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Leveraging a virtual alley with continuously varying width modulates step width variability during self-paced treadmill walking

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ABSTRACT

Increased fall risk in older adults and clinical populations is linked with increased amount and altered temporal structure of step width variability. One approach to rehabilitation seeks to reduce fall risk in older adults by reducing the amount of step width variability and restoring the temporal structure characteristic of healthy young adults. The success of such a program depends on our ability to modulate step width variability effectively. To this end, we investigated how manipulation of the visual walking space in a virtual environment could modulate the amount and temporal structure of step width variability. Nine healthy adults performed self-paced treadmill walking in a virtual alley in a fixed-width Control condition (1.91 m) and two conditions in which the alley's width oscillated sinusoidally at 0.03 Hz: between 0.38 and 1.14 m and 0.38–2.67 m in Narrow and Wide conditions, respectively. The step width time series from each condition was evaluated using: (i) the standard deviation to identify changes in the amount of variability and (ii) the fractal scaling exponent estimated using detrended fluctuation analysis (DFA) to identify changes in the temporal structure of variability in terms of persistence in fluctuations. The Wide condition neither affected the standard deviation nor the fractal scaling exponent of step width time series. The Narrow condition did not affect the standard deviation of step width time series compared to the Control condition but significantly increased its fractal scaling exponent compared to the Control and Wide conditions, suggestive of more persistent fluctuations characteristic of a healthy gait. These results show that virtual reality based rehabilitative intervention can modulate step width variability to potentially reduce fall risk in older adults and clinical populations.

1. Introduction

Increased step width variability in older adults strongly predicts fall risk factors and incidence [1–10]. One way to reduce fall risk in older adults might be to restore patterns of step width variability characteristic of healthy young adults, that is, by reducing the amount of step width variability and increasing the persistence of fluctuations in step width. Step width, or the lateral stepping part of walking, requires active control, whereas step length, or the forward stepping part, is passively stabilized through the mechanics of motion. The active control of mediolateral foot placement is the most critical factor affecting step width variability during walking. For instance, externally assisted lateral stabilization during walking enhances mediolateral foot placement, reducing step width and step width variability [11,12]. The disruption of the active control of mediolateral foot placement in older adults leads to increased step width variability [13,14] and gait instability [15–17].

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Chronic stroke survivors with balance deficits and a high risk of falling also show disrupted active control of mediolateral foot placement, as revealed by greater step width and width variability than age-matched healthy counterparts [18]. All this evidence supports the possibility that rehabilitation strategies targeting the active control of mediolateral foot placement can modulate the amount and temporal structure of step width variability, potentially reducing fall risk in older adults and clinical populations.

The optimal movement variability hypothesis posits that gait variability (i.e., the fact that human steps never repeat themselves exactly) exhibits optimal forms typically found in healthy individuals [19–21]. These temporal correlations very much resemble fractional Gaussian noise (fGn) whose power-law decay of autoregressive coefficient ρ with lag k as $\rho(k) = \frac{1}{2}\left(|k+1|^{2\alpha} - 2|k|^{2\alpha} + |k-1|^{2\alpha}\right)$, and following α-DFA (detrended fluctuation analysis), the moments of the autocorrelation diverge for $0.5 <$ α-DFA ≤ 1. fGn is often referred to as "pink noise" [22,23]. Pink noise is "fractal," or statistically self-similar with fluctuations scaling invariantly with time [24]. The lack of a pink noise structure is referred to as a "white noise" structure. The α-DFA reveals the degree of persistent correlation (0.5 < α-DFA < 1.0; large values are followed by large values and vice versa) or antipersistent correlation (0 < α-DFA < 0.5; large values are followed by small values and vice versa) in the time series. A time series whose α-DFA = 0.5 can be considered as having a spectrum that represents white noise, while a measurement time series whose α-DFA = 1 can be considered as having a spectrum that represents pink noise. Healthy gait variability exhibits temporal correlations that fall into the pink noise classification [25–27], and aging and disease are associated with a loss of pink noise in variability [28–31].

