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ORIGINAL PAPER

Fractal properties of postural sway during quiet stance with changed visual and proprioceptive inputs

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Abstract We studied the fractal dynamics of postural sway during quiet stance with changed visual and/or proprioceptive information. Radius-vector length and angle of rotation of center of foot pressure (COP) displacements were used as parameters of postural sway. The experiments were performed on 24 healthy volunteers of both sexes aged 20–30 years. Using a battery of nonlinearity tests, differences in the degree of fractality of both parameters during stance were found. We found that the behavior of radius-vector was similar to fractional Brownian motion, while that of angle of rotation was similar to flicker noise. Quantitative parameters that can be used to characterize the changes in radius-vector length and angle of rotation include self-similarity intervals and fractal dimension. In healthy subjects, the process of postural control maintains its fractal structure independently of altered sensory information. We believe that this analysis provides information about new methods for evaluating postural sway behavior during quiet stance.

Keywords Body sway · Postural control · Nonlinear analysis · Fractal dynamics

Introduction

The maintenance of quiet upright stance involves complex mechanisms of integrating information from the visual, vestibular, and proprioceptive systems. The evaluation of postural sway measurements has been the subject of intense research in recent decades. Measurements of body balance are mostly based on displacements of the center-of-foot-pressure (COP) in the plane under the feet. Stabilograms describe the COP coordinates along the x-axis or medial-lateral (ML), and along the y-axis or anterior-posterior (AP), as time series: ML $= f(t)$ and AP $= f(t)$. The curve showing how the COP shifts in the Cartesian coordinate system [$y = f(x)$] is called a statokinesigram. The COP position in the statokinesigram is characterized by the radius-vector length (RD) and angle of rotation (β) between two consecutive COP points [1–4].

There are two main approaches for evaluating postural steadiness. The first one evaluates the COP displacements by standard statistical analysis of basic parameters such as mean amplitude, mean velocity, length of sway path, sway area, and frequency parameters of the power spectrum [5–7]. The second approach is based on recent nonlinear techniques for analysis of the postural control systems [8–12]. These studies have focused on the nonlinear properties of postural sway that are not evident in the classic basic descriptive parameters. The stabilogram diffusion analysis (SDA) and the detrended fluctuation analysis (DFA) are the most used nonlinear dynamic analyses of postural control [11, 12].

SDA is based on the theory of pure fractional Brownian motion [8, 9, 13]. Collins and De Luca [8] estimated the stochastic properties of the COP dynamics by the Hurst exponent. They hypothesized that there are two stochastic processes in the control of posture during quiet stance with different scaling exponents: a short-term process ($t < 1$ s) with an open-loop control mechanism and a long-term process with a closed-loop mechanism.

Delignieres et al. [12] argued that the SDA method was inappropriate for the pure fractional Brownian motion and

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proposed the DFA analysis to assess the fractal characteristics of COP. DFA is a method of integrating and detrending the data series; it allows for the scaling exponent to be calculated. Amoud et al. [14], however, reported differences between the postural sway of elderly and young persons using SDA and DFA and found that both analyses are relevant. The nonlinear properties of postural sways have also been analyzed using fractal dimensions calculated by means of Higuchi's algorithm [15–18].

All these findings suggest that postural stability may be described by an exponential decreased law of $1/f^{\alpha}$. Thus, it would be of great interest to investigate how this law will be modified when the visual and/or somatosensory inputs are altered and whether the components of decomposed postural sways follow the same law.

The aim of the present study was to determine the nonlinear properties of body sways measured in quiet stance under normal conditions and under conditions of sensory conflicted stance when the visual and proprioceptive inputs are changed. The postural sway was characterized by the radius-vector length and angle of rotation of COP displacements. We also estimated the separate contribution of these parameters in terms of the fractal dimension (D_f) and structure functions (SF).

Methods

Experimental setup and data recording

Twenty-four healthy subjects, 10 males and 14 females, aged between 20 and 30 years (mean ± SD, 24.2 ± 3.6) without a history of vestibular, musculoskeletal, or neurological disorders were investigated. All participants were volunteers and gave their informed consent prior to taking part in the experiments, which were approved by the Bioethics Committee of the Institute of Neurobiology, BAS, Sofia.

