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The use of fractal dimension methods in clinical epidemiology: an application for postural assessment

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ABSTRACT

BACKGROUND: this study considers the analysis of postural sway by comparing the use of a fractal dimension outcome (DBOX) with the usual sway ellipse area (SEA), calculated by the least squares method. Both the response variables come from centre of pressure (COP) dynamics detected by means of a force platform.

METHODS: recent literature regarding postural stability assessment in subjects with muscular-skeletal disorders, or neuromuscular diseases affecting their motor skills, has suggested, both for practical and theoretical reasons, the use of some fractal dimension as a good outcome measurement for overall postural status. A sample group of 24 male subjects was recruited. The postural stabilogram was recorded both with eyes open (EO) and eyes closed (EC) while standing upright. A matched-pair comparison of the sway ellipse area with the COP dynamics box counting dimension was performed. A ROC analysis of the outcome variables was performed. Then, a ROC comparison of the tests, using the area under the curve (AUC) index, was conducted.

RESULTS: the comparison of paired groups showed a statistically significant difference between EO and EC status, according to the sway ellipse area and the fractal dimension ($p<0.05$). The ROC analysis, describing the test performance in terms of AUC difference, was statistically significant ($p<0.05$). The comparison of the AUCs showed an overall superior performance of the DBOX with respect to SEA ($p<0.05$).

CONCLUSIONS: this study showed a statistically significant better overall performance of DBOX with respect to SEA, suggesting possible improvements of clinical practice, as well as theoretical insights into the response patterns.

Key words: Postural sway; Statokinesigram; Fractal dimension; ROC analysis

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INTRODUCTION

Fractal geometry is gaining increasing importance within biomedical sciences. The ‘fractal’ mathematical concept arose from the difficulty of classical Euclidean geometry in describing complex and irregular shapes that are present in nature and, particularly, in biomedical sciences. According to Mandelbrot, it is a matter of fact that ‘a cloud is not a sphere, nor is a mountain a cone’. The principal aspects of the ‘geometry of nature’ are self-similarity and dimensionality, which are usually used to characterise the complexity of the system analysed.

Despite fractal dimension not constituting an absolute measurement of complexity with some cautions to be adopted, it has widely demonstrated its usefulness in biosciences. The current areas of application are the morphology of anatomical structures, such as those of vascular networks, the interface between healthy tissue and a tumour or even the edges of a cutaneous lesion; likewise, fractal analysis is also applied to physiological phenomena, such as the behaviour of a heartbeat or electroencephalographic brain waves [1].

Posturography is a subject of growing interest in those areas treating subjects affected by motor and neuromotor control, due both to disabling disease and musculoskeletal trauma [2-4]. This interest is mainly concerned with the development of new, possibly more powerful, diagnostic procedures [5] and the quantitative assessment of neuromotor rehabilitative protocols.

The human upright posture is usually modelled as an inverted pendulum, assuming the body segments involved are rigid bodies in which the axial muscles act as springs, with centrally controlled viscoelastic parameters [6]. Postural stability reflects the overall coordination of visual, proprioceptive, and vestibular systems for maintaining a standing posture, and it is usually characterised as referring to the displacements of the body centre of mass (COM), within a specified base of support [7].

Neuromuscular control and its nonlinear responses let the COM move with very small oscillations: the so-called postural sway. These oscillations are recorded on a force platform as movements of the centre of pressure (COP), treated as a proxy of the COM trajectory and referred to as statokinesigram.

The methods found in literature for analysing the postural sway range from Fourier analysis to power spectral density to SEA [8]. In all cases, the software accompanying the force platform provides outcome measurements that are not always easily interpretable in clinical terms [9]. SEA, for instance, is obtained by performing a mean square regression of the raw data fitting an ellipse [10]. Such a widespread choice has a major drawback in the lack of information about the way the COP pattern fills in the plain (i.e., the complexity of the COP path). Highly irregular postural sway makes it a candidate for physiological chaos in the postural control system [11]. In particular, according to many authors, the unpredictability of the sensorimotor control system may be regarded as evidence of the presence of deterministic chaos in human postural control [12]. This problem has been recognised in literature by some authors, who have suggested the use of some type of fractal dimension accounting for the complexity observed in statokinesigram or in some other non-linear dynamical system quantifiers [13] that use correlation dimensions and the largest Lyapunov exponent to distinguish healthy subjects from Parkinsonians; similarly, Ladislao and Fioretti [14] studied different visual conditions on postural sway in normal subjects using traditional linear posturographic measures and the largest Lyapunov exponents. The range of possible choices is rich but usually far from the clinical demand for immediate responses being, as much as possible, easy to interpret. The work of Blaszczyk used a box-counting dimension (DBOX) approach to investigate differences between older and younger patients, yielding a statistically significant difference [9]. This approach seems promising in the clinical context, for example, in orthopaedic trauma, because of its precise meaning and easy computational implementation.

