Postural Sway Area of Elderly Subjects

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Abstract: A new method has been developed to analyse the area of the centre of pressure (COP) trajectory (postural sway). It consists of determination of the area outline and its description in terms of Fourier coefficients. Asymmetric fitting is done by the downhill simplex method considering the different weights for inner and outer points and taking into account also the outline bending energy. The procedure was applied to the data of 20 healthy subjects, aged 68 ± 3 years. It was shown that the area of COP movements could be reliably determined from 30 s measurements by the first 10 Fourier coefficients considering the outline bending parameter of 10^{-3} together with the asymmetry parameter in the range from 10 to 20. This method proved to be simple to implement and offered additional information about the shape of COP area.

Key–Words: stabilometry, elderly, force platform, sway area, Fourier analysis

1 Introduction

Measurement of the human body centre of pressure (COP) movement with a force platform (stabilometry) is a standard procedure for assessment of postural stability in elderly and during rehabilitation. A subject stands still on a special platform that is mounted on pressure sensors transmitting data via analogue to digital converter to a computer. With a suitable software the time dependence of the trajectory of the COP (sway) can be monitored.

As the human balance control system depends on feedback from the somatosensory, vestibular and visual systems, stabilometry can give clues about their functioning. COP measurements have an intrinsic variability that affects the reliability of the postural control measures[1]. Many data acquisition protocols have been proposed to quantify postural steadiness to assess differences between age groups[2], different pathological conditions[3], to distinguish between fallers and non-fallers in elderly population[3, 4] and as outcome measurement after different treatment protocols[5, 6]. Time intervals for the data acquisition range from 10 s[5], 30 s[7] up to 120 s[1, 8]. However, the elderly subjects are quite fragile and have diminished balance with difficulties to stay on the narrow base with their feet together for longer time, so quite often even 30 s is too demanding for them, especially under the conditions of limited sensory input. Namely, assessing the COP fluctuations in different sensory conditions allows us to determine on which sensory input subjects relay most[9]. An intensive research effort in stabilometry resulted also in developing quantitative models that take into account integration of various sensory inputs in postural control[10].

Different interpretations in terms of nonlinear dynamics are also very promising; such as difusion plot analysis[11], determination of time or space fractal dimension etc. Recently it was shown that the most reliable measures of COP are the fractal dimension and the total sway area [12]. As for elderly subjects the reliability of the fractal dimension calculation is questionable due to short attainable measuring times[13], we decided for the area analysis.

The most common procedure to determine the area within which the movement of COP is confined is by the principal component analysis (PCA) of the covariant matrix[7]. Here the eigenvalues (σ_0^2) are calculated from the covariant matrix σ_{xy}^2:

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

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

The two eigenvalues are thus

$$\sigma_0^2 = \left(\sigma_{xx}^2 + \sigma_{yy}^2 \pm \sqrt{(\sigma_{xx}^2 - \sigma_{yy}^2)^2 + 4(\sigma_{xy}^2)^2}\,\right)/2. \qquad (2)$$

The sway area may be then reproduced by the ellipse with the two principal axes $1.96\sigma_0$ at the angle θ [7]:

$$\tan\theta = \frac{\sigma_{xy}^2}{\sigma_0^2 - \sigma_{yy}^2}. \tag{3}$$

Such an ellipse includes 95 % points along each axes if the distribution is bivaraite Gaussian and only 85.35 % of the data points lie within its perimeter[7]. It is thus doubtful whether this method is 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 Fourier analysis of the sway area outline (FAO)[14]. It more realistically approximates the postural sway area and also gives some indications about its shape[14].

In this paper a modification of the method of the Fourier analysis of the sway area outline is presented. It will be shown that with the asymmetric fitting and by considering the sway area bending, reliable representation of the measured postural sway area is obtained. The outline of the COP area is determined by detecting the points that are furtherest from the centre in a given angular interval. To this outline Fourier series is fitted by minimising the characteristic function. It is constructed as the sum of the square differences of the distances from the centre to which the outline bending terms are added. To get the outline that remains mostly outside the sway area the function is weighted differently depending on whether the calculeted value is outside or inside the sway region. In such a way obtained Fourier coefficients are similar to the Fourier descriptors usually employed in shape recognition [15, 16, 17]. The difference is that our outline points are function of the angle rather than the distance along the outline path. Although other shape description measures, such as moments or even simple compactness, were sometimes shown to be equivalent to Fourier descriptors [18] our choice was motivated by the ease of interpretation of the results and by the possibility of simple inclusion of bending energy as described in[14].