During the experimental sessions the subjects stood freely upright on the platform with their heels separated by a distance of 2.5 cm, feet positioned with a 25° angle between their medial sides, and with arms freely hanging alongside the body. The quiet stance task was performed either on a stable support or on a foam pad with dimensions of 400 × 400 × 150 mm, density of 77.5 kg/m^3, and elastic modulus of 74.9 N/m^2.

Two visual input conditions were used: eyes open (gaze fixed on a point 2 m in front of the subject and at eye level) and eyes closed. Each trial lasted 30 s.

Postural sway was measured by a static posturographic system (Fig. 1) [19, 20]. A position-sensitive photodetector (PSD) fixed on the bottom of the platform was used to record the COP displacements in two orthogonal directions in the plane under the feet. A laser source of light was installed on top of the platform above the PSD so that it moved in all directions proportionally to the difference in pressure between the two feet. The action of the PSD, sensitive to visible light, was based on the lengthways photoeffect. The nonlinearity of the position curve of PSD in both directions was 1.3%. The photopotentials generated by PSD when the body was upright were proportional to the COP displacements in both X and Y directions. The sensitivity of the measurement of the platform was 0.1 mm/bit. The signals were digitized with sampling interval of 10 ms (sampling frequency $F_s = 100$ Hz).

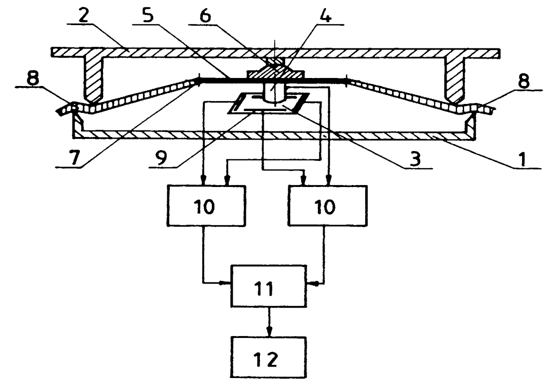

Fig. 1 Schematic of posturographic platform. *1* Basis, *2* moving face plate, *3* position sensitive photodetector (PSD), *4* light source, *5* moving small plate, *6* and *7* moving couplings, *8* arms, *9* electrodes, *10* amplifier, *11* analog-digital converter, *12* personal computer

Data processing

A digital Hamming low-pass filter with a cut-off frequency of 10 Hz was used to remove high frequency noise.

The radius-vector length and its angle were calculated according to the following equations:

$$\mathrm{RD}(n) = [\mathrm{AP}(n)^2 + \mathrm{ML}(n)^2]^{1/2}; \quad n = 1, N \qquad (1)$$

$$\beta(n) = \mathrm{actg}[\mathrm{AP}(n+1)/\mathrm{ML}(n+1)] - \mathrm{actg}[\mathrm{AP}(n)/\mathrm{ML}(n)]; \quad n = 2, N-1 \qquad (2)$$

where N is the number of samples, n the transitory value of postural sway, and AP and ML are the anterior-posterior and medial-lateral planes, respectively. Raw samples of statokinesigrams of one person are shown in Fig. 2.

The first step in the nonlinear analysis is to check the type of distribution as normal distribution and stationarity of data are required for conventional linear analyses. There are three possibilities in cases where the distribution is non-Gaussian: (1) the process is linear but non-Gaussian; (2) the process has linear dynamics, but the observations are obtained by nonlinear "static" transformation, and (3) the process has nonlinear dynamics [21].

