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Temporal structure of variability reveals similar control mechanisms during lateral stepping and forward walking

Shane R. Wurdeman [a,b], Nicholas Stergiou [a,b,*]

[a] Nebraska Biomechanics Core Facility, University of Nebraska at Omaha, Omaha, NE, USA
[b] College of Public Health, University of Nebraska Medical Center, Omaha, NE, USA

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ABSTRACT

Previous research exploring a lateral stepping gait utilized amount of variability (i.e. coefficient of variation) in the medial-lateral (ML) and anterior-posterior (AP) direction to propose that the central nervous system's active control over gait in any direction is dependent on the direction of progression. This study sought to further explore this notion through the study of the temporal structure of variability which is reflective of the neuromuscular system's organization of the movement over time. The largest Lyapunov exponent (LyE) of the reconstructed attractors for the foot's movement in the AP and ML was calculated. Results revealed that despite the obvious mechanical differences between a lateral stepping gait and typical forward walking, the central nervous system's organization of the movement of the feet is similar in the primary planes of progression, as well as the secondary planes of progression, despite being different anatomical planes during the locomotive tasks. In addition, consistent with previous studies exploring amount of variability, the secondary plane for both locomotive tasks proved to have larger LyE values than the primary plane of progression ($F_{1,9} = 35.086$, $p < 0.001$). This is consistent with less dependency from stride-to-stride in the secondary plane implying increased active control.

1. Introduction

Previous studies that demonstrated increased variability in the medial-lateral (ML) direction compared to the anterior-posterior (AP) direction during walking has led human movement scientists to believe that the ML direction is under greater active control while the AP direction is more influenced by passive mechanisms [1–3]. It is possible that the AP and ML directional control are inherently organized according to fixed anatomical planes[1]. However, it may also be that the amount of active control is an effect of the passive mechanics present during walking.

The role of passive mechanics in upright stabilization during walking cannot be questioned. Kuo [4] demonstrated through a passive walking model the impact of passive mechanics to keep the model from falling over in the AP direction. In experimental work, Donelan et al. [2] utilized elastic bands to add increased ML force at the waist. The result was decreased variability in the ML direction. Their interpretation was that the addition of a stabilizing force increased the amount of passive control in the ML direction which would otherwise require more active control for upright stabilization. Dean et al. [5] extended this work by applying the lateral stabilizing force to the elderly and similarly found a reduced amount of variability. Such results in the elderly are significant as they are speculated to have impaired active control due to aging which results in an increased amount of variability in the ML direction [6].

Recent experimental research investigating a lateral stepping gait suggests that the mechanics of motion act to offload the amount of active control present in any direction during gait [7]. Specifically, subjects performing a lateral stepping gait, where the ML direction is the direction of progression instead of the AP, experienced a reversal of what is found in typical forward walking; the AP direction had a greater amount of variability than the ML. These results persisted in light of the limitation of the novelty of the lateral stepping gait.

Such findings may have strong rehabilitation implications. The amount of variability in the ML direction during typical forward walking has been strongly linked with fall risk and incidence [6,8,9]. Thus, step variability in the ML direction has logically been a primary target for decreased fall risk. However, if active control is dependent on the direction of progression and not linked to anatomical planes, then it may be possible to improve the amount of step variability by targeting the plane of motion least benefiting from the mechanics of motion. This would be the ML direction during typical forward walking, but is actually the AP direction during the lateral stepping gait.

* Corresponding author at: Nebraska Biomechanics Core Facility, University of Nebraska at Omaha, Omaha, NE 68182-0216, USA. Tel.: +1 402 554 3247.
E-mail address: nstergiou@unomaha.edu (N. Stergiou).

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However, the results from the Wurdeman et al. [7] study may have been influenced by the usage of a treadmill. A treadmill has a moving belt that provides a constrained area where movement is safely tolerated. The amount of variability in any direction is limited by the physical dimensions. For example, consider during the lateral stepping gait if an imaginary line was present running the length of the treadmill labeled the zero point (Fig. 1). Then in the AP direction (aligned with the width of the treadmill during lateral stepping gait) the constraints of the movement would be one arbitrary unit to each side. One arbitrary unit is equal to half the width of the treadmill belt. Then the maximum possible amount of variability (i.e. standard deviation) after nine steps would be approximately equal to one arbitrary unit. Other measures of the amount of variability such as coefficient of variation would exhibit similar boundary restrictions having certain maximum possible values. However, the potential for variations to the structure of variability is nearly limitless. The structure of variability pertains to the time ordered variance within the movement. So, if the nine steps in our example landed on positions -1, 0, and 1 each of three separate times, the standard deviation would be less than 1 regardless the order that the step positions occurred; however, there are 216 different variations with which the order of those nine steps could occur.

