in LyE can be attributed to the change in treadmill condition. The lack of change in COM LyE between treadmill conditions suggests systems were not becoming unstable and subjects' balance was not significantly altered when placed on this new training paradigm.

The UTM enables natural within-cycle and between-cycle fluctuations without penalty, which may enable greater dynamic structure of variability in lower extremity joint angles. A decrease in hip, knee, and ankle joint angle LyE and mediolateral, vertical, and anteroposterior accelerations on the FTM may indicate fixed-speed treadmills do not allow for the within-cycle and between-cycle fluctuations that typically occur during everyday locomotion.

This study has several limitations. First, this study has a small sample size and a longer trial length may allow for a more complete description of the dynamic variability; however, because of the achieved power, we believe the smaller population and shorter trial length sufficiently demonstrated differences between the UTM and FTM. Similar studies assessing dynamic variability used comparable sample sizes [5,17]. Due to differences in individual calculation methods of the LyE, between-study comparisons cannot be made, although trends are similar across studies. While an order effect may be possible, because the FTM trials always followed UTM trials, any fatigue would likely increase the LyE of the FTM trials, which we did not see. Finally, an overground analysis was unable to be performed to directly test the hypothesis that the UTM is more similar to overground walking. The lack of overground comparison was due to LyE needing a long, continuous trajectory as performed by Dingwell et al. (2001).

The UTM may be a more effective rehabilitation tool for improving gait than FTM, as it enables more natural gait mechanics and may improve transfer of skills from the treadmill to overground gait for impaired populations that experience asymmetries in dynamic structure of variability such as individuals post-stroke and post-ACL injury [18,20].

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