The aim of this study was to develop the Fourier analysis of the outline (FAO) procedure, to test it on real data and to estimate its applicability to the study of elderly subjects where the data acquisition times are often quite short.

1.1 Methods

20 healthy community dwelling subjects aged 68 ± 3 years with no known neurological or musculoskeletal disease participated in this study. They all had normal or corrected to normal vision, were relatively physically fit and regularly participated in organized physical exercises.

With all of them four different measurements were performed while standing still for 60 seconds on the force platform with their arms relaxed on either side of the body. Subjects were bare footed, standing with their feet closely together on a solid and on a compliant (soft) surface with their eyes open and closed. They were instructed to stand as still as possible, with the head upright and in the case of open-eyes experiment with the eyes fixed to a black point approximately 2 m in front of them. The recording began after the subject were estimated to have had stabilized their position, which usually took them about 3 seconds.

Experimental data were collected by a portable force platform (Kistler 9286AA) with 50 Hz sampling rate using Bioware software. Raw data were uploaded to a Linux server running on a Pentium IV computer where a system for data analysis had been developed. Such central data processing greatly simplified software maintenance and development. The user interface was written in PHP using Apache web server. It controls user logins, data uploads and calls shell scripts and specially developed programs for data analysis and manipulations. The programs were mostly written in Fortran and C whereas data plotting was done using the Gnuplot program.

The typical analysis of the stabilometry data started by selecting the desired time interval and by optional data smoothing by calculating moving average over the chosen number of points (usually 10). It then proceeded by plotting time and frequency distribution diagrams, and finished by determining the outline of the measured data, calculating its Fourier coefficients, area and other parameters.

1.2 Determination of the sway area outline

To determine the sway area outline all data points are converted into polar coordinates by calculating their distance R_i from the centre ($\overline{x}$, $\overline{y}$) and the respective polar angle ϕ_i. The full angle is then divided into chosen number of intervals, depending on the number of experimental data points and the required precision. For our measurements usually 50 intervals were sufficient. In each angular interval the point that is furtherest from the centre is determined. These points represent the first approximation for the sway area outline. It must be noted that such an outline is uniquely defined for every selected angular value i.e. for every angle the radial vector from the centre crosses the outline only once.

In stabilometry we are usually not interested in

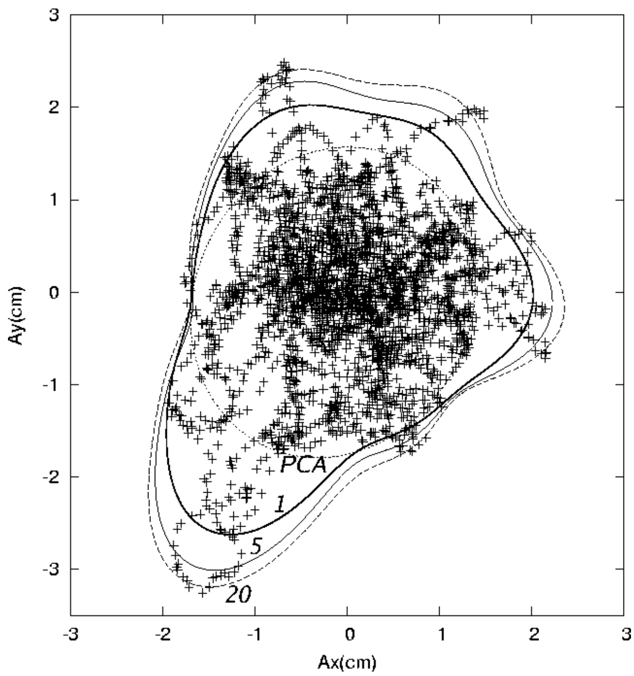

Figure 1: Stabilometry data with the outlines determined by three different values of the asymmetry parameter (ω = 1, 5 and 20), the bending parameter $\gamma = 0.001$ and by the PCA method. The subject was 66 years old, standing for 60 s with her eyes open on a compliant surface.

