Long-range correlations in human standing

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Abstract

We estimated long-range correlations in the dynamics of sway during prolonged human standing. Two methods were used in this estimation: detrended fluctuation analysis (DFA) and power spectral analysis. Both methods yielded similar results: we observed long-range correlations with single scaling exponents over a broad range, from 10 s to 10 min, of standing. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Since humans adopted their bipedal stance, they have been challenged to maintain equilibrium of the body over a small area of support. Only when the ability to control the upright stance deteriorates, as for example in elderly people and in certain pathologies (e.g., vestibular disorders and stroke), does one realize how difficult and crucial this task is. Maintaining balance is a complex task achieved by integrating various types of sensory information (visual, vestibular, and somatosensory) and relying on the passive properties of the musculo-skeletal system. A remarkable example of the human efforts to understand postural control is the study on adaptation to microgravity environment performed by a space shuttle crew [1].

When asked to stand quietly, humans do not stay motionless — they sway. This sway is usually recorded with a force platform, a measuring device on which the subjects stand during the experiments. The most common variable to analyze this sway is the location of the center of pressure (COP), the point of application of the resultant of vertical forces acting on the surface of support. The COP displacement represents a collective outcome of the postural control system and the force of gravity [2]. The COP displacement over short periods of time ($\leqslant 1$ min) during quiet stance has been modeled as a random walk process, interpreting the outcome of the posture control system as a stochastic process rather than as a deterministic one [3]. It was reported that COP displacement was persistent up to about intervals of 1 s (positive correlations), and for intervals of 1 to about 10 s an anti-persistent behavior was present (negative or anti-correlations). Based on the boundaries of the base of support during mo-

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tionless standing, the authors hypothesized that the process should saturate at the region of 10 to 30 s, i.e., no long-range correlations for time intervals above 30 s were expected during quiet stance; but the authors recognized that longer time series were necessary for a final conclusion [3]. Recently, an analysis of quiet standing by wavelet statistics has shown different scaling regions (multifractal) in short time series [4].

One shortcoming in the studies of human standing is that quiet stance tasks with the instruction "to stay as still as possible" are limited to only a few minutes due to fatigue. On the contrary, natural standing over prolonged periods, longer than few minutes, is a very common situation in daily life, such as standing in line, or standing while talking with somebody. This standing is characterized by repeated changes in the body position, which are self-induced, performed almost unconsciously, and cannot be generally associated with any external source. Such natural standing is not fatiguing and can be reproduced in the laboratory by a standing task during which a person is allowed to do any movement without any constraint, except to stay within the limited area of the force plate. This unconstrained standing in healthy adults was examined by Duarte and Zatsiorsky [5] who observed very low frequencies in the displacement of COP during unconstrained standing, a typical signature of a long-range correlation process or long-memory process. Recently, Duarte and Zatsiorsky [6] used the classical rescaled adjusted range analysis or R/S statistic [15] to describe the fractal properties of the COP time series during natural standing. The average fractal or Hurst exponent (H) was 0.35 ± 0.06. In this Letter, we used more robust methods and performed a surrogate test to quantify the long-range correlation phenomena during prolonged periods of unconstrained standing.

Long-range correlation processes present very long-term fluctuations in addition to very short-term fluctuations, where the dependence of data farther apart is higher than it is expected for independent data. This phenomenon has been observed in very diverse areas of nature. Related to biological systems and specifically to humans, it has been observed in stride intervals during walking [7], human cognition [8], intervals between rhythmic tapping movements [9], heartbeat variability [10,11] and certain DNA sequences [12,13].

2. Methods

In this study, ten healthy subjects (28 ± 5 yr, 1.79 ± 0.09 m, and 78 ± 14 kg) were asked to stand in an unconstrained upright bipedal posture on a 40×90 cm force plate for 30 min (the methods were described in detail elsewhere [5]). We analyzed the COP trajectories for the anterior–posterior (a–p) and medial–lateral (m–l) direction. Examples of stabilograms (the mapping of COP a–p versus COP m–l) and a exemplary time series are shown in Fig. 1.

The stochastic model of fractional Gaussian noise (or the integrated function, fractional Brownian motion) is an example of a self-similar process (like a fractal) appropriate to model such long-range correlation phenomena. This model has been successfully used in many of the above examples and it was used here. Several heuristic methods have been suggested to estimate long-range correlations since the classical R/S statistics proposed by Hurst in hydrology context (for a review of models and methods, see [14]). Two methods were used to estimate long-range correlations: power spectral analysis (PSA) [14], performed in the frequency domain, and detrended fluctuation analysis (DFA) [10], performed in the time domain.

The PSA method involves plotting the power spectra of a sample path on a log–log scale. If the sample path presents long-range correlations over a range of frequencies then significant linear regression in the log–log plot captures the relation between frequency and power of the type $1/f^{-\beta}$, where f is the frequency and β is the scaling exponent. The exponent β is 0 for white noise, -1 for $1/f$ noise, and -2 for Brownian noise.