One approach to gait rehabilitation—based on principles of optimal movement variability hypothesis—seeks to restore the pink noise structure in gait variability. In such efforts, patients performed treadmill walking while being paced by visual cues with pre-specified gait events either in space (e.g., obstacles and targets projected on the treadmill's belt) (e.g., [32–34]) or in time (e.g., auditory or visual) (e.g., [35,36]). Pacing with specific visual cues constrains the patient's foot placement and induces altered gait patterns. Cueing incorporating the pink noise structure has produced altered variability in participants' gait, enhancing the pink-noise-like features of gait variability [37–42]. Consequently, for example, older adults or individuals with neurodegenerative diseases, through the intervention of such cueing, can walk with characteristics found in the gait of healthy young adults [35,36,43–45]. So far, this fractional noise approach has been primarily focused on the forward stepping part (step time and step length variability). In contrast, the potential of this approach to restore healthy patterns of step width variability remains unknown.

We investigated how manipulation of the visual walking space in a virtual environment could modulate the amount and temporal structure of step width variability. Healthy adults walked in a virtual alley at a self-selected pace while the alley's width remained fixed or was made to oscillate sinusoidally in a narrow and wide range. We hypothesized that this manipulation would reduce the amount of step width variability and increase the persistence of fluctuations in step width by bringing the step width under active control from the passive mechanics of motion. However, the manipulation was designed to specifically target step width. Therefore, we did not expect these effects to hold for step length.

2. Methods

2.1. Participants

Nine healthy adults (Mean ± SD age: 26 ± 5 years) with no self-reported history of lower extremity injuries and visual/vestibular deficit participated after providing informed consent approved by the Institutional Review Board at the University of Nebraska Medical Center.

2.2. Instrumentation

Each participant walked on a treadmill (Bertec Inc., Columbus, OH) while wearing a safety harness (Fig. 1). An endless virtual alley coded in OpenGL (Silicon Graphics Inc., Sunnyvale, CA) with realistic sidewalls was rendered on a 180° 2.49 × 1.72 m curved screen 3 m in front of the participant in the Gait Real-time Analysis Interactive Lab (GRAIL; Motek, Inc., Amsterdam, Netherlands). We piloted with different widths changing rates of widths to identify-two conditions in which the alley's width oscillated sinusoidally at 0.03 Hz: between 0.38 and 1.14 m and 0.38–2.67 m in "Narrow" and "Wide" conditions, respectively. The oscillating frequency of 0.03 Hz was established through pilot work to provide a realistic transition across the changing widths. In the Narrow condition, the maximum width of the virtual alley was chosen to resemble the width of a typical doorway. In the Wide condition, the maximum width of the virtual alley was chosen to resemble the width of an open walkway. In this way, the Narrow and Wide conditions imposed different constraints on gait. In the "Control" condition, a 1.91 m wide virtual alley was used; this length was chosen because it resembles the width of a supermarket aisle—a condition that participants frequently encounter in everyday lives. The speed of the optic flow of the moving virtual alley was matched to the participant's self-selected walking pace. The participant's motion and spatial coordinates of the right and left heel and toe landmarks were obtained using a Motion Capture System (100 Hz, 3D Investigator, Northern Digital Inc., Waterloo, Canada) and synchronized with the virtual rendering using First Principles Software (Northern Digital Inc., Ontario, Canada).

2.3. Procedures and protocol

Before data collection, each participant walked for 5 min on the treadmill with its speed manipulated to determine their self-selected pace (Mean ± SD = 0.77 ± 0.19 m•sec^{-1}, N = 9 participants). The relatively slow walking speed of 0.77 m/s, as opposed to up to 1.1 m/s reported for healthy adults [46], most likely reflects the fact that it was participants' first exposure to such a unique walking environment in virtual reality and hence, their self-selected walking speeds reduced to normal speed for community ambulators. Then 6 min continuous walking in the fixed-width Control condition and the Narrow and Wide conditions followed with 2-min rest between conditions. The order of conditions was randomized for each participant.

