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On the fractal properties of natural human standing

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Abstract

We analyzed the temporal evolution of the displacement of the center of pressure (COP) during prolonged unconstrained standing (30 min) in non-impaired human subjects. The COP represents the collective outcome of the postural control system and the force of gravity and is the main parameter used in studies on postural control. Our analysis showed that the COP displacement during human standing displays fractal properties that were quantified by the *Hurst* exponent obtained from the classical rescaled adjusted range analysis. The average fractal or *Hurst* exponent (H) was 0.35 ± 0.06. The presence of long-range correlations from a few seconds to several minutes due to the fractal characteristics of the postural control system has several important implications for the analysis of human balance. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

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Humans usually take for granted their ability to stand upright and maintain their balance. It is only when postural disorders arise that we recognize the complexity of controlling upright stance. Injuries and even loss of life due to falls are frequent problems for the elderly [12]. Maintaining balance during standing is a complex task achieved by the postural control system which integrates information from visual, vestibular, and somatosensory receptors of the body, in conjunction with the passive properties of the musculoskeletal system. Nevertheless, standing for prolonged periods is a common task in daily life. For example, we stand in line, stand and talk with someone, and commonly work in a standing position. This form of standing is characterized by repeated changes in body position, which are self-induced and performed almost unconsciously. Even when a subject is asked to stand as still as possible, his or her body moves continuously to counteract the constantly occurring small perturbations in order to stay within the small area of support provided by the base of the feet. In this letter we report that these fluctuations during natural standing display properties typical of fractals and we address implications of this finding for the study of the human standing.

The main parameter registered in balance studies is the center of pressure (COP) location using a force plate. The COP is the point of application of the resultant of vertical forces acting on the surface of support; it represents the collective outcome of the postural control system and the force of gravity. The COP position is different from the center of gravity (COG) position; while the latter indicates the global position of the body, the COP includes dynamic components due to the body's acceleration. At low frequencies of sway, below 0.1 Hz, however, the COP and the horizontal location of the COG (the gravity line) are similar [19]. Such low frequencies are studied here, so our COP data also applies to the body sway. The fractal nature of the COP displacement during natural standing was conjectured after we observed very low frequency components in the data [5], a fingerprint of a long-range correlation process which is a typical characteristic of fractals. Recently, we quantified these long-range correlations: the COP data during natural standing resembled *1/f* noise [4].

To study the fractal nature of the COP movements during unconstrained standing we asked 10 non-impaired subjects (28 ± 5 years, 1.79 ± 0.09 m, and 78 ± 14 kg) to stand in an unconstrained upright bipedal posture on a 40×90 cm force

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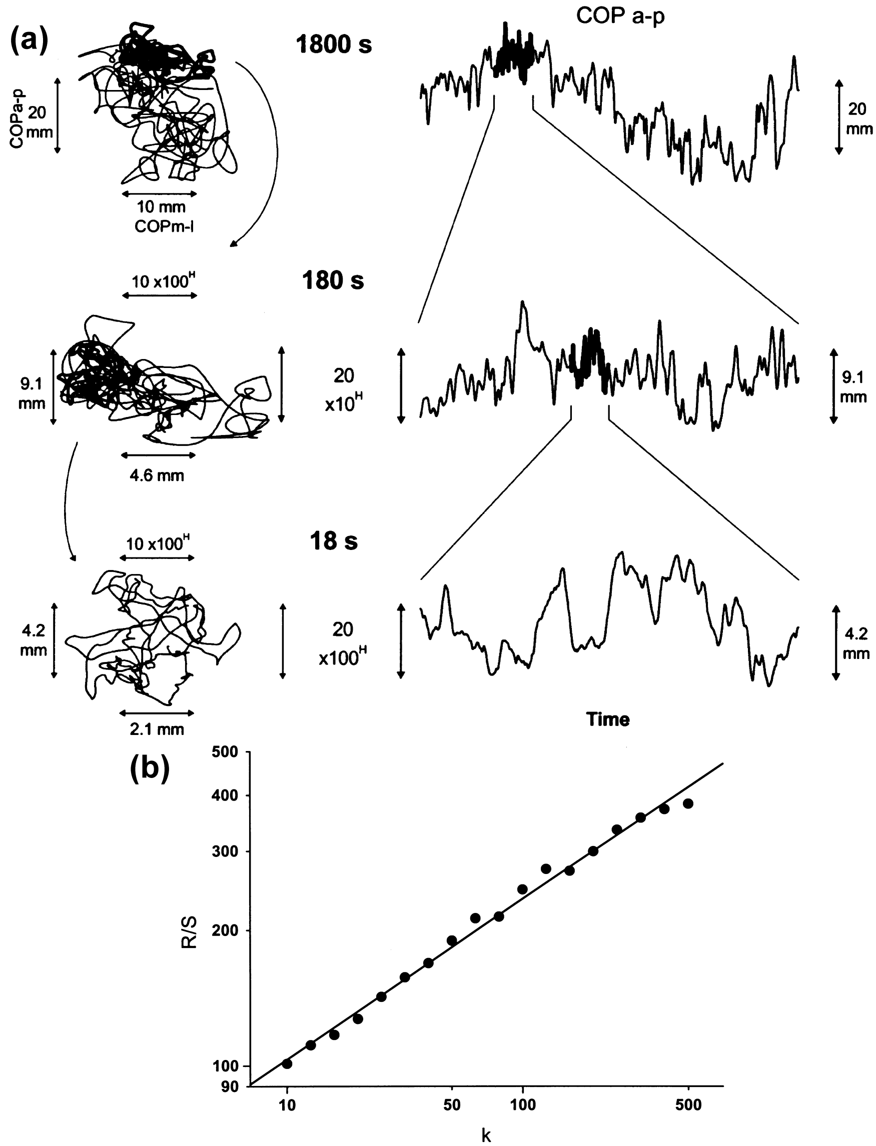