The DFA method is a modification of the root-mean square analysis of a random walk [15] and it is less sensitive than the PSA method to possible nonstationarities and noise in the data such as the COP displacement during unconstrained standing. For a random walk process, the net displacement of a walker after k steps is $y(k) = \sum_{i=1}^{k} u(i)$, where $u(i)$ is a sample path of a random walk process or a Brownian motion. Using the DFA method, the integrated sample path, y, of total length N is divided into windows of length ℓ; each window steps forward by an interval ℓ/s, where s is the overlapping parameter set to 2 in the present study, and $N/(\ell/s)$ is the total number of windows. For each window, the local trend is estimated by a lin-
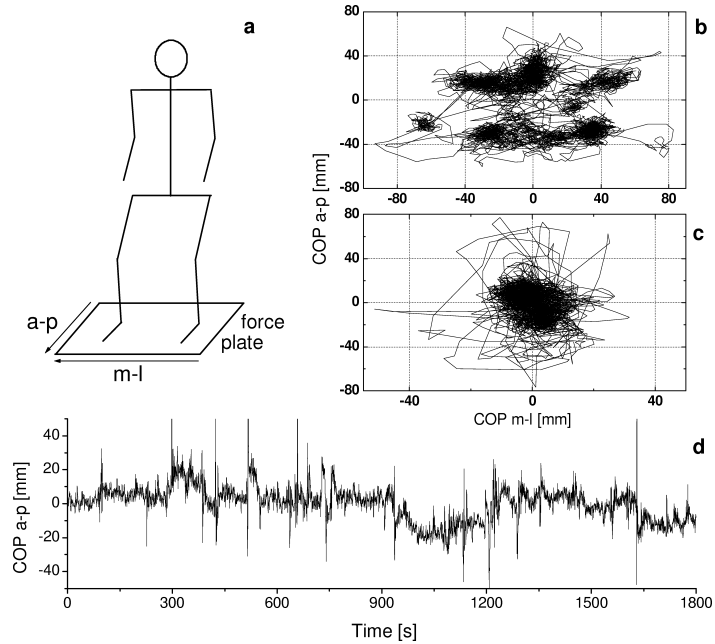
Fig. 1. Position of the subjects on the force plate and axes convention (a). Two examples of stabilograms during a 30 min PUS: multi-region (b) and single-region standing (c). Exemplary COP time series (d).

ear least-squares fit, $\hat{y}$, and the curve is subsequently detrended. The variance of each window's detrended sample path is calculated. The root of the mean variances of all windows of length ℓ is the detrended fluctuation, F, of the walker:

$$F(\ell) = \sqrt{\frac{\ell/s}{N} \sum_{n=1}^{N/(\ell/s)} \frac{1}{\ell} \sum_{k=1}^{\ell} [y(k) - \hat{y}(k)]^2}.$$

The root-mean square fluctuations increase with ℓ, and if there is a linear relationship in a log–log scale of F with ℓ, the data obey a power-law function, $F(\ell) \sim \ell^{\alpha}$, where α is the scaling exponent quantifying the long-range correlations. For white noise, the exponent α is 0.5, for $1/f$ noise it is 1, and 1.5 for Brownian noise. For data with infinite length, the exponents α and β are related by the expression $\beta = 1 - 2\alpha$ [16].

3. Results and discussion

Long-range correlations for the COP data were analyzed for lags/window lengths greater than 10 s and up to one-third (10 min) of the 30 min data. The

lower limit was selected to ignore the already reported short-range correlations for quiet stance in the range of 1 s [3]. The upper limit was chosen to obtain three independent sets of data, in order to increase the statistical power of the results. The fitted line for each trial in the region of 10 s to 10 min representing the scaling exponent (slopes) obtained by the DFA and PSA methods are shown in Fig. 2. The α exponents were 0.98 ± 0.17 and 1.01 ± 0.26 for the a–p and m–l directions, respectively. The β exponents were -1.00 ± 0.42 and -1.27 ± 0.63 for the a–p and m–l directions, respectively. These results satisfied the relation $\beta = 1 - 2\alpha$ and indicated the presence of nontrivial long-range correlations. Because the reported values were less than the values for Brownian motion, the correlations were in fact anti-correlations (negative correlations).