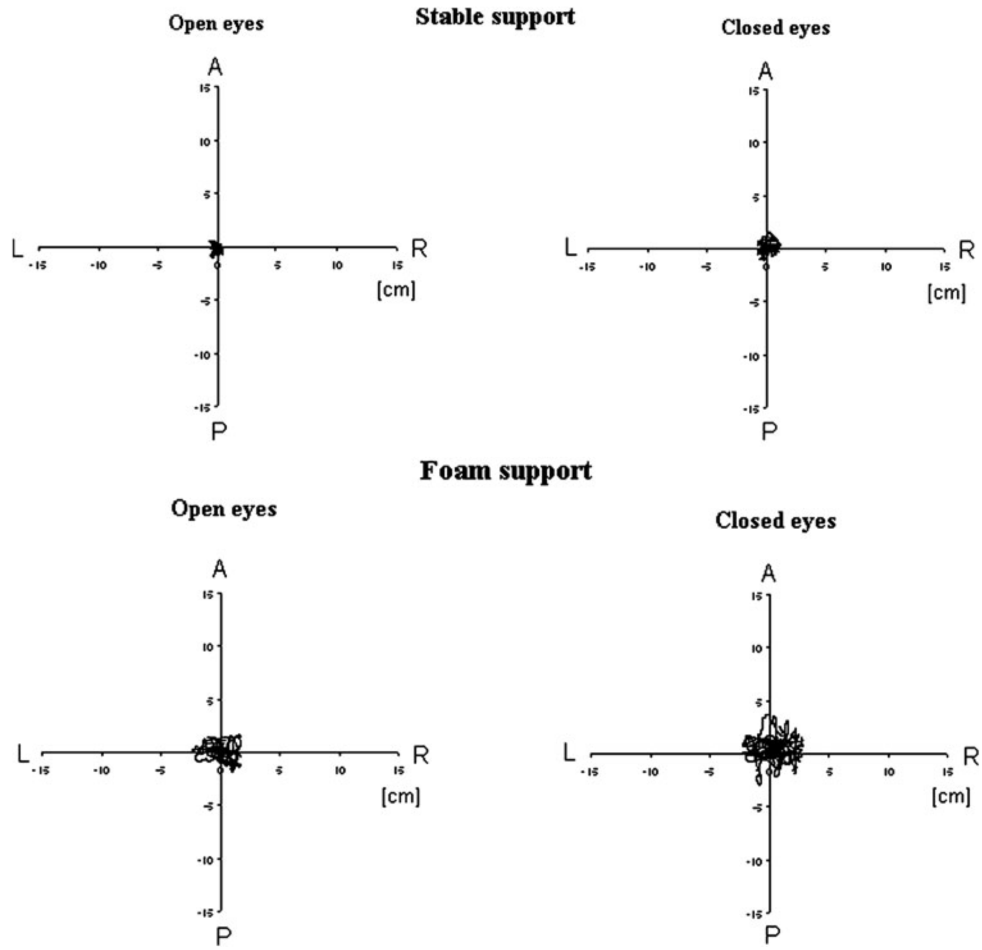

Fig. 2 Original 30-s raw samples of statokinesigrams from a 21-year-old man during quiet upright stance under four experimental conditions

In the present study we used the Kolmogorov-Smirnov test to check the amplitude distributions of RD and β. Three tests were applied to reveal the nonlinear dynamic structure of COP displacements during the quiet upright stance. The first one evaluated the self-similarity of the process of postural control by calculating the duration of self-similarity intervals and fractal dimension (D_f). The power spectrum (PS) of postural sways exhibited an exponential decreasing shape ($1/f^{\alpha}$) when plotted on the double logarithmic scale. The self-similarity intervals included the linear part of the slope. The fractal dimension was calculated from the linear slope α of the log-log plot of the PS. According to Higuchi [18], there is a direct relation between α and D_f. The fractal dimensions have to be calculated as follows: when $1 < \alpha < 3$, $D_f = (5 - \alpha)/2$; when $\alpha \geq 3$, $D_f = (7 - \alpha)/2$; and when $\alpha \leq 1$, $D_f = (3 - \alpha)/2$. In case of a fractional Brownian motion process with $\alpha = 2$, D_f is equal to 1.5.