2.4. Data processing and detrended fluctuation analysis (DFA)

We processed all data in R [47]. We performed "data smoothing" and interpolation with quintic splines using the GCVSPL routine [48]. We used the anteroposterior coordinates of the digitized heel and toe markers to determine gait events to calculate step length (the anteroposterior distance between the locations of the sequential left and right heel strikes) and step width (the mediolateral distance between the locations of the sequential left and right heel strikes). Heel strikes were detected when heel marker's position along the vertical axis reached a minimum before the contralateral toe went off the ground and after the ipsilateral toe went off the ground in order to verify that gait events occur in order. Standard deviation (SD) quantified the amount of step length and step width variability, and α-DFA obtained from the detrended fluctuation analysis (DFA) using the evenly spaced algorithm [49,50] quantified the temporal structure in step length and step width variability in terms of persistence in fluctuations. Each participant had at least 440 steps in each condition, sufficient to compute reliable, meaningful values of α-DFA [50]. The α-DFA reveals the degree of persistent correlation (0.5 < α-DFA < 1.0; large values are followed by large values and vice versa) or antipersistent correlation (0 < α-DFA < 0.5; large values are followed by small values and vice versa) in the time

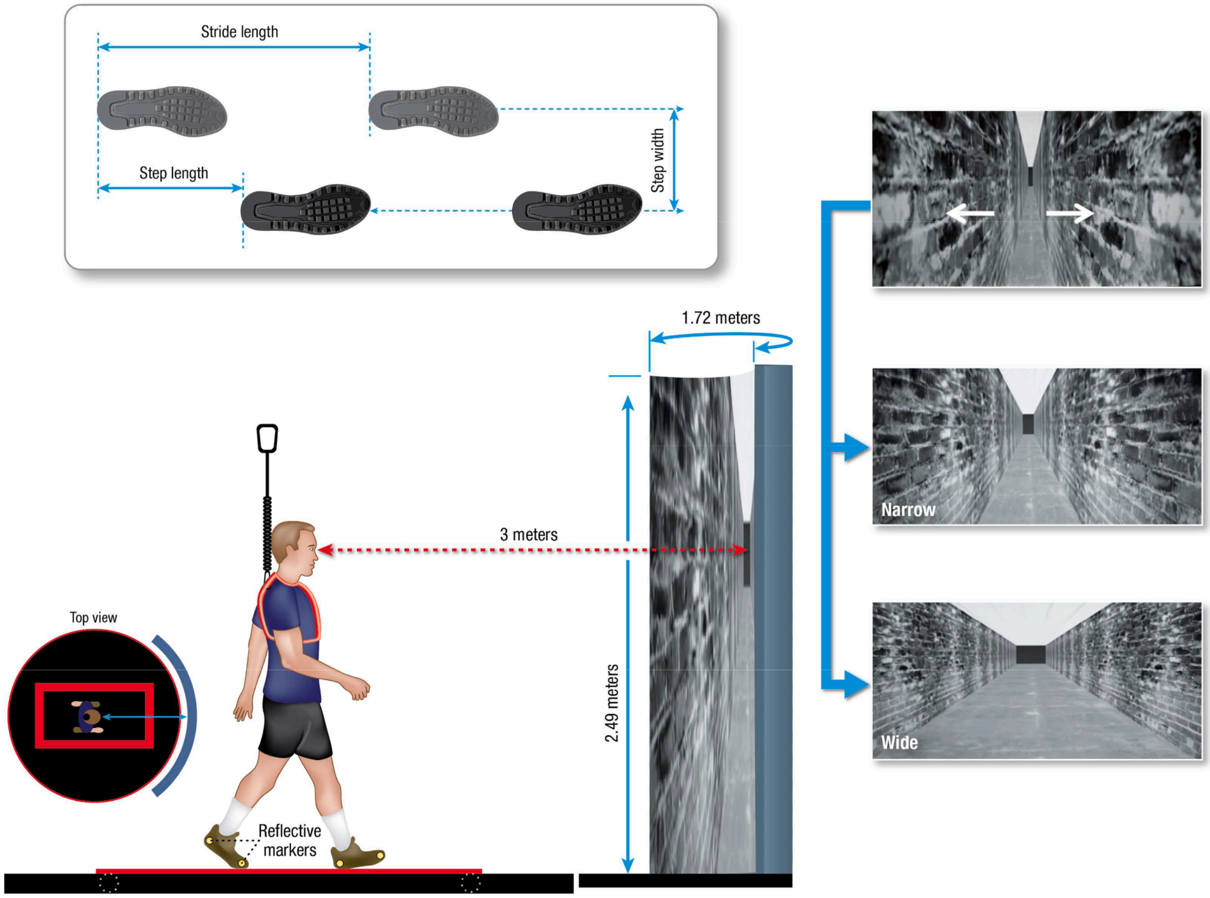

Fig. 1. Experimental setup and conditions. Participants performed self-paced treadmill walking in a virtual alley with its width either fixed (1.91 m; Control condition) or oscillated sinusoidally at 0.03 Hz. In the Narrow condition, the width oscillated between 0.38 and 1.14 m; in the Wide condition, the width oscillated between 0.38 and 2.67 m. The distance between two successive footprints, measured from the heel of one footprint to the heel of the following footprint, constituted step length. The distance between the furthest borders of two subsequent footprints constituted step width.

