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Performance of an attention-demanding task during treadmill walking shifts the noise qualities of step-to-step variation in step width

Mark D. Grabiner[a,*], Jane R. Marone[b], Marilynn Wyatt[c], Pinata Sessoms[d], Kenton R. Kaufman[e]

[a] *University of Illinois at Chicago, Department of Kinesiology and Nutrition, 1919 W. Taylor Street, Room 648, Chicago, IL 60612, United States*
[b] *University of Illinois at Chicago, Department of Kinesiology and Nutrition, 901 W. Roosevelt Rd, 336 PEB, Chicago, IL 60612, United States*
[c] *Naval Medical Center San Diego, 34800 Bob Wilson Drive, San Diego, CA 92134, United States*
[d] *Naval Health Research Center, San Diego, 140 Sylvester Rd., San Diego, CA 92106-3521, United States*
[e] *Motion Analysis Laboratory, Dan Abraham Health Living Center 4-214A, Mayo Clinic, 200 First St. SW, Rochester, MN 55905, United States*

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ABSTRACT

Background: The fractal scaling evident in the step-to-step fluctuations of stepping-related time series reflects, to some degree, neuromotor noise.

Research question: The primary purpose of this study was to determine the extent to which the fractal scaling of step width, step width and step width variability are affected by performance of an attention-demanding task. We hypothesized that the attention-demanding task would shift the structure of the step width time series toward white, uncorrelated noise.

Methods: Subjects performed two 10-min treadmill walking trials, a control trial of undisturbed walking and a trial during which they performed a mental arithmetic/texting task. Motion capture data was converted to step width time series, the fractal scaling of which were determined from their power spectra.

Results: Fractal scaling decreased by 22% during the texting condition ($p < 0.001$) supporting the hypothesized shift toward white uncorrelated noise. Step width and step width variability increased 19% and five percent, respectively ($p < 0.001$). However, a stepwise discriminant analysis to which all three variables were input revealed that the control and dual task conditions were discriminated only by step width fractal scaling.

Significance: The change of the fractal scaling of step width is consistent with increased cognitive demand and suggests a transition in the characteristics of the signal noise. This may reflect an important advance toward the understanding of the manner in which neuromotor noise contributes to some types of falls. However, further investigation of the repeatability of the results, the sensitivity of the results to progressive increases in cognitive load imposed by attention-demanding tasks, and the extent to which the results can be generalized to the gait of older adults seems warranted.

1. Introduction

The variability that characterizes human movement has been attributed to error correction and neuromotor noise [1]. Neuromotor noise arises from all levels of the neuromotor system including sensory transduction/amplification, synaptic transmission, network interactions, motor neurons and muscle fibers [2]. Recently, the age-related increase in the variability of stride kinematics was attributed to increased neuromotor noise and was not associated with age-related degradation of the ability to correct errors [3]. It seems reasonable to assume that age-related changes to step width variability may also be attributed to neuromotor noise. If true, this may be important as it has long been thought, although not demonstrated, that increased step width variability increases gait-related fall risk [4].

Both step width and stride width are measures of the medial-lateral distance between the feet during double support. During locomotion both are biomechanically significant for laterally-directed dynamic stability [5–7] Nevertheless, the strength and direction of the association between step width, step width variability and prospectively-measured falls is not clear. There are a limited number of prospective studies with regard to step width [8–12] and only three prospective studies that have reported step width variability [9,13,14]. Most published studies of the relationships between step width, step width variability and falls have been cross-sectional. Overall, step/stride width variability, historically measured statistically using indices such as standard deviation and coefficient of variability, has been reported to

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* Corresponding author.
E-mail addresses: grabiner@uic.edu (M.D. Grabiner), janem@uic.edu (J.R. Marone), marilynn.p.wyatt.civ@mail.mil (M. Wyatt), pinata.h.sessoms.civ@mail.mil (P. Sessoms), Kaufman.Kenton@mayo.edu (K.R. Kaufman).

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not distinguish older adults who have a history of falls from those who do not [15]. This is underscored by the finding that the greater likelihood of a retrospectively reported fall by older adults who have normal walking speed was associated with either an extremely high or an extremely low value of step width variability [16].

The use of the statistical variability to represent neuromotor noise, has a long history in the discipline of motor control (e.g., [17,18]). Indeed, most studies of step width variability have quantified variability in this manner. However, as a means to probe the underlying control systems that influence step width the standard deviation may be limited [19]. The step-to-step fluctuations in gait-related time series demonstrate complex order-sensitive structure (e.g., step time: [20–25] and stride length: [21,22]) to which linear measures of variability such as standard deviation, are insensitive. Specifically, shuffling, or randomizing the order of data in a step kinematic time series does not change its mean and standard deviation. However, shuffling the order of data in a step kinematic time series causes fractal scaling to be lost and to take on the spectral characteristic of white, i.e., uncorrelated noise. Fractal scaling is not present in white, noise but it is present in pink, i.e., correlated noise, examples of which include step kinematics. The presence of fractal scaling in a time series can be quantified by converting a time series (in the amplitude-time domain) to its power spectral density (in the amplitude-frequency domain) and determining that the power spectral density is inversely proportional to frequency. This is referred to as “1/f”. For physiological time series such step kinematics, fractal scaling is thought to arise from the non-linear interaction between the input and output of multiple control systems, such as the multiple elements of the central and peripheral nervous systems that operate at different temporal and/or spatial scales [26]. The presence of fractal scaling, which again, arise from the non-linear interaction between the input and output of multiple control systems, is considered to be reflective of an adaptive system [23,24]. Fractal scaling of step kinematics is sensitive to chronological age [20], disease [27–29] and auditory cues [24]. Specifically, this sensitivity is revealed by a loss/reduction of fractal scaling marked by a transition from the characteristics of pink noise toward those of white noise and associated with the structural and functional changes caused by aging and/or pathology.