The second test distinguishes the fractal from the chaotic nature of the signals through the inspection of the structure function (SF) shape presented in the log-log plot for the raw data epochs and its first derivative [22]. SF was determined according to the formula:

$$SF(n) = \sum (y(t + n\Delta t) - y(t))^2 \quad (3)$$

where $t = 1$ to $N - n$ and $y(t)$ are the samples of the scalar signal.

According to Provenzale et al. [22], when the process is chaotic, the SF(n) increases for small n and saturates for large n for both the original signal and its first derivative. In contrast, the fractal noisy processes are characterized by increased SF(n) at the large scale for the real signal and saturated for the first derivative of the signal.

The third test is based on the surrogate data method for detection of possible chaotic dynamics of postural sways. The idea is to generate many realizations from a single real data recording by preserving its linear properties and by removing some nonlinear properties that may exist. The important characteristic of the chaotic dynamics is the correlation dimension D_2 computed by the algorithm of Grasberger-Procaccia [23].

In this study we used the amplitude-adjusted Fourier transform algorithm (AAFT) [24] to generate 10 surrogate data epochs. This algorithm removes the possible nonlinear properties of the real data epochs by randomizing the phases after the fast Fourier transformation (FFT), while preserving all of their linear properties. The null hypothesis was that the real time series was generated after the monotonic nonlinear transformation of a linear Gaussian process. D_2 was computed for values of embedding dimension $m = 2, 4,\ldots, 18$. For reconstruction in the phase space, time delay $\tau = 2$ was chosen according to the zero-crossing of the autocorrelation function. The correlation dimension of surrogate data ($D_{2\ \mathrm{sur}}$) was computed by the modified algorithm (re-embedding) procedure with $m = 10$ and $m = 20$ [25]. The significance of the differences between D_2 for real data ($D_{2\ \mathrm{real}}$) and $D_{2\ \mathrm{sur}}$ was statistically estimated.

All statistical analyses were performed using the statistical package Statistica 7.0 (Stat Soft, USA, 2004). The significances of the differences in mean values were assessed with Wilcoxon's nonparametric rank test. Data are presented as mean value ± SD, and $p \leq 0.05$ was considered significant.

Results

By testing the null hypothesis using the maximum distance D between real and Gaussian cumulative distributions, we revealed that the amplitude distributions of RD and β for all experimental conditions were asymmetrical and non-Gaussian according to the Kolmogorov-Smirnov test. The null hypothesis should be rejected if $D > D_a$, where D_a is the critical value for a chosen level of significance. For all experimental conditions, D was higher than D_a, and the null hypothesis was rejected with $p < 0.05$. This result indicates possible nonlinear dynamics of RD and β.

The power spectra of RD and β plotted on a double logarithmic scale consisted of two segments with different slopes (Fig. 3). The first segment started in the very low frequency area and was characterized by an almost flat curve with a zero slope, similar to the random white noise. The second segment had a linear decreasing curve, which was characteristic of a process with long-range correlation with fractal properties.

The slope (α) of the second segment was determined by fitting a linear polynomial regression function and was used to compute D_f of the selected segment (Fig. 3). The slope is limited by two characteristic frequencies. Their reciprocal values determined the domain of the interval between trial numbers with a long-range correlation of RD and β, where the self-similarity was exhibited (Tables 1, 2).

For all conditions, the slopes of RD (α_{RD}) were in the range of $1 < \alpha < 3$ (mean 2.59 ± 0.4) and D_f was equal to 1.2 ± 0.19, indicating fractional Brownian processes within the selected frequency bands [18]. Significant differences in the mean values of $\alpha_{\ RD}$ across the four experimental conditions were not observed (Table 1). The initial frequency of intervals for RD self-similarity during the stance on a foam support with closed eyes of all subjects was higher (0.72 Hz) than measured in the other three experimental conditions (Table 1). The foam pad stance led to significant decreases in the duration of self-similarity intervals compared with stable surface stance with eyes closed ($p < 0.01$). The lack of vision led to a significant decrease in this parameter during the foam pad stance ($p < 0.01$). Mean duration of the self-similarity intervals for the other experimental conditions was about 5 s, and significant differences were not observed. There were also significant differences of the D_f mean values between the stance on stable and foam support, both with open eyes ($p < 0.05$), and closed eyes ($p < 0.01$) (Table 1).

