Shape Analysis of Postural Sway Area

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Abstract — **Measurement of the human body centre of pressure (COP) movement (postural sway) with a force platform is a standard procedure for the assessment of postural stability. Recently we proposed a method where the outline of the sway region is expressed in terms of Fourier coefficients determined by asymmetric fitting and minimal outline bending. The index of sudden excursions (ISE) is defined as the ratio of this sway area to the one obtained by the standard principal component analysis. The meaning and the discriminative power of this index is still an open question, which is addressed in present work.**

Stabilometric data were simulated by considering movements of COP in a potential that consisted of a flat central ellipsoidal region and increased quadratically outside it. Using random walk procedure, combined with the Metropolis algorithm, positions of COP were simulated. The parameter called temperature was defined so that it was related to the probability of COP movements against the potential.

A large number of data were calculated for a set of different values of the temperature and the ISE values were determined. For the series of 3000 points the average values of ISE were found at first to increase with temperature from 1.3 to 1.85 as the temperature increased from 0 to 0.195 and then started to decrease towards 1.2 with temperature.

It was shown that ISE is sensitive to the actual shape of the measured postural sway area. It increases if there is a small number of large excursions of the COP outside the central region, which are mostly missed by the conventional analysis.

Keywords — **stabilometry, postural sway, force platform, sway area**

I. INTRODUCTION

Measurement of the movement of the human body centre of pressure (COP) with a force platform (stabilometry) is a standard procedure for assessment of postural stability. Here a subject stands still on a special platform that is mounted on pressure sensors that transmit data via analogue to digital converter to a computer. In such a way, with suitable software, the time dependence of the trajectory of the COP (postural sway) can be determined. Thus obtained stabilogram can be used to assess the balance properties of the investigated subjects. Although this method is well established, the interpretation of the results and the physiological meaning of the calculated parameters is still an open issue. Besides the standard parameters such as COP trajectory length, velocity, displacements and frequency distribution, the interpretations in terms of non-linear dynamics are also very promising [1]. Yet a simple measure to discriminate stabilograms of different populations, of mostly elderly subjects, is needed. For this purpose the shape and size of the area covered by the COP is determined.

The usual method to determine the area of a stabilogram is by the principal component analysis (PCA) of the covariant matrix [2]. The eigenvalues (σ_0^2) of the covariant matrix (σ_{xy}^2)

$$\sigma_{xy}{}^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) \tag{1}$$

are calculated as

$$\sigma_0{}^2 = \frac{1}{2}(\sigma_{xx}{}^2 + \sigma_{xy}{}^2 \pm \sqrt{(\sigma_{xx}{}^2 - \sigma_{xx}{}^2)^2 + 4(\sigma_{xx}{}^2)^2}) \tag{2}$$

where $\bar{x}$ and $\bar{y}$ are the average values and the summation is done over all N measured points.

The sway area is usually reproduced by the ellipse with the two principal axes of the size 1.96 σ_0^2. It thus includes 95 % of points along each axes if the distribution is bivariate Gaussian and as a result only 85.35 % of the data points are within the perimeter of the so defined ellipse [2]. This method reflects the general properties of the sway area but is not sensitive enough to differentiate between clinical conditions where the important changes are expected to be seen mostly near in the sway area perimeter.

This led us to develop a new method based on the Fourier analysis of the sway area outline (FAO) [3, 4]. It was shown that such an analysis realistically approximates the postural sway area and also gives the indications about its shape. This method is based on the observation that a suitable approximation to the sway area is a region determined by a rather simple, mostly convex outline which is predominantly at the outer border of the sway area. From the measured stabilogram the outline is determined by a boundary following algorithm [5]. Such an outline can be reproduced by a Fourier series:

$$\mathrm{R}(\varphi) = \mathrm{R}_0 + \sum_{m=1}^{m_{\max}}(A_m \cos m\varphi + B_m \sin m\varphi) \tag{3}$$

where φ is the polar angle to a point at the outline in a chosen coordinate system, A_m and B_m are the appropriate Fou-

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rier coefficients and m_{max} the maximal number of coefficients used to describe the outline - the more coefficients are used, the smaller details of the shape are reproduced. So defined Fourier coefficients are similar to the Fourier descriptors usually employed in shape recognition procedures [6, 7, 8], the difference is that our outline points are function of the angle rather than the distance along the outline path.

The fitting of the sway area outline is done by minimizing the characteristic function (F):

$$F = \sum_{i=1}^{N} \omega_i (R(\varphi) - R_i)^2 + \gamma \sum_{m=0}^{m_{max}} m^2 (m-1)^2 (A_m{}^2 + B_m{}^2) \quad (4)$$

where the first term is the asymmetric sum of the squares between the calculated (R(φ)) and the measured (R_i) outline points. The asymmetry parameter ω determines the distance the fitted curve can penetrate inside the measured sway area. It equals to one when the distance of the calculated point from the chosen centre is larger than the measured one otherwise it has a preselected value. The second term in eq.(4) is related to the outline bending energy and penalizes the short distance undulations of the outline, depending on the value of the parameter γ.