Fig. 1. (a) Stabilograms (left) and anterior-posterior (a-p) COP time series (right) for the entire data during natural standing (1800s, first row), for 1/10 of the data (180 s, second row), and for 1/100 of the data (18 s, third row). The *Hurst* exponent (*H*) for this example is 0.34, giving a reduction of 2.2 in the amplitude scale for each ten times of reduction of the time scale. Both scaled and real axes are indicated in the 180s and the 18 s plots for illustration. Notice that after each scaling (that is related to the fractal exponent and to the period of time), the three stabilograms and the time series present roughly the same amplitudes in space. For the sake of clarity, not all points are shown for the 1800 and 180 s plots. The difference in the fine structure, observed for the 18-s time series compared to the other two time series, is due to the fact that COP displacements for intervals of up to 1 s display a different behavior [3]. This behavior is most probably due to the inertial characteristics of the body or to the different mechanisms of control of balance (known as open-closed loop model [3]). (b) *R/S* plot in log-log scale for the 1800-s COP data of the previous example (fit for $k = 10$ to 600 s, slope $= 0.34$, $r = 0.99$, $P < 0.00001$).

plate for 30 min and recorded the movement of the COP over time (methods are described in detail elsewhere [5]). The subjects were allowed to move their body as long as they stayed within the area delimited by the force plate. In general, the observed movements consisted of postural adjustments without moving the position of the feet. We used the classical method of rescaled adjusted range or *R/S* statistic proposed by *Hurst* that were originally developed in hydrology to describe fractal properties of fluctuations in river levels but later also many other phenomena [1,9].

Let

$$y(k) = \sum_{i=1}^{k} u(i) \tag{1}$$

be the cumulative displacement of a random variable $u(i)$ after k steps. The *R/S* statistic computes a normalized range of the variable $y(k)$ (COP movement in our case) for each k steps (time periods); a measure of the fluctuations of the data for different window sizes

$$R(t,k) = \max_{0 \le i \le k} [y_{t+1} - y_t - \frac{i}{k}(y_{t+k} - y_t)] - \min_{0 \le i \le k} [y_{t+1} - y_t - \frac{i}{k}(y_{t+k} - y_t)] \quad (2)$$

R(t,k) is the adjusted range and in order to study the properties that are independent of the scale. Subsequently, *R(t,k)* is normalized by

$$S(t,k) = \sqrt{k^{-1} \sum_{i=t+1}^{t+k} (u_i - \bar{u}_{t,k})^2} \quad (3)$$

The ratio *R(t,k)/S(t,k)* is called the *R/S* statistic. When the plot of the logarithm of the R/S statistic versus the logarithm of k presents a linear relationship, the data obey a power-law function of type k^H, where H is the *Hurst* or fractal exponent obtained as the slope of a linear regression in this plot. If the data are completely random (uncorrelated data), like white noise, the observed regression line is flat and the H exponent is zero. If the data represent a pure random walk, or Brownian noise (accumulated white noise), H is 0.5, and the data are said to contain trivial long-range correlations. If H is different from 0 or 0.5, the data are said to be of the type of *1/f* noise, where *f* is the frequency of the phenomenon [1,9].