The slopes of angle of rotation of the COP displacements ($\alpha\beta$) were <1 (mean 0.8 ± 0.24) and $D_f =$ 1.09 ± 0.06, which is typical for a flicker-like noise process with blurred self-similarity (Table 2). The mean value of $\alpha\beta$ during stance on foam support with closed eyes was significantly higher ($p < 0.05$) than in the other experimental conditions (Table 2). The initial frequencies of self-similarity intervals of β were shifted to higher frequencies of the spectrum when standing on the foam support with

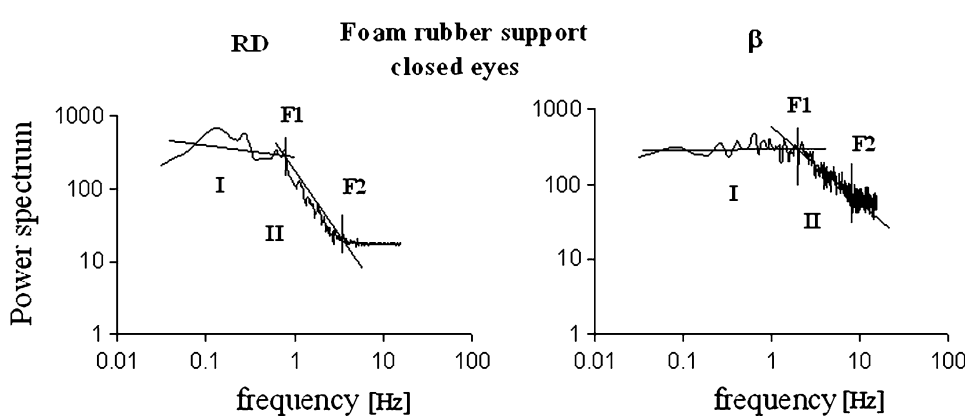

Fig. 3 Log-log plots of the RD and β power spectra for one person during stance on foam support with closed eyes. *Vertical bars* denote the frequency range where self-similarity exists

Table 1 Characteristics of radius-vector length (RD) of COP displacements for all subjects (mean ± SD) in four different experimental conditions

Experimental condition	Frequency range of slope		Duration of self-similarity intervals (s)	PS slope α	D_f
	F_1	F_2			
Stable support, open eyes	0.17 ± 0.02	1.32 ± 0.03	5.14 ± 0.53	2.58 ± 0.33	1.21 ± 0.12
Stable support, closed eyes	0.19 ± 0.02	2.20 ± 0.1	4.82 ± 0.52	2.45 ± 0.42	1.25 ± 0.17
Foam support, open eyes	0.19 ± 0.01	3.78 ± 0.03	5.01 ± 0.32	2.68 ± 0.41	1.16 ± 0.48[a]
Foam support, closed eyes	0.72 ± 0.07	4.25 ± 0.05	1.14 ± 0.09[b,c]	2.64 ± 0.39	1.18 ± 0.12[b]

[a] Significant difference ($p < 0.05$) between foam support versus stable support (open eyes)

[b] Significant difference ($p < 0.05$) between foam support versus stable support (closed eyes)

[c] Significant difference ($p < 0.05$) between closed eyes versus open eyes (foam support)

Table 2 Characteristics of the angle of rotation (β) of the COP displacements for all subjects (mean ± SD) in four different experimental conditions

Experimental condition	Frequency range of slope		Duration of self-similarity intervals (s)	PS slope α	D_f
	F_1	F_2			
Stable support, open eyes	0.47 ± 0.02	8.74 ± 0.06	2.02 ± 0.09	0.71 ± 0.25	1.14 ± 0.06
Stable support, closed eyes	0.53 ± 0.02	10.56 ± 0.04	1.8 ± 0.06	0.75 ± 0.3	1.12 ± 0.07
Foam support, open eyes	1.19 ± 0.03	10.69 ± 0.03	0.75 ± 0.02[a]	0.77 ± 0.23	1.11 ± 0.06
Foam support, closed eyes	2.16 ± 0.02	10.71 ± 0.09	0.37 ± 0.04[b,c]	0.96 ± 0.2[b,c]	1.02 ± 0.08[b,c]

