Analysis of Postural Sway Data of Elderly Subjects

DARJA RUGELJ
University of Ljubljana
University College of Health Studies
Poljanska 26a, 1000 Ljubljana
SLOVENIA

FRANCE SEVŠEK
University of Ljubljana
University College of Health Studies
Poljanska 26a, 1000 Ljubljana
SLOVENIA

Abstract: The centre of pressure (COP) trajectory (postural sway) for elderly subjects standing still on a force platform was measured. 20 healthy subjects, aged 68 ± 3 years, with no known neurological or musculoskeletal disease, participated in this study. 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}. This method proved to be fast, 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 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 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. It was shown that somatosensory function declines with age[1], diabetic neuropathy and often with stroke[2], resulting in diminished motor performance. An intensive research effort in stabilometry resulted also in developing quantitative models that take into account integration of various sensory inputs in postural control[3].

COP measurements have an intrinsic variability that affects the reliability of postural control measures[4]. Many data acquisition protocols have been proposed to quantify postural steadiness to assess differences between age groups[1], pathologies[5] and as outcome measurement after treatment protocol[6]. Assessing the COP fluctuations in different sensory conditions allows us to determine on which sensory input subjects relay most[7]. Time intervals for the data acquisition range from 10 s[6], 15 s[8], 20 s[5], 30 s[9] up to 120 s[4, 10]. Reliable data acquisition protocol for COP measurements proposed by [4] consists of 3 trials of 120 s. However, the elderly subjects are quite fragile and have diminished balance with difficulties to stay on the narrow base (feet together) for longer time periods.

From the measured COP trajectory simple statistical parameters related to the distance and velocity of COP are usually determined. Quite often it is also of interest to compare the areas within which the movement of COP is confined[11]. In this case the principal component analysis (PCA) of the covariant matrix is mostly used where the eigenvalues are calculated from the covariant matrix[9]. Recently we proposed a new method based on Fourier analysis of the data outline[11].

Thus, for given conditions, it is very important to select the most appropriate analysis of the trajectory. In this paper a new method for the calculation of the outline of the COP movement area is presented. 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 usual sum of the square differences of the distances from the centre to which the linear and outline bending terms are added. Thus obtained Fourier coefficients are similar to the Fourier descriptors usually employed in shape recognition [12, 13, 14]. The difference is that our contour points are function of the angle rather than the distance along the contour path. Although other shape description measures, such as moments or even simple compactness, were sometimes shown to be equivalent to Fourier descriptors [15] our choice was motivated by the ease of interpretation of the results and the possibility of simple bending energy as described in [11].

The aim of this study was to test our procedure on real data and to estimate its applicability to the study of 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. With all of them four different measurements were performed while standing still for 60 seconds on the force platform. 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.

Experimental data were collected by a 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 the Fourier coefficients, area and other parameters.

1.2 Determination of the sway area contour

To determine the sway area contour 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 then is divided into chosen number of intervals, depending on the number of data points and 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 detailed structure of the measured area but want to get some general information about COP movements over the base of support. This is the surface where the 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 such an outline can be easily reproduced by Fourier analysis, considering also outline bending energy[11].

