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Characterizing the human postural control system using detrended fluctuation analysis

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ABSTRACT

Detrended fluctuation analysis is used to study the behaviour of the time series of the position of the center of pressure, output from the activity of a human postural control system. The results suggest that these trajectories present a crossover in their scaling properties from persistent (for high frequencies, short-range time scale) to anti-persistent (for low frequencies, long-range time scale) behaviours. The values of the scaling exponent found for the persistent parts of the trajectories are very similar for all the cases analysed. The similarity of the results obtained for the measurements done with both eyes open and both eyes closed indicate either that the visual system may be disregarded by the postural control system, while maintaining quiet standing, or that the control mechanisms associated with each type of information (visual, vestibular and somatosensory) cannot be disentangled with this technique.

1. Introduction

The human postural control system (PCS) integrates various mechanisms that prevent the human body from falling in both statical and dynamical conditions. Information coming from the proprioceptive, vestibular and visual systems is integrated for this purpose and manifests in postural sway. These three systems include a backup procedure which permits a correct body balance in case some of them fail.

The main tool used to investigate this complex balance system has been the stabilogram, which is a measure of the time behaviour of the center of pressure (CoP) of a person standing on top of a force platform. An important part of the investigations carried out by means of the stabilogram were restricted to "simple" statistics of the CoP path, such as distances from the geometric mean CoP, average CoP velocity, total CoP excursion, maximum distance between any two points on the CoP path, enclosed area, etc. [1]. However, the dynamic characteristics of the stabilogram are of fundamental importance, even in the case of quiet standing, and a great number of recent works, mainly in the last decade, have focused on the analysis of the non-stationary time properties of the CoP path [2–6].

The purpose of this work is to apply detrended fluctuation analysis (DFA) to a set of experimental data including 20 measurements for each of the 20 subjects forming the sampling group. Our purpose is twofold. First we want to address the controversy between Collins and De Luca [2] and Delignières et al. [6] with respect to the actual presence of a crossover from persistent to anti-persistent behaviour. On the other hand, having at our disposal a large quantity of measurements, we want to find more quantitative results for the scaling properties of the CoP trajectories.

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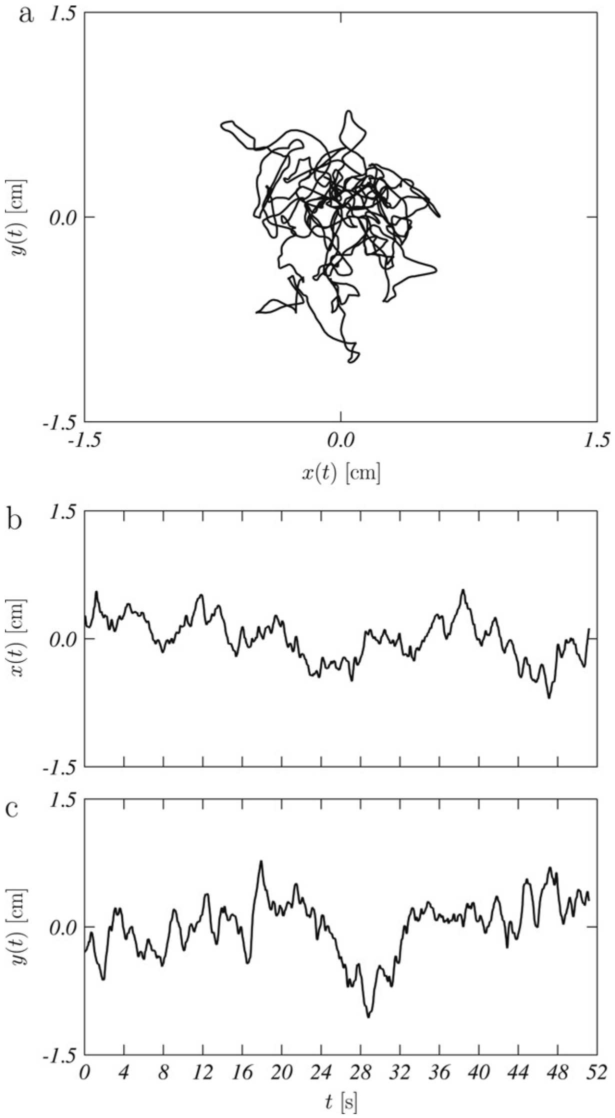

Fig. 1. (a) Typical CoP trajectory obtained from our measurements. The two components $x(t)$ (b) and $y(t)$ (c) are obtained from the CoP trajectory and analysed as separate time series. These results correspond to subject number 4 (eighth measurement) under **eo** conditions.