series. A time series whose α-DFA = 0.5 can be considered as having a spectrum that represents white noise, while a measurement time series whose α-DFA = 1 can be considered as having a spectrum that represents pink noise.

2.5. Surrogate testing using shuffled time series

Surrogate testing identified the deterministic origin of the observed variability in step length and step width time series [51–53]. The series were shuffled to preserve the probability distribution but destroyed any temporal correlations. Thus, the null hypothesis of the surrogate test, H_0, was that the collected data were indistinguishable from independent and identically distributed (IID) noise. Rejection of H_0 would indicate that the collected data had a deterministic temporal structure. To this end, we compared the α-DFA values for the collected data with the α-DFA values for the shuffled surrogates using a two-sided rank-order test at a 95 % confidence level. We set the significance level at $\alpha_{adjusted} = 0.005$ (Bonferroni correction) to compensate for multiple comparisons (i.e., N = 9 participants). Therefore, we generated $\beta = 2/\alpha_{adjusted} - 1 = 399$ surrogates for each original time series. We calculated p-values for the surrogate test by ranking the α-DFA values (i.e., 399 surrogates + 1 observed = 400 values) in numerical order and determining the rank of the α-DFA value for the original time series (i.e., p-value = rank/400).

2.6. Statistical analysis

We used linear mixed-effects models to compare the amount and temporal structure of variability in step length and step width across the three walking conditions: Control, Narrow, and Wide; we allowed the intercept to vary across participants. We used Tukey's multiple comparison tests to compare the fixed effects of the walking conditions. Cohen's f (f < 0.10 negligible, f < 0.25 small, f < 0.40 moderate, otherwise interpreted as a large effect) and Cohen's d (d < 0.02 negligible, d < 0.50 small, d < 0.80 moderate, otherwise interpreted as a large effect) were used to report effect size (ES) for the linear mixed effects model and the Tukey's tests, respectively. Significance was set at the two-tailed α level of 0.05. Statistical analyses were performed in R [47] using the packages "nlme" [54], "multcomp" [55], and "metap" [56].

3. Results

Oscillations in the virtual alley's width affected the SD of step width time series ($F_{2,16} = 4.32$, $P = 0.032$, $f = 0.74$; Fig. 2**A**). SD showed a decreasing trend from the Wide to Control to Narrow condition. Post-hoc analysis revealed that the SD of step width time series were significantly smaller in the Narrow condition (1.87 ± 0.37 cm) than in the Wide condition (2.06 ± 0.50 cm; $P = 0.015$, $d = 0.94$). In contrast, oscillations in the virtual alley's width did not affect the SD of step length time series ($P > 0.05$; Fig. 2**B**).

Oscillations in the virtual alley's width affected the α-DFA of step width time series ($F_{2,16} = 11.5$, $P < 0.001$, $f = 1.20$; Fig. 3**A**). In general, the α-DFA showed an increasing trend from the Wide to Control to Narrow condition, with the Narrow and Wide conditions showing the α-DFA resembling pink noise and white noise, respectively. Post-hoc analysis revealed that the α-DFA of step width time series was