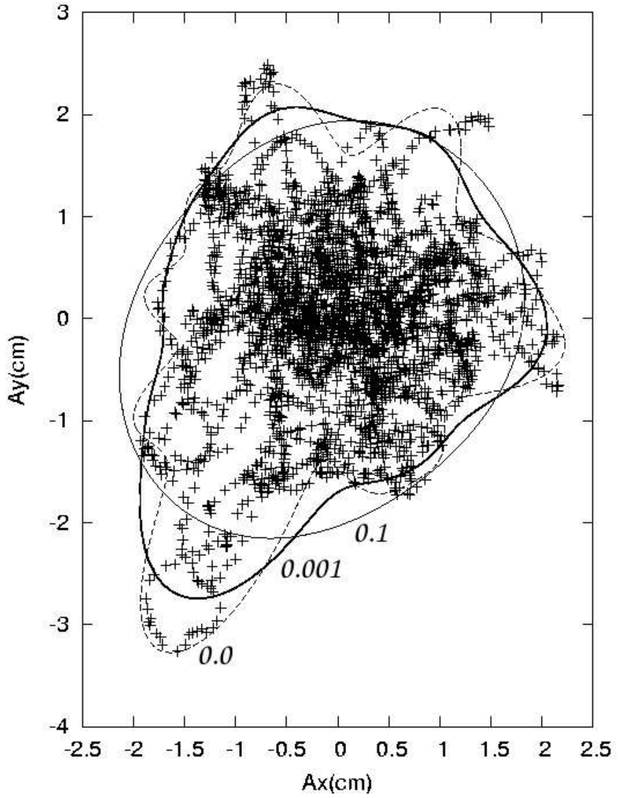

Fig.1: Stabilometry data measured for 60 s with outlines determined with three different values of the bending parameter (γ = 0.0, 0.001 and 0.1). The subject was 66 years old, standing with eyes open on a compliant surface.

1.3 Fourier coefficients of the contour

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 contour point at a given polar angle ϕ[16].

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

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

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

$$\begin{aligned} F = & \sum_{i=1}^{N} [R(\phi) - R_i]^2 + \\ & + \gamma \sum_{m=1}^{m_{max}} m^2(m^2-1)[A_m^2 + B_m^2]. \end{aligned} \tag{2}$$

The first term is the usual sum of the squares of the differences between the calculated and experimental points. The second term in eq.(2) 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 coefficients order[17]. 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 $m = 1$. The positive parameter γ determines the relative importance of this term. The large it is, the more are higher m modes penalized in F and thus the simpler becomes the calculated outline. In the limiting cases γ may be very large and the obtained outline becomes spherical, whereas at $\gamma = 0$ all modes are equally weighted and the calculated outline follows the experimentally determined one. Fig. 1 illustrates the role of the bending parameter γ by plotting the data outlines as calculated by three different values of γ.

Fitting was done by minimising the function F of eq.(2) and considering $\frac{dF}{dA_m} = 0$ and $\frac{dF}{dB_m} = 0$. If we use the expansion in eq.(1) these relations give 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 [18]. It 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.

As the resulting Fourier coefficients A_1 and B_1 are generally not zero the centre of the contour is moved to ($\overline{x}$,$\overline{y}$) and all the coefficients are recalculated.

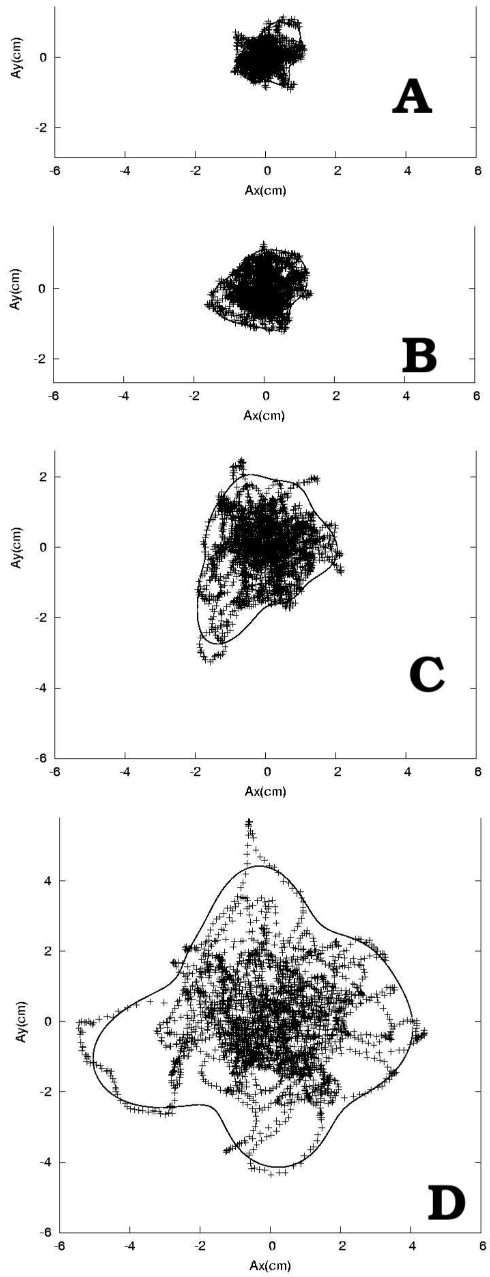

Fig.2: Measured postural sway data for a subject standing still on a solid surface with eyes open (A) and closed (B) and on a compliant surface with her eyes open (C) and closed (D). The outlines were determined by the first 10 Fourier coefficients and with the bending parameter $\gamma = 10^{-3}$.