2. The experiment

CoP paths from 20 healthy subjects (13 females and 7 males) with an average age, weight and height of 33.7±8.2 years, 65.3±14.8 kg and 1.65±0.11 m, respectively, were collected with a force platform manufactured by Satel [7]. Measurements were performed in quiet standing, with the subjects looking in the forward direction and with their arms at their sides. In all cases the subjects stood barefoot on the platform. Trials of two types were carried out under both eyes open (**eo**) and eyes closed (**ec**) conditions. Each measurement lasted for 51.2 s and was repeated ten times, on different days, in order to study the reproducibility and consistency. A sampling rate of 40 Hz was used. The duration of the measurements tries to avoid the possible influence of the tiredness of the subjects in their postural control system. However, other authors consider 20 and 30 s [5,6] and 90 s [2]. The possible influence of this time on the final results has not yet been studied. However, our time series include 2^{11} points and DFA should produce feasible results [8].

For the analysis, the CoP trajectory is separated into its mediolateral, $x(t)$, and anteroposterior, $y(t)$, components which provide time series which are studied separately, as we can see in Fig. 1.

3. The DFA method

The DFA method, which was first introduced by Peng et al. [9], is a scaling analysis method that provides a scaling exponent, α, which gives information concerning the correlation properties of the signal.

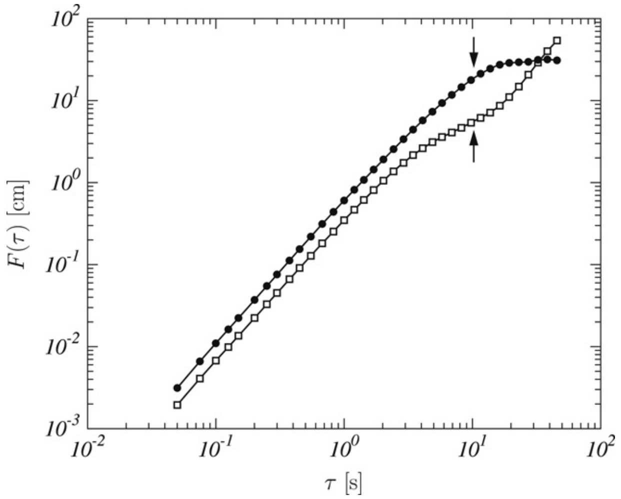

Fig. 2. Values of $F(\tau)$ obtained for both the x (black points) and y (white points) coordinates as a function of the box size τ. The arrows indicate the biggest value of τ used for the calculation of α.

The procedure begins with an N-point time series $\{z_t, t = 1, \dots, N\}$. First, we calculate the accumulated series

$$Z(t) = \sum_{u=1}^{t} (z_u - \langle z \rangle),$$

where

$$\langle z \rangle = \frac{1}{N} \sum_{t=1}^{N} z_t$$

is the global mean. Second, a certain number N_b of boxes of equal length τ are extracted from the series Z. These boxes contain N_τ points and can overlap or not. In each box, the so-called local trend is obtained by fitting the values $Z(t)$ to a polynomial. This local trend is labelled Z_{fit}^k, where the index k indicates the box number. The detrended fluctuation function in each box is then obtained as

$$\psi^k(t) = Z(t) - Z_{\text{fit}}^k(t).$$

For each τ, we calculate the function

$$F(\tau) = \left(\frac{1}{N_b} \sum_{k=1}^{N_b} \frac{1}{N_\tau} \sum_{t=1}^{N_\tau} \left[\psi^k(t) \right]^2 \right)^{1/2}.$$

This function measures the root mean squared fluctuations. The presence of scaling is characterized by

$$F(\tau) \sim \tau^\alpha.$$

The scaling exponent α includes the information concerning the correlation properties of the signal: $\alpha = 1.5$ is characteristic of an uncorrelated random series (or white noise), while the signal presents positive (negative) correlations if $\alpha > 1.5$ ($\alpha < 1.5$). In the following, we use the notation α_S and α_L to indicate the values of the scaling exponent for the short-range and long-range time scales, respectively.