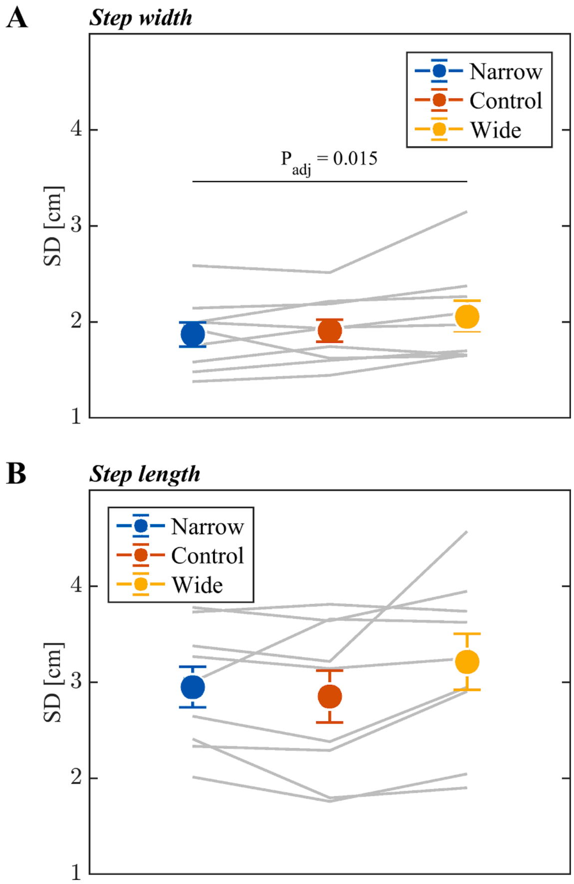

Fig. 2. The effects of self-paced treadmill walking in a virtual alley with a fixed width (Control) and sinusoidally changing width (Narrow and Wide conditions) on the amount of variability—estimated by the SD—in step width time series (A) and step length time series (B). Vertical bars indicate S.E.M. (N = 9). Grey lines indicate SD values for individual participants. Black horizontal bars indicate significant differences confirmed by Tukey's multiple comparison test.

significantly greater in the Narrow condition (0.79 ± 0.10) than in the Wide condition (0.68 ± 0.10; $P < 0.001$, $d = 1.60$). The α-DFA was also significantly greater in the Narrow condition than the Control condition (0.73 ± 0.11; $P = 0.029$, $d = 0.85$). Notably, this trend was opposite to that observed in the SD of step width time series. In contrast, oscillations in the virtual alley's width did not affect the α-DFA of step length time series ($P > 0.05$; Fig. 3**B**).

Surrogate testing confirmed that seven participants in the Control condition, all nine participants in the Narrow condition, and three participants in the Wide condition exhibited the deterministic origin of persistent fluctuations in step width in the Narrow condition (Fig. 4A). Notably, the difference of five participants between the Wide and the Control conditions strengthens the conclusion that the Narrow condition increased the persistence of fluctuations in step width. In contrast, only five participants in the Control condition, four participants in the Narrow condition, and five participants in the Wide condition—exhibited deterministic characteristics of persistent fluctuations in step length (Fig. 4B).

4. Discussion

We investigated how manipulation of the visual walking space in a virtual environment could modulate the amount and temporal structure of step width variability. Healthy adults walked in a virtual alley at a self-selected pace while the alley's width remained fixed or was made to oscillate sinusoidally in a narrow and wide range. We found that the wider contraction and expansion of the virtual alley's width neither