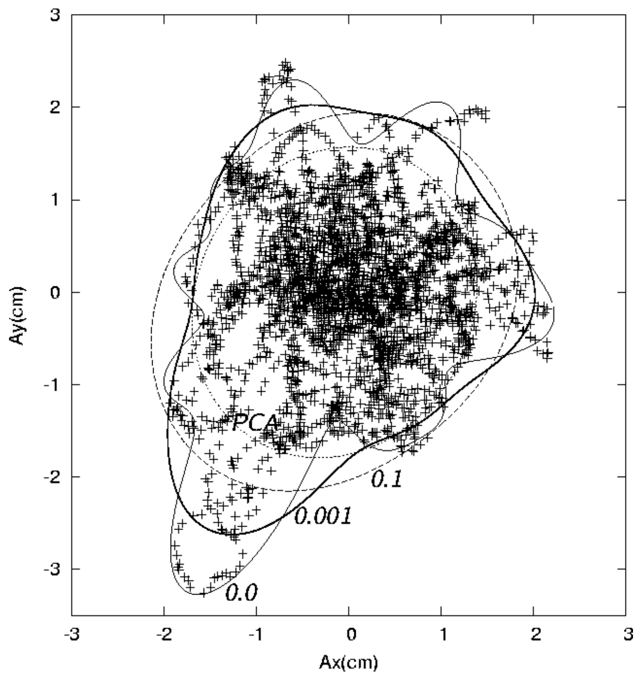

Figure 2: The same data as in Fig.1 but with the outlines determined by the symmetric fitting (ω =1) with three different values of the bending parameter (γ = 0.0, 0.001 and 0.1).The inner ellipsis was determined by the PCA method.

the detailed structure of the measured area but require some general information about the COP movements over the base of support. This is the surface over which the body COP could travel during the experiment while the subject maintained upright stance. How much of it is actually used could be in principle determined by prolonging the measuring time, but because of subject fatiguing effects such results would be of little use. A suitable approximation to the sway area is thus a region determined by a rather simple, mostly convex outline which is predominantly at the outer border of the area. It was shown that sway area outline could be easily reproduced by Fourier analysis when the outline bending energy is taken into accout, too[14]. For the requirement that the outline remains mainly outside the area asymmetric fitting was proposed[19]. It was thus of great interest to investigate the possibilities of implementation and use of these two approaches combined.

1.3 Fourier coefficients of the outline

The smooth sway area outline can be conveniently expressed in polar coordinates $R(\phi)$, where R is the distance from the chosen origin of the coordinate system to the outline point at a given polar angle ϕ[20].

$$R(\phi) = R_0 + \sum_{m=1}^{m_{max}} [A_m cos(m\phi) + B_m sin(m\phi)], \tag{4}$$

where A_m and B_m are the appropriate Fourier coefficients and m_{max} the maximal number of coefficients used to describe the outline. The more coefficients are chosen, the smaller details of the shape can be reproduced.

The sway area can be simply calculated from the Fourier coefficients of the outline as:

$$A = \int_0^{2\pi} R(\phi)\, dR\, d\phi = \pi R_0^2 + \pi \sum_{m=1}^{m_{max}} [A_m^2 + B_m^2]. \tag{5}$$

There are various methods to obtain Fourier coefficients from the determined sway area outlines. Since we wanted to include in the fitting procedure also the bending energy and consider asymmetry we decided for the most straightforward method - minimising the function (F):

Table 1: Average postural sway areas as determined by the Fourier analysis of outline (FAO) with the asymmetry parameter $\omega = 20$ and the bending parameter $\gamma = 10^{-3}$ for four experimental conditions. Principle component analysis (PCA) results and their ratios to FAO are also shown, as well as the values relative to the first condition (solid surface, eyes open).

Experimental condition	FAO		PCA		FAO/PCA
	Area $\pm$ SD $[cm^2]$	Relative values	Area $\pm$ SD $[cm^2]$	Relative values	
1. Solid surface, eyes open	4.8 ± 2.1	1.0	2.9 ± 1.2	1.0	1.71 ± 0.28
2. Solid surface, eyes closed	8.0 ± 4.2	1.7 ± 0.5	4.5 ± 2.7	1.6 ± 0.5	1.84 ± 0.33
3. Soft surface, eyes open	21.1 ± 10.4	5.0 ± 2.8	12.0 ± 5.5	4.9 ± 2.6	1.74 ± 0.28
4. Soft surface, eyes closed	61.7 ± 29.9	15.1 ± 11.5	37.2 ± 17.9	16.9 ± 15.1	1.66 ± 0.15

$$F = \sum_{i=1}^{N} \omega_i [R(\phi) - R_i]^2 + + \gamma \sum_{m=1}^{m_{max}} m^2(m^2-1)[A_m^2 + B_m^2] \quad (6)$$

where

$$\omega_i = \begin{cases} 1 \quad for \quad R(\phi) > R_i, \\ \omega \quad for \quad R(\phi) \leq R_i. \end{cases} \quad (7)$$