4. Results

In Fig. 2 we show a typical result of the analysis done in this work. Here we have used the so-called DFA-2 in which a second-order polynomial is considered for Z_{fit}^k.

In Table 1 we summarize the values of α_S and α_L obtained with the full set of measurements done (labelled "total") and with those performed in **eo** and **ec** conditions for the two coordinates x and y.

The first result that deserves comment is the fact that no differences are observed between **eo** and **ec** conditions. As we can see, the average values of both α_S and α_L are statistically compatible for the two measurement condition types. This indicates that the absence of visual information does not modify the scaling properties extracted by the DFA. However, Thurner et al. [5] have found some differences between **eo** and **ec** conditions in the analysis of a set of similar measurements using wavelet techniques. Thus, our results seem to indicate the inability of the DFA to elucidate the effect of the visual information in this context.

Table 1
Average values of α_S and α_L in **eo** and **ec** conditions and for all the measurements. The results obtained for both the x and y directions are shown.

	eo	**ec**	Total
	x		
α_S	2.19±0.14	2.21±0.13	2.20±0.14
α_L	0.95±0.31	0.81±0.31	0.88±0.31
	y		
α_S	2.14±0.15	2.17±0.15	2.15±0.15
α_L	1.09±0.36	0.91±0.30	1.00±0.34

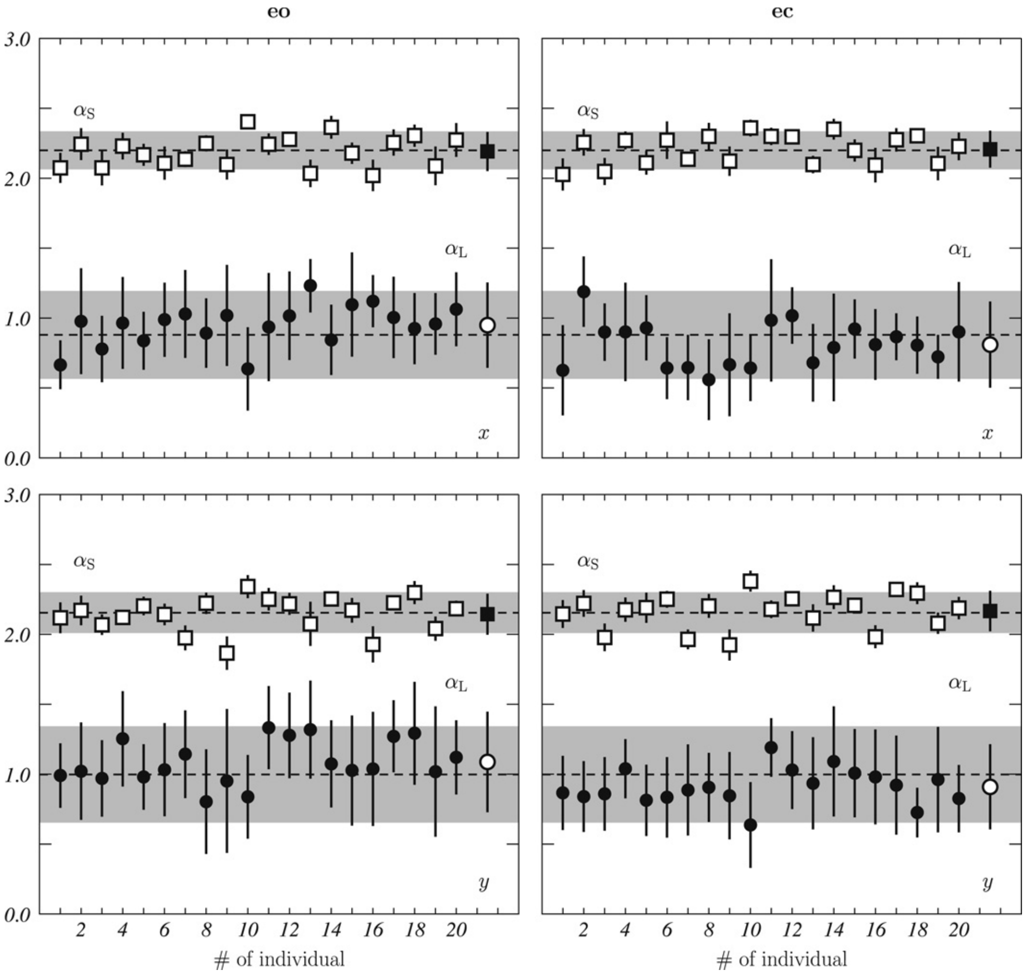

Fig. 3. Values of the average of the α exponent for different situations (see the text).