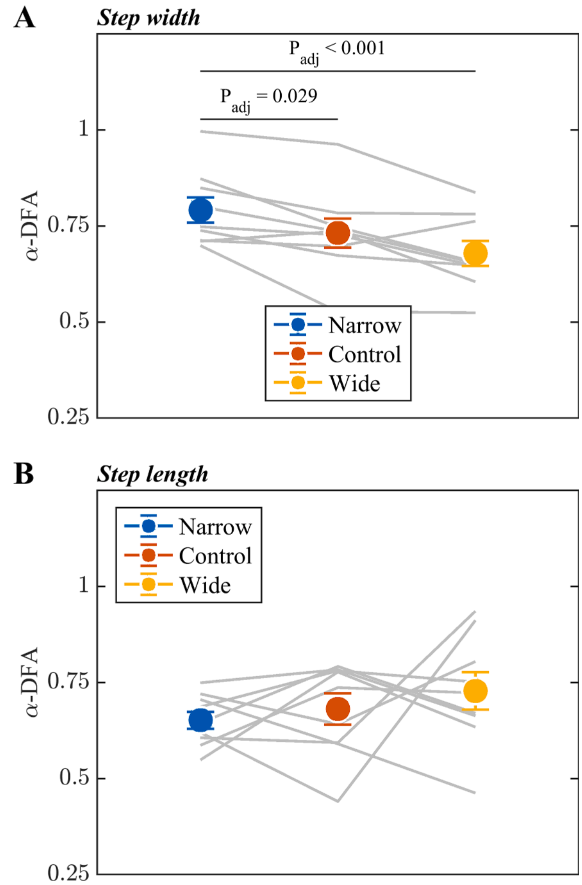

Fig. 3. The effects of self-paced treadmill walking in a virtual alley with a fixed width (Control) and sinusoidally changing width (Narrow and Wide conditions) on the temporal structure of variability in step width time series (A) and step length time series (B), estimated by the fractal scaling exponent α-DFA quantifying the persistence ($\alpha < 0.5$) / antipersistence ($\alpha < 1$) of fluctuations. Vertical bars indicate S.E.M. (N = 9). Grey lines indicate α-DFA values for individual participants. Black horizontal bars indicate significant differences confirmed by Tukey's multiple comparison test.

affected the standard deviation nor the fractal scaling exponent of step width time series. In contrast, the narrower contraction and expansion of the virtual alley's width did not affect the standard deviation of step width time series but significantly increased its fractal scaling exponent, suggestive of more persistent fluctuations characteristic of a healthy gait. Because the manipulation was designed to specifically target step width, this effect did not hold for step length. These results suggest that manipulating the visual walking space in a virtual environment can modulate step width variability and potentially reduce fall risk in older adults and clinical populations. We discuss the theoretical implications of these results below.

While walking in the fixed-width virtual alley, the fractal scaling exponent of 0.73 represented correlated pink noise and was consistent with previous reports [57,58]. However, in the Narrow condition, step width time series—and not step length time series—gained some time-dependent structure (persistence in fluctuations) that distinguishes correlated pink noise from uncorrelated white noise. We attribute this result to the visual constraints imposed by oscillations in the virtual alley's width. A width-changing virtual alley affects the visual control of locomotion speed [59,60] and its acceleration [61]. Previous findings have reported a direct relationship between locomotion speed and the virtual alley's width, the speed increasing or reducing linearly with the narrowing and expanding width [62,63]. Thus, it can be argued that the changing width of the virtual alley modulated the visual control of locomotion speed through cues present within the optic flow (e.g.,