The first term is the asymmetric sum of the squares of the differences between the calculated ($R(\phi)$) and experimental (R_i) points. When $\omega = 1$ the fitting is the usual symmetric one, whereas $\omega > 1$ decreases the distance the fitted curve can penetrate inside the sway area. It can be interpreted as sway area elasticity: the larger ω, the more rigid gets the sway area and the more difficult it is for the fitted curve to compress it. This interpretation is even more realistic, as we have defined the energy function F to be quadratic. The actual influence of such asymmetric fitting is illustrated in Fig.1 where outlines are shown as determined by three different values of the parameter ω.

The second term in eq.(6) is related to the outline bending energy. It is constructed similarly to the bending energy of the three dimensional thin membrane of a vesicle. If the curvatures are small only the second order terms may be considered, yielding the fourth order dependence in m[21]. The form of bending energy must not depend on rotation of the coordinate system, thence $[A_m^2 + B_m^2]$ term, and must vanish for $m = 0$ and $m = \pm 1$. It must be regretfully noted that in [14] a typing error has misplaced the square sign in the bending term, making it nonzero for $m = -1$. The positive parameter γ determines the relative importance of the outline bending energy term. The larger it is, the more are higher modes (with larger values of m) penalized in F and as the consequence the simpler becomes the calculated outline. In the limiting cases γ may be very large and the obtained outline gets spherical, whereas at $\gamma = 0$ all modes are equally weighted and the calculated outline follows the experimentally determined one. Fig.2 illustrates the role of the bending parameter γ by plotting the data outlines as calculated by three different values of γ.

It was shown previously[22] that for the symmetric case ($\omega = 1$) minimising of F (eq.(6)) can be very easyly done by considering $\frac{dF}{dA_m} = 0$ and $\frac{dF}{dB_m} = 0$. Using the expansion in eq.(4) these relations result in a system of equations that is represented by a matrix equation where the left hand side is a of type $\alpha_{mk} X_m X_k$ and the right hand side is $\beta_m X_m$ where X_m stands for A_m or B_m. Such a system can be easily solved by the method of LU decomposition [23] which decomposes the matrix into the product of a lower and an upper triangular one from which the solutions can be calculated by a simple substitution.

But, introducing the local asymmetry by ω_i greatly complicates the case. Here the derivatives cannot be simply calculated as for each point the inner or outer derivative must be selected. Thus we chose the downhill simplex method[23] to minimise the asymmetric case. This method is not very efficient in terms of number of function evaluations that it requires and is thus rather slow. But it requires only function evaluations, not the derivatives. Anyhow, it must be supplied by a reasonable starting values of the parameters. For this reason we always start by calculating the coefficients for the symmetric case by LU decomposition, as described above. This coeffcients are then taken as the starting point for the downhill simplex method. From it the initial simplex is constructed in N_{par}-dimensional space, where $N_{par} = 2m_{max} + 1$ is the number of free fitting parameters when Fourier coefficients up to m_{max} are required. The points of the initial simplex are calculated by randomly choosing the values of the parameters in the vicintiy of the starting point.

As the resulting Fourier coefficients A_1 and B_1 are after such a fitting procedure generally not zero, the centre of the outline is after fitting moved to outline centre ($\overline{x}$,$\overline{y}$) and all the coefficients are recalculated with respect to this new origin.

2 Results and Discussion

Sway area was measured by a force platform. Maximal time for each measurement was 60 s. Although this time seems quite short for reliable data collection and analysis, it nevertheless quite often proved to be too long for some subjects. For this reason we selected a group of elderly people that were relatively physically fit. They were all community dwelling and regularly participated in organized physical exercises. All subjects were asked to perform four tests: standing still with their feet closely together on a solid and on a compliant (soft) surface with their eyes open and closed. Centre of pressure trajectories were determined and analysed as described above. All 20 subjects were able to preform the first three tests for 60 seconds, whereas 19 participants were able to stand still on the compliant surface with their eyes closed for 30 seconds and only 16 could complete the test after 60 s. Fig. 3 shows an example of such a series of measurements. It is evident, that by eliminating any particular sensory input the measured postural sway area increases.