[a] Significant difference ($p < 0.05$) between foam support versus stable support (open eyes)

[b] Significant difference ($p < 0.05$) between foam support versus stable support (closed eyes)

[c] Significant difference ($p < 0.05$) between xlosed eyes versus open eyes (foam support)

both open and closed eyes compared to when standing on the hard support. The durations of self-similarity intervals of the angles in subjects with both open and closed eyes when standing on the foam pad were significantly smaller ($p < 0.05$) than during the stable surface stance (Table 2). The β self-similarity interval was between 2 s for the stable support and 0.4 s for the foam support (Table 2). Significant differences in D_f were observed between subjects on stable and foam supports ($p < 0.001$) with eyes closed and between subjects with open and closed eyes standing on the foam support ($p < 0.001$).

Figure 4 illustrates the double log plots of SF and their first derivatives for RD (Fig. 4a) and β (Fig. 4b). SF for RD increased for small n and saturated for large n, while the first derivatives of SF were almost constant (Fig. 4a). According to the criteria of Provenzale et al. [22], these changes in SF and its first derivative suggest a nonlinear stochastic process with fractal dynamics. The shapes of both SF and its first derivative for β were approximately identical with flat plateaus with zero slopes (Fig. 4b). These results suggested possible chaotic dynamics of β [22].

Some classes of the stationary random processes with $1/f^{\alpha}$ spectrum exhibit nonlinear fractal properties that could be erroneously classified as chaotic dynamics. The RD showed typical fractal dynamics, while β presented ambiguous behavior (fractal or chaotic). To clarify these findings, an additional test was applied to test the surrogate data.

In order to select the proper embedding dimension, the correlation integrals and their first derivatives (D_2) were computed for $m = 2, 4,\ldots, 18$. A saturation of the plot D_2 for real data ($D_{2\ \mathrm{real}}$) was reached after $m = 14$ (Fig. 5). The null hypothesis Ho ($D_{2\ \mathrm{real}} = D_{2\ \mathrm{sur}}$) was not rejected (Wilcoxon's test, $p < 0.05$). In other words, chaotic dynamics of β was not observed for all experimental conditions (Table 3). Rather, β had a fractal structure with a blurred self-similarity.

Discussion

The results of this study support the hypothesis of fractal behavior of postural sway during quiet upright stance promoted by some authors, who have used various nonlinear methods and posturographic measurements for study [11–16]. We described a simple technique for estimating the nonlinear properties of two parameters (radius-vector length and angle of rotation) of COP displacements in support under the feet by an estimation of duration of the