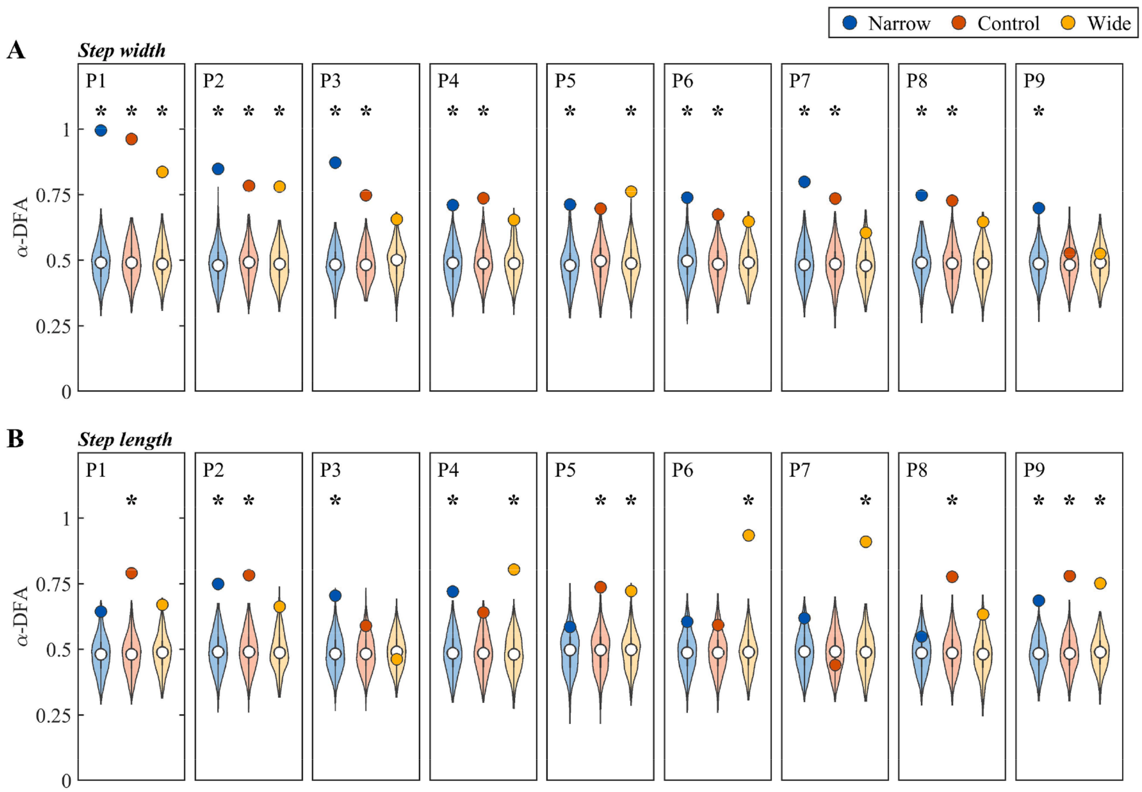

Fig. 4. Outcomes of surrogate testing for step width time series (A) and step length time series (B) for each participant (#1–9) using α-DFA as the discriminating statistic. Colored dots represent the observed α-DFA values for each condition (Narrow, Control, Wide). Violin plots represent the distribution of the α-DFA for surrogate series. Vertical lines represent the interquartile range of the surrogate α-DFA values and white dots represent the median of the surrogate the α-DFA for surrogate series. Asterisks indicate that the observed α-DFA value for the original time series was significantly greater than α-DFA values for the corresponding 399 surrogate time series, indicating a significant difference from uncorrelated white noise. *$p \leq 0.005$.

global optical flow rate). Nonetheless, when treadmill walking requires maintaining a constant speed (on average), the nervous system immediately corrects only the task-relevant variable of step speed as these features show anti-persistent fluctuations. In contrast, task-irrelevant variables such as step duration and step length show persistent fluctuations [64]. The persistent fluctuations in the temporal structure of step width variability observed in the present study suggest that step width was not controlled step-by-step based on visual cues.

It can also be argued that small path width may reduce step width below typical value, introducing a deterministic component at the stimulus frequency for the narrow path. However, we kept the minimum path width and the oscillating frequency the same in the Narrow and Wide conditions, which implies that any such effect should have been observed for both the Narrow and Wide conditions. However, the observed distinct effects between the two conditions seem to refute this possibility.

The optic flow plays a critical role during walking. Several studies have applied mediolateral perturbations of optic flow during treadmill walking to induce an illusion of self-motion and create instability along the mediolateral axis [16,58,65–69]. The visual information is decoupled from the other sources of information about self-motion, evoking postural adjustments for minimizing the sensory conflicts between visual and other sensory information. However, the present results cannot be explained in terms of resolving sensory conflicts. First, the amount of step width variability did not depend on the amplitude of change in the virtual alley's width. Second, sensory cues about self-motion remained congruent throughout. Hence, it is unlikely that gait was adapted to minimize sensory conflicts like in the previous studies involving perturbations of optic flow.

The mediolateral foot placement while walking along a width-changing virtual alley is likely driven by changes in the global optic flow rate. It is well known that people use visual cues within the optic flow to steer down passageways [70,71]. For example, the "visual equalization strategy" postulates that people steer down an alley by equating the bilateral global optic flow rate, the splay angles of base lines, and the visual angles of the texture of the left and right walls [71]. The expansion and contraction of the virtual alley's width modified the right and left global optic flow rate that the participants perceived when walking along the virtual alley. The global optic flow rate associated with walking at a constant speed parallel to a vertical alley is inversely related to the perpendicular distance from the participant's eye position. We speculate that the width-changing virtual alley used in the present study might have caused the steps to fluctuate mediolaterally to equalize optic flow patterns, inducing long-term step fluctuations rather than step-by-step postural corrections. Future work could test this possibility in greater detail by implementing laterally asymmetric changes in the virtual alley's width.

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CRediT authorship contribution statement

Madhur Mangalam: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing, Visualization. **Andreas Skiadopoulos:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Ka-Chun Siu:** Conceptualization, Data curation, Writing – review & editing. **Mukul Mukherjee:**

Conceptualization, Writing – review & editing, Supervision, Project administration. **Aaron Likens:** Methodology, Data curation, Writing – review & editing. **Nick Stergiou:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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