The resulting average values of the areas, calculated with Fourier analysis of the outline for $\omega = 20$ and $\gamma = 10^{-3}$, are given in Table 1, together with the values obtained by the PCA method. The analysis was done from the first 30 s data for 20 or 19 elderly participants for the first three tests and the last one, respectively. The relative values with respect to the hard surface, open-eyes measurements are also given, as well as the ratio between the areas calculated by our method to the ones, obtainded by the PCA. It is interesting to note that this ratio is close to 1.7 for all four experimental setups.

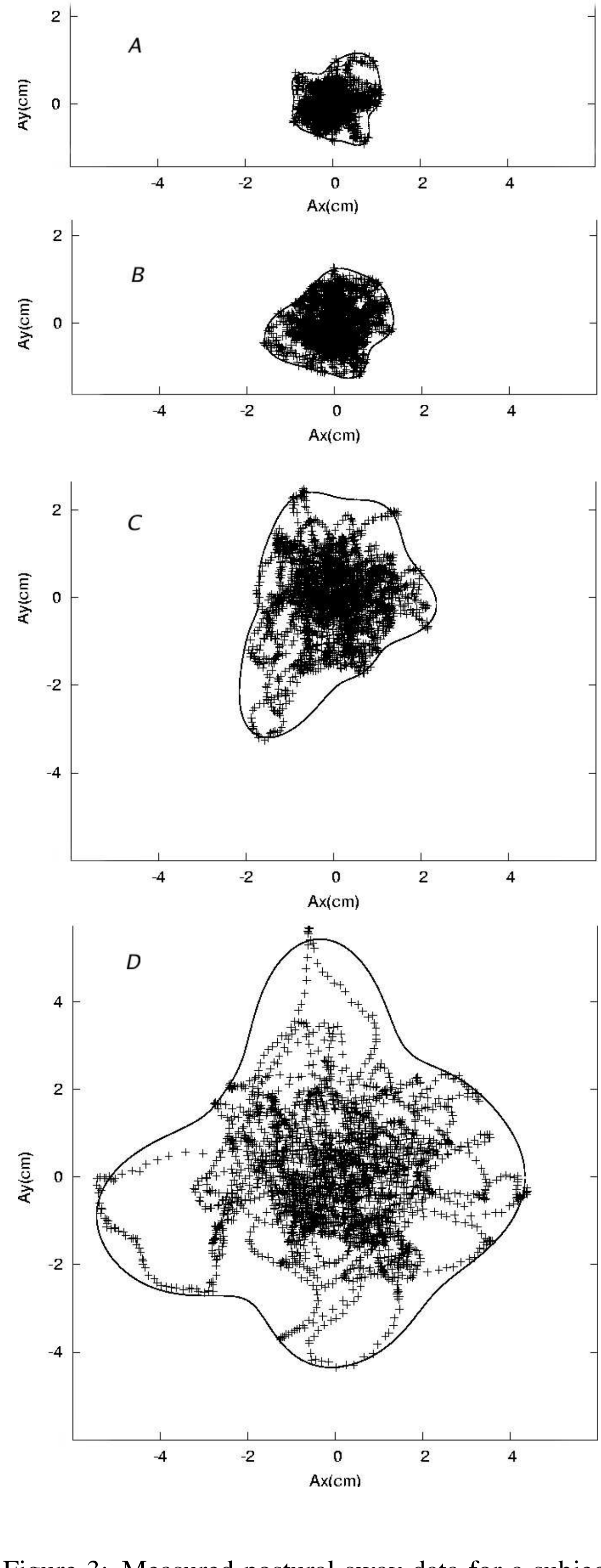

Figure 3: Measured postural sway data for a subject standing still on a solid surface with eyes open (A) and closed (B) and on a compliant surface with her eyes open (C) and closed (D). The outlines were determined by the first 10 Fourier coefficients and with the bending parameter $\gamma = 10^{-3}$ and $\omega = 20$.

3 Conclusion

It was shown that Fourier analysis of the sway area outline is suitable for data interpretation. By adjusting the bending and asymmetry parameters (γ and ω) it is possible to get the sway area outline that reasonably describes the shape of the area and yet is general enough to eliminate the random variations of the particular session. It was shown that the calculated areas differentiate well between measurements with various sensory inputs, such as standing on solid or soft surface, with eyes open or closed. It was seen that the shapes of the sway areas under all four different experimental conditions were very similar, so that the ratios between the average areas as calculated by our method and by PCA were all very similar, although the size of the areas differed for more than a factor 15.

All the described computer programs are available from the authors upon request.

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