Also, there are no significant differences between the results observed for the x and y coordinates. This permits us, at least in principle, to analyse only one of the coordinates and, eventually, could be a tool for detecting patients with problems (by checking possible differences between the $F(\tau)$ functions found for the two coordinates). This similarity of the results obtained for the x and y coordinates has been found by other authors [2,10,6].

It is important to note that our analysis indicates clearly the presence of two scaling regimes in the CoP trajectory. In the low-τ end, the slope is larger than 1.5, showing a persistent behaviour, while in the large-τ end an anti-persistent shape appears. This is in agreement with the earlier findings of Collins and De Luca [2]. On the other hand, our results contradict those of Delignières et al. [6] who did not find such a change of regime. Their conclusion was based on the fact that the slopes for short and long time intervals were visually similar for the subjects considered, and they did not consider it necessary to analyse them separately. The average scaling exponent that they obtained was 1.054 (1.103) for the x (y) coordinate.

In Fig. 3 the average values of the exponent α for the various individuals are plotted. The upper panels correspond to the x direction and the left (right) panel corresponds to **eo** (**ec**) conditions. In each panel the black points give the average values of α_L for the ten measurements performed for each individual. Open squares correspond to α_S. Open circles (black squares) give the average of the values of α_L (α_S) found for the measurements performed in the corresponding conditions (these last results are also given in Table 1). In all cases, the vertical lines provide the corresponding statistical uncertainties. Finally, the gray bands give the statistical uncertainties for the total set of measurements (that is, including **eo** and **ec** measurements); the corresponding average value is indicated with a dashed line (values also given in Table 1). Lower panels in Fig. 3 provide the same information but for the *y* direction.

The situation for α_L is much more noisy due, basically, to the statistical noise observed in $F(\tau)$ for large τ. In any case, Peng et al. [11] have found the same scaling exponent for the heartbeat time series for healthy subjects, $\alpha_L = 1.00 \pm 0.11$. This suggests high complexity of the physiological mechanisms that produce this long-range correlation process. These authors found also a crossover in the scaling similar to the one that we have obtained.

The log–log plot of $F(\tau)$ (see Fig. 2) shows a slight curvature that indicates a progressive change from persistent to anti-persistent behaviour. This is due probably to the coexistence of the two behaviours around the crossover point.

It is worth pointing out that the variance found for the low-frequency part of the CoP trajectory is much larger than the one shown by the high-frequency one. This result is in accordance with the findings of Zatsiorsky and Duarte [4] for the rambling and trembling components of the stabilogram.

5. Conclusions

We have not found differences between the results obtained under **eo** and **ec** conditions. This indicates that the DFA is not able to elucidate the role played by the visual information.

Also, no significant differences are observed for the results obtained for the *x* and *y* coordinates.

The CoP trajectories show a persistent behaviour ($\alpha > 1.5$) at low τ values (high frequencies). This behaviour changes to anti-persistent showing $\alpha \sim 1$ for large τ values (low frequencies).

The scalings of all the CoP trajectories studied at low τ values show similar exponents, suggesting the existence of a hidden physiological mechanism. We hypothesize that this constant scaling in the persistent region is due to peripheral reflexes controlled by the spinal cord, such as the myotatic reflex. These mechanisms help to maintain the postural tone but the persistent nature found indicates that they are not able to keep human balance by themselves.

The scaling exponent at large τ values appears to be more noisy, though an average value $\alpha_L \sim 1.0$ has been found for all the cases analysed. This region can be assumed to be controlled by visual, vestibular and somatosensory inputs and acting at low frequencies. The anti-persistent nature suggests that these mechanisms are able to control the whole human body in order to maintain the quiet stance.

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