The use of fractal dimension analysis in postural assessment aims to obtain an easily computable outcome measurement for postural status and, according to the wide-ranging variety of choices for areas surrounding the COP path along time, to reach a reasonable idea of the sway span complexity. The intent of this study is to compare the ‘smooth’ behaviour of the sway ellipse area (SEA) and the box-counting dimension index (DBOX), which accounts for the complexity of postural behaviour.

Despite the evidence of successful applications of fractal dimensions in the analysis of postural behaviour, there is a lack of quantitative comparisons of the methods. The detection of statistically significant differences, using both the classical sway ellipse area or sway ellipse path, among others, or nonlinear outcome variables, such as fractal dimensions or Lyapunov exponents, is not enough to build a comparatively reliable test characterising the appropriate set of cut-offs and the corresponding sensitivity and specificity. This a major focus of the clinical research, addressing both the need for diagnostic tools to compare the therapeutic protocols [15].

The twofold goal of this paper is to show the possibility of building a test using the box-counting dimension, as well as to compare its performance, given a data set, with the sway ellipse area.

In our manuscript, we compare the overall performance of the SEA and DBOX methods by performing a ROC analysis on a group of 24 healthy male subjects after they underwent a postural trial, both with eyes opened and eyes closed. The problem we face, according to the dichotomic condition of eyes opened/eyes closed, is to investigate the possibility of using a test based on fractal dimensions vs. the classical test, exploiting the sway ellipse area and accounting for the complexity of postural sway [16], as well as providing a measurement for easy clinical use.

METHODS

Twenty-four male subjects, ages 22-31 years old, practising physical activities at least once a week, participated in this study voluntarily.

The subjects were allowed to get accustomed to the experimental procedures before the trials and were asked about the presence of wounds or trauma affecting their legs or feet.

Postural sway was assessed when subjects were standing upright on a force platform (Muscle-Lab, Ergotest Technology, Langesund, Norway), facing 1 m away from the corner of a room. The walls were draped with black curtains, and a 1 cm red square was placed in the corner at eye height. When necessary (eyes-open trial), the wearing of spectacles was permitted to ensure that all subjects had normal binocular vision and that they were able to fixate comfortably on this square [17]. The feet were placed such that the medial malleoli were approximately 2.5 cm apart. However, the appropriate toe and heel positions were marked on the platform to ensure the consistency of the foot position among trials. The subjects were also instructed to place their hands on their waists and keep their knees extended during the test. They performed two trials in random order with a 2-min pause between trials, with each trial lasting 30 seconds. The two trials were conducted with the subjects' eyes open (fixating on the red square) and with their eyes closed. The trials were considered unsuccessful if the subjects took a step or if they opened their eyes during an eyes-closed trial [18]. All of the measurements were performed in one day (in the second half of the morning) and were supervised by a tester. Postural sway was measured with a COP spatial resolution of 0.1 mm-0.2 mm. The signal given by each subject was divided into its mediolateral (ML) and anterioposterior (AP) components of COP displacements. Because filtering is a potentially dangerous activity that can affect dimension estimates and other calculations [19], filtering was avoided in this study. The outcome variables characterising postural sway were: the sway ellipse area (SEA) formed by the centre of pressure, recorded at 100 Hz (Figure 1), and the DBOX drawn by the centre of pressure (Figure 2). Generally speaking, a fractal describes 'the way a shape covers the space', geometrically accounting for the complexity of the pattern drawn, so that it matches the clinical need for a synthetic portrait of the postural behaviour. The general definition used for the dimension of an