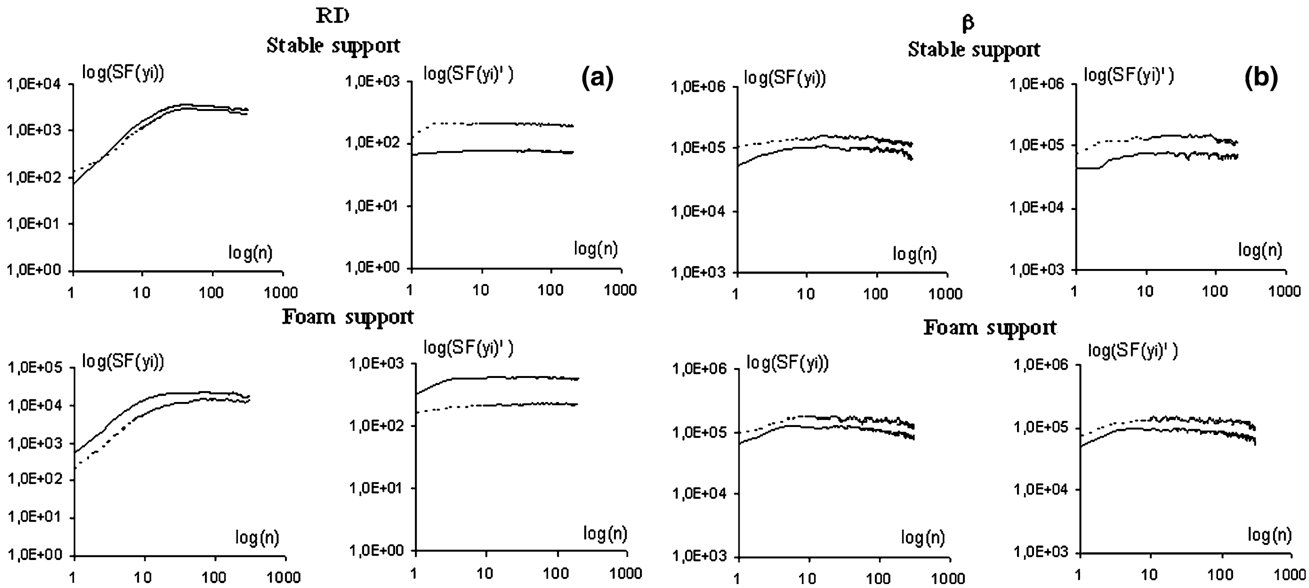

Fig. 4 Structure function (*left*) and its first derivative (*right*) for one subject during stance on both stable and foam supports with open and closed eyes. **a** RD **b** β. *Solid line* represents closed eyes and *dotted line* open eyes

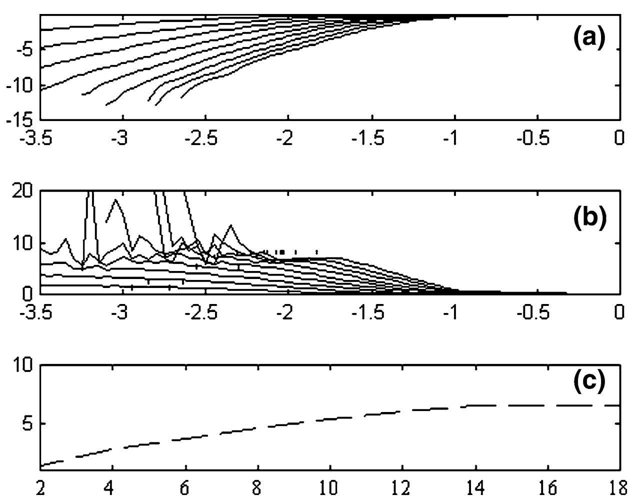

Fig. 5 **a** Correlation integrals family for β (foam support, eyes open) for embedding dimension $m = 2, 4, \ldots, 18$ (*top to bottom*). **b** Family of correlation dimensions D_2 for embedding dimension $m = 2, 4, \ldots, 18$ (*bottom to top*). The *small vertical marks* in D_2 plots denote the plateau for a given m. **c** Correlation dimension $D_2 = f(m)$, when embedding dimension $m = 2, 4, \ldots, 18$. Saturation is reached after $m = 14$

Table 3 Correlation dimensions for real angle of COP displacement and for its 10 surrogates under various experimental conditions

Experimental sessions	Correlation dimension D2	
	Real data	Surrogate data
Eyes open, stable support	8.97	8.79 ± 0.76
Eyes closed, stable support	8.73	9.34 ± 0.55
Eyes open, foam support	6.65	6.46 ± 1.12
Eyes closed, foam support	6.54	5.74 ± 1.03

self-similarity intervals, fractal dimension, and structural function. Our results showed that in healthy subjects during quiet stance, RD and β have nonlinear properties that can still be described by the $1/f^{\alpha}$ law, regardless of changes due to the altered visual and/or proprioceptive inputs. The length of the linear slope α in the log-log plot of the PS, the duration of the self-similarity intervals, and the fractal dimension were different for RD and β, which defined their different levels of the fractality. The RD structure shows typical fractional Brownian motion (α about 2 and D_f between 1 and 1.5), while β showed a blurred self-similarity identical to the flicker noise ($\alpha < 1$ and D_f close to 1).