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 proved to be too long for some subjects. Especially with the limited sensory input, as for instance standing on a compliant surface, many elderly subjects barely managed to stand still for more than 30 s. It was thus of great importance to determine if any relevant information can be extracted form such short measurements.

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 first three tests for 60 s, whereas 19 participants were able to stand still on the compliant surface with their eyes closed for 30 s and only 16 could finish the test. Fig. 2 shows an example of such a series of measurements. It is evident, that by eliminating any one of the sensory inputs the measured postural sway area increases.

For the analysis we divided the experimental data for every subject into two halves and calculated the areas for the whole 60 s interval and its two 30 s parts, with different values of the bending parameter γ as defined in eq.(2). Some typical values are shown in Table 1. It may be noticed that the average area of the whole 60 s interval is always larger that the areas of the two shorter parts. Besides, the areas determined from the second half of the experimental interval are on average larger that the ones from the first part. To determine whether these differences are statistically significant we used one-way ANOVA with Bonferoni post hoc test. The only significant differences were between the 60 s interval and its second part. These values are marked by (*) in Table 1 when $p < 0.01$. But, as expected, the experimental conditions, such as eyes open or closed, or standing on hard or compliant surface, influence much more the calculated sway areas. It is also interesting to note that the bending parameter γ had very little influence on the value of the calculated sway area, although it resulted in quite different outline shape, as shown in Fig.1.

Table 1: Average postural sway areas for 20 elderly subjects as calculated for different values of the bending parameter γ for the total time interval of 60 s and separately for its two halves. The values where the differences between the 60 s interval and its second part were significant ($p < 0.01$) are marked by *.

	$\gamma = 0.01$	$\gamma = 0.001$	$\gamma = 0.0001$
	Solid surface, eyes open		
Time $[s]$	Area ± SD $[cm^2]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$
0 – 60	5.0 ± 2.6	5.0 ± 2.1	5.0 ± 2.2
0 – 30	3.7 ± 1.6	3.7 ± 1.6	4.0 ± 1.7
30 – 60	2.9 ± 1.3*	3.0 ± 1.4*	3.1 ± 1.3*
	Solid surface, eyes closed		
Time $[s]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$
0 – 60	8.3 ± 5.3	8.5 ± 5.8	8.5 ± 5.8
0 – 30	6.1 ± 3.2	6.5 ± 3.3	6.5 ± 3.3
30 – 60	5.1 ± 4.7	5.7 ± 5.2	5.4 ± 5.0
	Compliant surface, eyes open		
Time $[s]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$
0 – 60	21.1 ± 9.3	21.1 ± 9.5	21.6 ± 9.4
0 – 30	16.3 ± 8.2	17.1 ± 8.6	17.2 ± 8.5
30 – 60	14.2 ±6.5*	14.8 ± 7.0	15.1 ±6.7*
	Compliant surface, eyes closed		
Time $[s]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$	Area± SD $[cm^2]$
0 – 60	57.6 ± 29.2	56.9 ± 29.4	60.9 ± 29.4
0 – 30	50.4 ± 25.9	51.4 ± 25.9	51.3 ± 26.1
30 – 60	40.3 ± 24.3	41.0 ± 24.6	38.2 ± 16.8

3 Conclusion

It was shown that Fourier analysis of the sway area outline is suitable for data interpretation. With suitably chosen bending parameter (e.g. $\gamma \approx 10^{-3}$) the calculated shapes still represent the general features of the sway area and yet seem general enough, without detailed random variations in COP positions. By comparison of the results of the data subset analysis it was concluded that even from 30 s measurements some information about sway area could be extracted and different sensory conditions could be distinguished. Anyhow, it must be noted that the calculated sway area increases with the measurement time as the number of larger out of centre COP excursions is approximately proportional to observational time. It is thus not surprising that the area calculated for the 60 s measurement is larger than the areas calculated from any subset of data.

It was also noted that the exact value of the bending parameter γ did not significantly influence the calculated areas. This parameter mainly takes care of the outline shape which is then least-square fitted to the experimental area outline. It is believed that this parameter will be most useful if applied in combination with the asymmetric outline fitting[19] which is being currently developed.

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

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