From our previous work [3] the ratio between the areas as determined by the FAO and PCA methods seemed to be the most promising discriminating parameter between the stabilograms that differed mainly by the small number of COP excursions from the central region. We thus named it the index of sudden excursions (ISE). To better understand the meaning and properties of this index we, in as follows, analyze the simulated data using the same procedure as for the experimental data.

II. METHODS

The meaning of the index of sudden excursions (ISE) which is defined as the ratio between the FAO and PCA areas was thoroughly studied by analyzing simple simulated data.

The fluctuation of the COP position was described by a model that was equivalent to the movement of a particle in a potential that is flat in the central ellipsoidal region and quadratic outside it. In such a way COP could move outside the chosen central region, but the probability of finding it there decreased with the distance from the boundary whereas the temperature parameter (T) defined this probability.

Thus the calculations were done by considering completely free random movement of the COP within a chosen ellipsoidal region and with Boltzmann distribution of the probability to find it outside. For this purpose random walk procedure was used combined with Metropolis algorithm

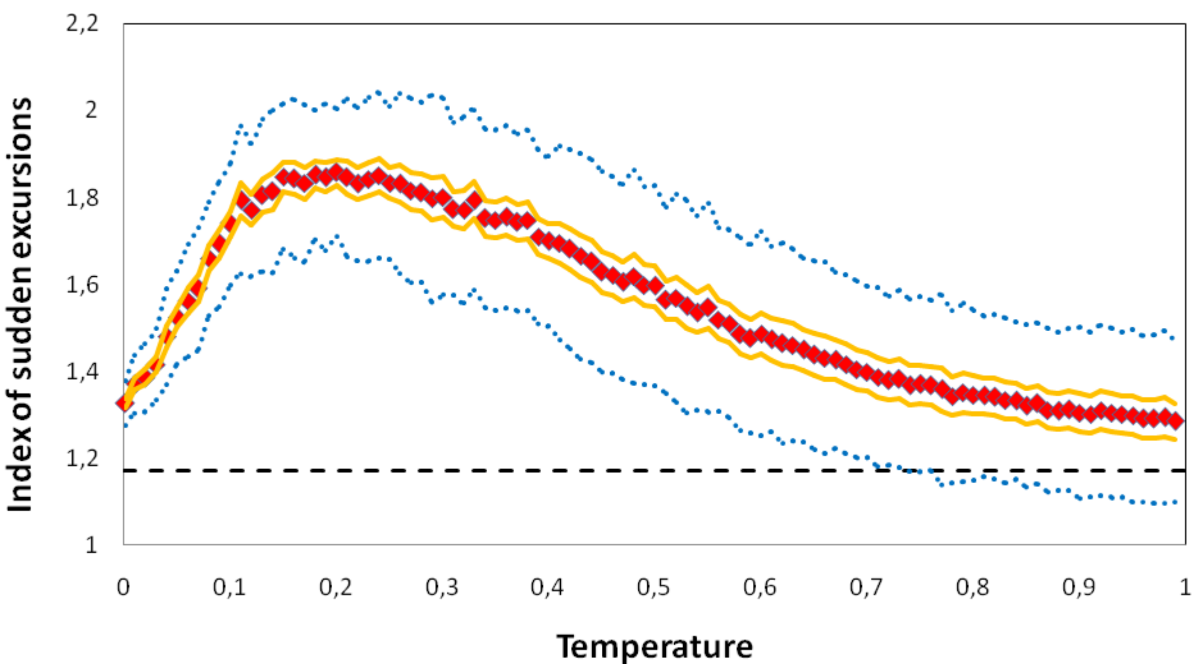

Fig. 1 Index of sudden excursion (ISE) as a function of temperature parameter in units of 1/2π, as defined in text, for the simulated data of 3000 points. Besides the calculated average values of 20 simulation runs (red squares), the lines represent the region of the standard error (yellow) and standard deviation (dotted blue) whereas the dashed line at 1.2 represents the low temperature limit.