In order to maintain postural stability, the central nervous system integrates information from multiple sensory channels and generates complex motor responses. Two major mechanisms are responsible for postural adjustment: (1) compensatory postural adjustment (feedback mechanisms), activated by sensory events related to posture unsteadiness and (2) anticipatory postural adjustment (feedforward mechanisms), predicting the disturbances and producing preprogrammed responses for the maintenance of stability. Some of the compensatory postural adjustments are innate, while others are learned during growth and daily life. The minor role of the visual system in the fractal behavior of postural sway has been observed in healthy adults during stance on stable support [14–16]. In these studies, the examination of COP trajectories was based on the evaluation of medial-lateral and anterior-posterior postural sways. Furthermore, no significant differences between subjects with open and closed eyes standing on hard support were established using a variety of nonlinear analysis techniques including detrended fluctuation analysis and diffusion coefficients [14], fractal dimension by modified pixel dilation (mPD) method [15], and Higuchi's algorithm [16]. Our results are in line with the above suggestion as we also did not observe significant differences in our investigated parameters—duration of the self-similarity intervals and D_f—between subjects with eyes open and closed during hard support stance. We assume that the central nervous system (CNS) has saved in memory a relatively stable model of postural control during quiet upright stance on firm support as this is the most widely encountered environment in daily life; the role of the visual system is less important here than proprioceptive and vestibular inputs [16, 26].

Collins and De Luca [8, 9] suggested that both closed-loop and open-loop mechanisms of postural control are present to control postural sway. Open-loop control and closed-loop control are closely related to the concepts of feedforward and feedback, respectively. All of these concepts are derived from systems and control engineering, and they provide descriptions of two different ways in which the nervous system behaves in controlling movement. Feedback control is often referred to as closed-loop control because the outgoing commands, the effectors, the feedback signals, and the control center all form a loop. Feedforward control is often referred to as open-loop control in order to emphasize that feedback sensory signals do not directly affect the timing of the response. In general, closed-loop control can supplement open-loop control in maintaining upright stance stability, since feedback can be utilized by the CNS to control postural sway when there are challenges to the central program. The long duration of self-similarity intervals of RD (about 5 s) and β (about 2 s) can be explained by this hypothesis [8, 9] for postural stability during stance on firm support.

The ability to assess pressure distribution and body orientation decreases when standing on a foam pad, where proprioception and tactile information are altered [27]. In addition, the compliant visco-elastic surface reduces the effectiveness of the ankle torque required for the postural stabilization [28]. These facts can explain why, during the upright stance on the foam pad, we observed significant differences in the mean duration of self-similarity intervals and mean values of fractal dimension D_f under both conditions—open and closed eyes.

In case of a heavy sensory conflict, when postural control was relying on the vestibular system only (stance on foam support with closed eyes), the self-similarity intervals were shorter and the D_f decreased (by about 1) for both the linear and angular parameters of the COP displacements. This indicates an enhanced contribution of the open-loop mechanism related to feedforward postural control. When the vestibular input was predominantly active, the CNS produced an adequate response to correct for postural instability. It is likely that the influence of vestibular information is essential to accomplish the necessary changes in postural control strategy from ankle to hip during stance on unstable support [31]. The changed information from the visual and proprioceptive inputs in healthy subjects, however, impacts only the degree of fractality, while the total fractal structure of postural control process is preserved.

The visual system participates in the maintenance of postural stability, especially when other sensory systems are compromised [29, 30]. Our results during stance on the foam support with eyes open also support the suggestion that vision provides an effect of stabilization in the case of altered proprioceptive and tactile information.

In conclusion, the present results indicate that the COP displacements during quiet stance have complex dynamics and nonlinear characteristics. The self-similarity interval and fractal dimension of both radius-vector length and angle of rotation of COP are quantitative parameters related to the dynamic characteristics of the process-generating program of postural control and can be used for investigation of postural stability.

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