Therefore, the investigation of the temporal structure of variability in the AP and ML directions during typical forward walking and lateral stepping gait could provide additional insights into the active control organization of gait by overcoming the boundaries of the amount of space available during stepping on a treadmill. In particular, if the active control of movement is related to the direction of progression [7], then it could be expected that the temporal structure of variability for the movement pattern that emerges in the primary plane of progression during typical forward walking (i.e. AP) and the primary plane of progression during lateral stepping gait (i.e. ML) would be similar. Furthermore, the secondary plane of progression during these modes of locomotion would also be similar. However, as observed in the amount of variability analysis [7], we would expect the temporal structure of variability to be different between the two planes (AP and ML), reflective of different active control strategies. The temporal structure of variability can be analyzed through the largest Lyapunov exponent (LyE). The LyE measures the amount of divergence within the reconstructed state space of a time series [10]. We expect increased LyE values (greater divergence within the movement pattern) for the secondary plane of progression as the active control processes must continuously search for the best movement within the confines of the task.

Table 1
Subject Demographics.

Gender	6 M, 4 F
Age (years)	24.80 ± 4.39
Lateral Stepping Preferred Speed (m/s)	0.344 ± 0.037
Forward Walking Preferred Speed (m/s)	1.104 ± 0.197
Height (cm)	175.32 ± 11.10
Mass (kg)	73.39 ± 17.11

2. Methods

2.1. Subjects

Ten healthy young subjects (Table 1) were recruited to participate. All subjects gave written informed consent in accordance with the Medical Center's Investigational Review Board. All subjects were required to have capacity to provide consent and were currently exercising 2–3 times a week. Subjects were excluded based on inability to provide consent, pregnancy, or presence of any neurological, vestibular, or musculoskeletal conditions that may affect gait.

2.2. Study Protocol

Subjects came to the motion analysis laboratory to perform a lateral stepping gait. Subjects wore their own standard athletic shoes. Retroreflective markers were affixed to the posterior heel and second metatarsophalangeal joint on both subject's feet. Subjects performed a lateral stepping gait on a standard treadmill (Bodyguard Fitness, St. Georges, QC, Canada) at their preferred speed. An eight-camera motion capture system (EvaRT, Motion Analysis Corp., Santa Rosa, CA, USA) sampling at 60 Hz. The sampling frequency was determined a priori through power spectral analysis, which showed 99% of the signal to exist under 6 Hz. Thus, 60 Hz satisfied the minimum determined by Nyquist frequency, and at a magnitude of 10 times the maximum frequency of 6 Hz would be able to capture any spurious movement up to 30 Hz. Subjects faced to their left such that their left leg was in the lag leg position. Subjects were instructed to keep their head up while stepping, to not cross their feet, and at no point to have both feet off the ground (i.e. no aerial phase).

Preferred speed was determined by incrementally increasing the treadmill speed at 0.045 m/s until the individual communicated that the comfortable preferred speed was reached. At that point, the speed was increased another increment to confirm that the speed was at that point too fast. Upon confirmation, the

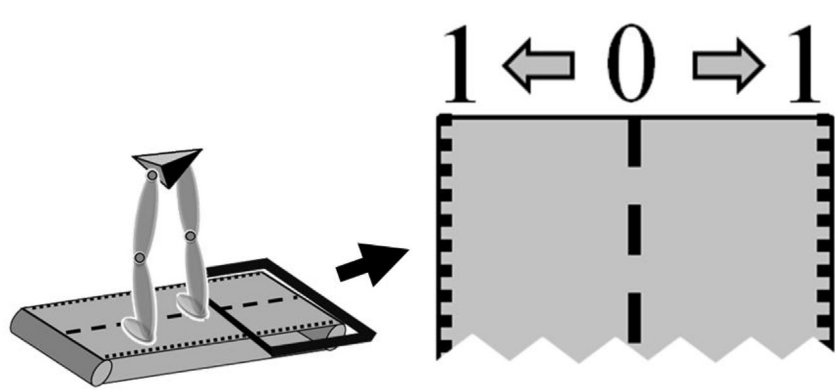

Fig. 1. The physical constraints of the treadmill may be limiting the amount of variability. If the middle of the belt were the "0" point, and then either direction to the side was a maximum of 1 arbitrary unit, then the maximum standard deviation in that direction could only be approximately 1 arbitrary unit. However, the temporal structure of variability has nearly limitless variations that the order of steps could occur.