If step width variability reflects neuromotor noise, then it seems reasonable to expect a change in the noise-related characteristics of the step-to-step variations while performing an attention-demanding task. Although walking normally requires a minimum of attention-demanding executive control resources, numerous factors can compromise the automaticity of walking [30]. Performance of an attention-demanding task during gait is one such factor and has been shown to influence both step width [31–37] and step width variability [33–38]. In light of the order-insensitivity of variability measures such as the standard deviation, the extent to which an increase in the standard deviation of a step width time series reflects increased neuromotor noise cannot be directly evaluated. However, quantification of fractal scaling can reveal shifts in the characteristics of noise in a time series. Notably, performance of an attention-demanding task during overground walking significantly decreased the fractal scaling of stride time from structured, correlated pink noise in the direction toward unstructured, uncorrelated white noise [39]. Step width during treadmill walking has been reported as fractal [28,40,41] but there are no published reports of whether the fractal scaling is altered during dual-task conditions.

The purposes of the present study were to determine the extent to which the fractal scaling of step width was affected by the performance of an attention-demanding task during treadmill walking. We hypothesized that the attention-demanding task would be associated with a decrease in fractal scaling, marking a change of the structure of the time series toward that of white, uncorrelated noise. If this hypothesis was supported, the second purpose was to compare step width fractal scaling, step width and step width variability with regard to their ability to statistically discriminate between the control and dual task conditions.

2. Methods

We re-analyzed a previously collected data set from which the effect of an attention-demanding task during treadmill walking on the frontal plane margin of stability was quantified [42]. The methods, previously been described in detail [42], included recruiting 20 healthy young college age men and women (age: 23.3 ± 2.3 years; height 170.2 ± 8.9 cm; mass: 66.1 ± 11.5 kg). All of the subjects were considered experienced/skilled cellular phone “texters”, exceeding 200 texts per month.

After providing written informed consent subjects performed four, randomly ordered 10-min treadmill walking trials at the same self-selected velocity (1.19 ± 0.19 m/s). The two conditions of interest for the present study were the control trial, during which the subjects walked “normally”, and the trial during which the subject texted answers to sequential arithmetic calculations performed mentally while holding the device bimanually. Starting with a number provided by an investigator, the subject mentally performed the following calculation: (((starting number − 7) + 4) * 2), the answer to which was texted and then used as the starting number in the subsequent iteration. When the answer approached 1000 subjects verbally signaled the investigator who provided a new starting number and the calculations continued. A visual guide for the calculation was placed on the wall in front of the treadmill. On average, subjects walked 1065 ± 82 and 1075 ± 80 steps during the control and texting conditions, respectively.

An 8-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) tracked the motions of 22 reflective markers that were used to construct a 12-segment, rigid, whole-body model from which step width time series were extracted. The left and right feet were represented as rigid segments defined by markers placed on the shoes over the second metatarsophalangeal joints and heels. Step width was calculated as the frontal plane distance between the midpoints of the foot segments at midstance during two consecutive stance phases. Step width variability was computed as the standard deviation of the step width time series.

Fractal scaling of the step width time series was represented by the slope of the regression line, referred to as β, calculated for the log-log transformed power spectrum [43]. The mean value of the step width time series was removed from the time series. The power spectrum was then computed using Welch’s method in which the time series was divided into eight equal length segments with a 50% overlap. A Hamming window (sidelobe attenuation = 42.5 dB) was applied to each segment. The periodogram was computed to produce the power spectral density estimate and the eight periodograms were averaged. The resulting power spectral density estimate was log-log transformed and subjected to a linear regression from which the value for the slope coefficient, β, which reflects the fractal scaling of the time series, was extracted (Fig. 1). A slope coefficient of zero indicates a non-fractal, white noise signal in which sequential values are uncorrelated. As the slope decreases toward −1, indicative of pink noise, the signals become more correlated. Values ranging from −0.5 to −1.5 are considered pink noise [44]. Computations were performed with MATLAB (Mathworks, Inc, Version R2011A, Natick, MA).

Comparisons between the control and texting conditions were conducted using paired *t*-tests. Those variables for which significant between-condition differences were found were entered into a stepwise discriminant analysis in which the control and texting conditions were used as “group membership”. All statistical tests were performed using SPSS (SPSS, Version 24, Armonk, NY).

3. Results

Fractal scaling was present in the step width time series during both