The variability of α (expressed by the mean standard deviations) was about 2.5 times lower than the variability of β. As expected, this indicated that the DFA method yielded more robust results that were less sensitive to nonstationarities. The average value of α for the COP data in the a–p and m–l directions was 1.00 ± 0.22 (range: 0.68–1.47), which is equivalent to
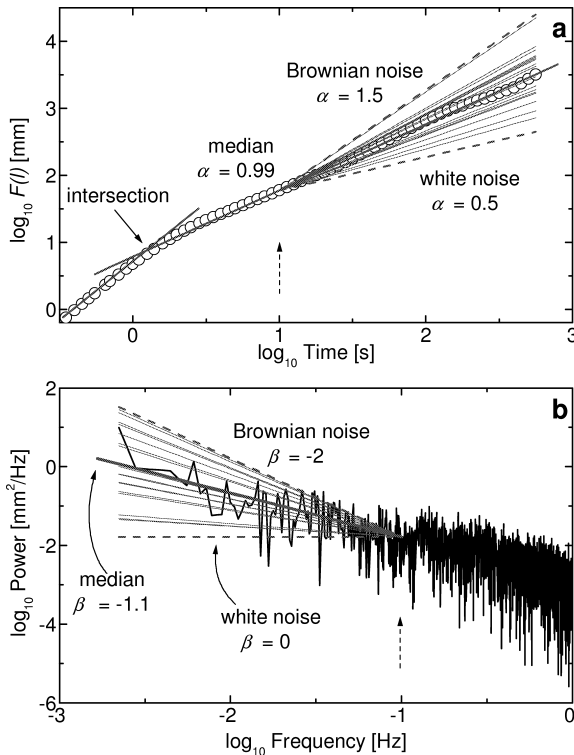
Fig. 2. DFA exponents α (a) and PSA exponents β (b). Thin lines are the slopes for the ten subjects and both directions for lags greater than 10 s or frequencies smaller than 10^{-1} Hz (indicated by the dashed arrows). The median values are shown with thick lines. The lines and values of the scaling exponents for white and Brownian noise are shown for comparison (dashed lines).

the value $\alpha = 1$ for $1/f$ noise, as shown in Fig. 2. The reported range of the scaling exponents for different subjects may suggest that the observed long-range correlations are not only a verification of the ubiquity of $1/f$ noise in the nature but rather a phenomenon manifesting differently across healthy adult subjects.

To determine the statistical significance of the results for long-range correlations, a surrogate test was performed [17]. To this end, ten new sample paths were created by randomly shuffling the original sample path; the created sample paths had the same mean and variance as the original ones but should have no long-range correlations, indicated by $\alpha = 0.5$ and $\beta = 0$. Comparing the mean of the scaling exponents for the set of shuffled data with the mean of the original sample path, the difference between the scaling exponents was well above three standard

deviations, for each of the ten subjects and for both methods. Therefore, the hypothesis of long-range correlations was accepted.

To test if the observed long-range correlations were just an effect of accumulated short-range correlations, the sample paths were divided into windows of 10 s length and the data within each window were shuffled separately. Now, the hypothesis was that the shuffled data should still present long-range correlations if it reflected the global structure of the data. For each of the ten subjects, the shuffled data still presented long-range correlations with scaling exponents close to the original ones for both methods. The hypothesis of long-range correlations reflecting a global structure of the data was therefore accepted again.

A matter of concern was whether the long-range correlations were created by the experimental setup, as electrical devices such as resistors in electrical circuits were shown to exhibit long-range correlations of the form of $1/f$ noise [18]. The force plate used to measure the applied forces and COP position is an electromechanical device based on strain gauges. Indeed, the COP sample path of a dummy with similar weight as our subjects on the force plate produced the expected $1/f$ noise with an $\alpha = 1.05$. However, this $1/f$ noise behavior from the experimental setup could be neglected because the magnitude of the fluctuations was about three orders smaller than the COP fluctuations and the power spectra were about six orders of magnitude smaller than the COP power spectra.

Fig. 2(a) shows the fitted line in the region of 10 s to 10 min for the median data extended to the region of 1 s and a fitted line for the data in the region of up to 1 s. The intersection of these two fits pointed in Fig. 2(a) exemplifies the commented transition in the region of 1 s of a persistent behavior (positive correlation in a short-range scale) to an anti-persistent behavior (negative correlation in a middle-range scale, up to 10 s) of the COP displacement [3]. These results observed in all trials, corroborate the findings of Collins and De Luca [3] and extend the discovery of an anti-persistent behavior from up to 10 s to up to 10 min. Note that in the present study, a more robust method was used (DFA versus classical random walk), the observations were performed during 30 min long trials (as compared to 1 min long trials used for the random walk analysis [3]), and a different task was stud-

ied (unconstrained standing instead of quiet stance). Contrary to the predictions for quiet stance, no indication of saturation of this anti-persistent behavior was found. We hypothesize that the observed saturation during quiet standing reflects the biomechanical constraint given by the base of support rather than a saturation in the neurophysiological processes underlying the anti-persistent behavior — when the biomechanical constraint is reduced, no saturation is observed.

In conclusion, we reported for the first time the existence of long-range correlations in prolonged unconstrained standing; a task similar to the natural standing of the daily life. An open issue is whether alterations in this fractal scaling in human standing may be applied to reveal pathophysiological disturbances as have been observed in heart-rate variability and stride-intervals during walking [7,10].

Acknowledgements

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