The analysis of the 30-min data was performed with the maximum window size of up to 10 min for both of the two directions of the COP movement, the anterior-posterior (a-p) and the medial-lateral (m-l) direction. The result of the R/S statistic for the ten subjects gave a *Hurst* exponent of 0.35 ± 0.06 (mean $\pm$ SD, $n = 20$), ranging from 0.25 to 0.50, with an average fractal dimension, *D*, of 1.65 ($D = 2 - H$). In general, we did not observe different values of H for different ranges in the *R/S* plots. The correlation coefficients of the least square linear regression were always above 0.9 and did not show any relation to the H values. Furthermore, in order to confirm the hypothesis of the presence of long-range correlations, we performed a test on surrogate data [16]. The results supported the hypothesis of long-range correlations. It can therefore be concluded that the COP movements have similar time and amplitude statistical characteristics when properly scaled by the fractal exponent in the range of a few seconds to 10 min. We did not observe any relation between the postural adjustments or movement of the feet and the H values. These findings are consistent with the ones using other methods to estimate the long-range correlations [4]. The left panels of Fig. 1a show examples of stabilograms (plots of COP in the a-p direction as a function of COP in the m-l direction); the right panels show the respective COP time series in the a-p direction ($H = 0.34$ for this example). The first row presents the entire data set (1800 s), the second row 1/10 of the data (180 s), and the third row 1/100 of the data (18 s). Fig. 1b shows the corresponding *R/S* statistic plot for the entire time series of Fig. 1a. The stabilograms illustrate the typical property of fractals which is self-similarity: When both axes are scaled by 10^{-H}, the data retain the main characteristics in that a similar oscillatory pattern of the COP is observed despite differences in amplitudes. The COP time series also illustrate the fractal property of self-affinity: When the time axis is scaled by ten and the amplitude axis is scaled by 10^{-H}, the data preserve their qualitative structure.

In similar studies on short COP time series Collins and De Luca analyzed correlations of up to 10 s and derived an open-closed loop model for the postural control system acting over such short periods of time [3]. In contrast, the present work analyzes a longer time scale, spanning from 10 s to 10 min. The presence of long-range correlations in the COP data during natural standing has several implications for its analysis and interpretation.

One important issue in postural studies is the period of data acquisition, i.e. for how long should one collect data to capture essential properties of human standing? In a frequently referenced study Powell and Dzendolet [15] reported low frequencies in the COP data of 130 s of duration. Different authors have cited this paper as a reference to justify the acquisition of data for no more than 2 min. Our study suggests that with longer acquisition time, even lower frequencies of COP were observed. We have shown that there is no limit for observing low frequencies in COP time series of up to an interval of 10 min. The important conclusion is that the choice of period of acquisition has to be based on which periods (frequencies) are regarded relevant for the study in question.

Another issue is that the distinction between non-stationarity and long-range correlations in time series analysis is an ill-posed problem, and studies on stationarity in COP data have indeed shown discrepant results. Given our findings of long-range correlations, such differences are the consequence that different investigators have tested only small portions of a longer process. Because of the presence of long-range correlations, apparent non-stationarities in short COP time series might actually represent consequences of fluctuations of a longer stationary process. Thus, the issue of stationarity cannot be adequately addressed using short time series of up to few minutes. Alternatively, this problem can be partially solved by applying a high pass filter to the data with a cut-off frequency related to the period of data acquisition [20]. This method removes the long-range correlations which are otherwise a possible source of error for the apparent non-stationarity in the data.

Finally, the property of self-affinity in COP data within the range studied here has important implications for comparing data acquired over different time periods. To properly compare time series of different lengths, the data should be scaled by the fractal exponent.

The ubiquity of fractals in nature has been observed in wide ranges of different properties of biological systems [2,6–8,13] and it has been applied to model the order of allometric scaling laws in biology [18]. The fact that the displacement of COP during natural prolonged standing follows a fractal scaling law is in line with these findings. Maintaining balance is executed by the postural control system which integrates information from different sources having different latencies and frequency responses and controls a multi-degree-of-freedom mechanical system with highly redundant actuators (many muscles crossing the same joint). Physiological perturbations, e.g. breathing and heartbeats (which also present long-range correlations [7]), continuously perturb the equilibrium. Each of these characteristics can be responsible for the long-range correlation process [10,11,14,17]. Within this scenario, it is unlikely that a single neurological or physiological factor can be identified as the source of the fractal behavior. Rather, this behavior is the outcome of a complex non-linear system involving a number of different systems on different time and length scales of the human body.

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