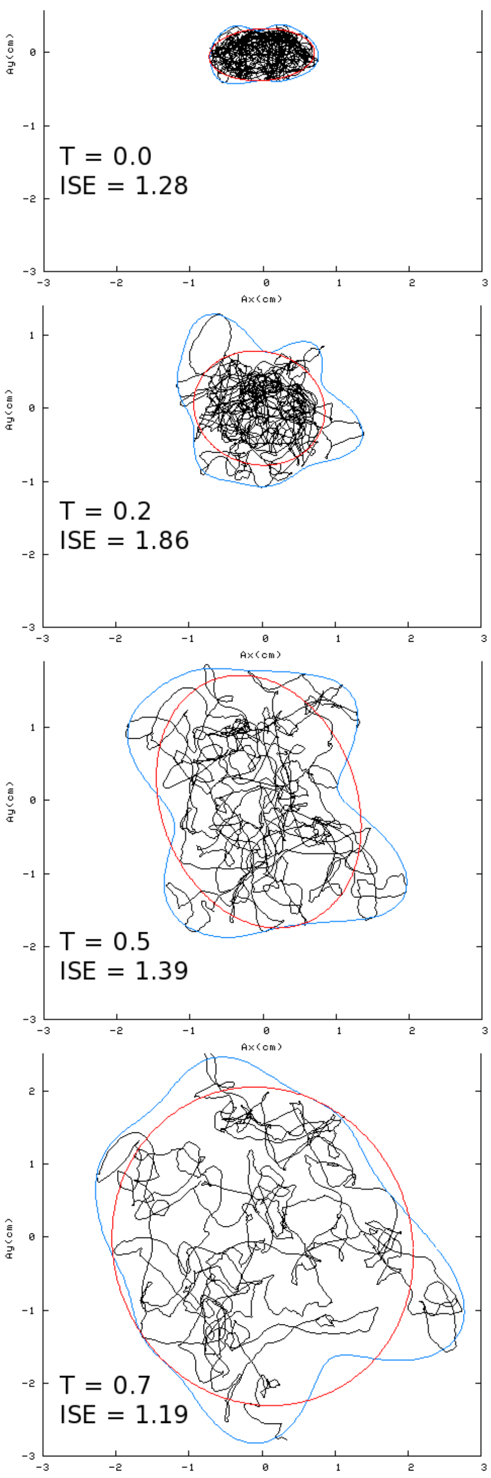

Fig. 2 Simulated data (black lines) for four different temperatures with the PCA ellipsis (red) and the FAO outlines (blue).

[9]. In each step the COP position was randomly moved. If the resulting position was within the central ellipsoidal region it was accepted and the procedure was repeated. But, when the resulting position was outside this region and the previous one was inside it, the distance (ΔR) from the border was calculated. Such a move was accepted only with the probability $\exp(-\Delta R^2/T)$, where ΔR^2 played the role of energy that was proportional to the square of the distance, whereas T corresponded to the temperature. The procedure was similar also in the case when the previous point was outside, but in this case the calculated value ΔR was the difference between the distances of the two points from the centre. If ΔR was negative, the move was accepted, otherwise it was accepted only with the probability $\exp(-\Delta R^2/T)$. After a large number of steps thus generated trajectory samples the configurations in accord with the canonical Boltzmann distribution. [9]

The actual calculation always started with a point somewhere inside the ellipsoidal region and the first few ten thousand points were rejected to allow the system to thermalize. After collecting the required number of data points they were analyzed with the same procedures as the experimental measurements.

The computations were mostly performed on a PC-type computer based on Pentium 2 GHz processor, running under Linux operating system. The data simulation program was written in Fortran and used the portable pseudo-random number generator ran3 [10], based on a subtractive method that has very long period and no evident defects.

III. Results and discussion

Data were simulated as described above with the Boltzmann distribution at different temperatures. Choosing arbitrary the ratio of the ellipsis axis to be a/b = 2 and the maximal step length in each simulation to be equal to the semiminor axis of the central ellipse (b) the only free parameter of the model remained the temperature (T). As it was measured in the units of b^2 the properties of the model were independent of the actual dimension of the simulated region. After eliminating the first 20000 steps the next 60000 moves were considered. This corresponded to the 20 consecutive series of 3000 points that were each comparable to 60 s of the experimental data with 50 Hz sampling rate.

As an example the simulated data for four different temperatures are shown in Fig. 2. The size of b was chosen to be $(1/2\pi)^{1/2}$ so that the area of the central ellipse was equal to one.

It may be noticed that for low temperatures most of the COP fluctuations are within the central region and the principal component method reproduces well the general properties of the area. As it encompasses 85.35 % of all points, the area ratio between the real outlines, as determined by the FAO method, and the one of the PCA, is expected to be close to 1.2 for long enough simulations. Thus at low temperature increasing it results in more excursions of the COP outside the central region during the observational time. The FAO to PCA area ratio thus at first increases with the temperature and is expected to depend upon the observational time - longer times result in more regular shapes. But at a certain temperature this trend is inverted - still further increasing the temperature results in lowering the FAO to PCA area ratio. This is not surprising since at higher temperatures the positions of the COP get more and more evenly distributed over the entire region.

This behavior is evident from the Fig. 1 where the average values of ISE for 20 simulation runs are shown together with the regions of the standard error and standard deviation. It is interesting to note that for our simulations the area ratio is maximal at the temperature $0.195 \pm 0.03\ b^2$ where it reaches the value of 1.850 ± 0.004. Due to the random nature of this calculation the exact position and value of this maximum cannot be determined from the calculated data as shown in Fig. 1.

IV. Conclusions

By analyzing a large series of simulated data it was shown that ISE is sensitive to the actual shape of the measured postural sway area. It increases if there are small number of large excursions of the COP outside the central region, which are mostly missed by the conventional analysis. Anyhow, the applicability and usefulness of the proposed index to clinical data still remains to be investigated.

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