FIGURE 1
SEA OF A POSTURAL SWAY EXAMINATION IN mm^2

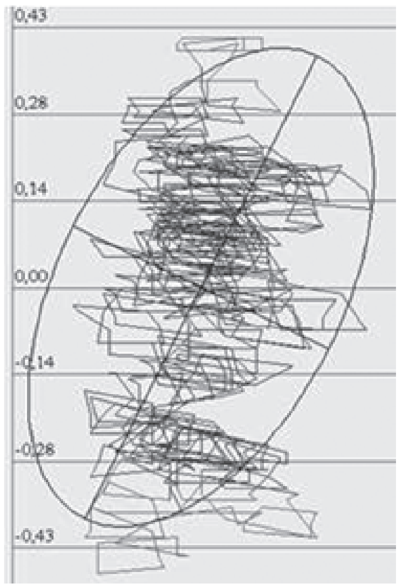
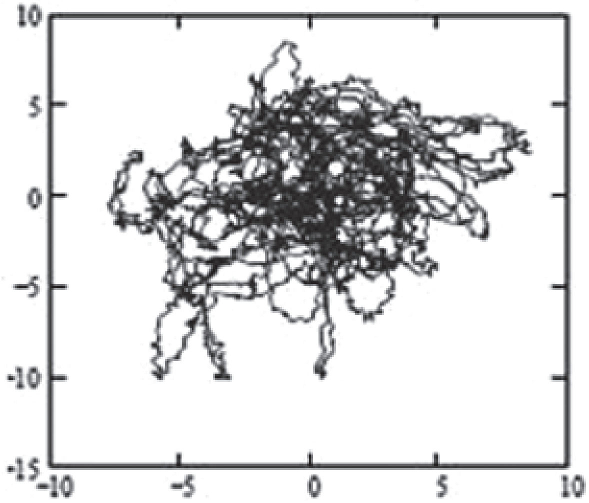


FIGURE 2

POSTURAL SWAY OF THE CENTER-OF-PRESSURE (COP) WITH LENGTH UNIT = mm



object with a hypervolume (i.e., length, area, volume or fractal hypervolume) given by $\tilde{V}$ is

$$DBOX = \frac{\log N - \log \tilde{V}}{\log(1/\delta)}$$

where N is the number of hypercubes of side length δ required to cover the object, so that rearranging the definition, we have the equation of a straight line, where the gradient of the line DBOX is the box-counting dimension of the object: log N = DBOX log(1/δ) + log $\tilde{V}$, which is the form used for calculations [20].

The DBOX was calculated using the box-count m-file running on Matlab (MathWorks, Inc.), written by Frederic Moisy (downloadable at http://www.fast.u-psud.fr/~moisy/ml). The SEA was calculated using the software associated with the platform device running under Matlab.

According to the goals of the study, given a Shapiro-Wilk test of normality, a preliminary paired matched t-test of both of the outcome variables was performed. Then, the overall behaviour of SEA and DBOX in singling out the eyes opened/eyes closed status was assessed, and the corresponding receiving operating curves (ROCs) were drawn, testing the null hypothesis AUC=0.5. The analysis compared the ROC curves of the SEA and of the fractal dimension testing for statistically significant differences with the corresponding AUC. The ROC analysis was performed using the statistical software STATA 10 (StataCorp LP).

RESULTS

A preliminary Shapiro-Wilk test of normality between subjects with eyes opened (EO) and eyes closed (EC), both for the SEA and DBOX, was performed without rejecting the normality assumption ($p>0.05$) (Figure 3 and Figure 4).

The t-test matched pair comparison of the SEA with EO with a mean of 166.18 (30.38) mm^2 against EC with a mean of 198.55 (55.26) mm^2 turned out to be statistically significant ($t = -2.68$; $p<0.05$), showing, as expected, that the SEA with EO is smaller than the SEA with EC. Likewise, the DBOX mean values, respectively calculated as 1.52 (0.11) with EO and 1.68 (0.06) with EC, were compared, yielding a statistically significantly smaller DBOX mean value for the EO group ($t = -5.35$; $p<0.05$).

To assess the overall performances of the SEA test and DBOX test, a ROC analysis was performed. The SEA AUC for the ROC was 0.72 (0.08), rejecting the null hypothesis AUC(SEA)=0.5 ($p<0.05$), and the DBOX AUC for the corresponding ROC was 0.91 (0.04), with AUC(DBOX)=0.5 ($p<0.05$).

The analysis ended with the comparison of the AUC for both of the outcome variables (Figure 5), adjusting for the correlation of the samples using

$$z = \frac{AUC_{SEA} - AUC_{DBOX}}{\sqrt{s^2_{SEA} + s^2_{DBOX} - 2 r s_{SEA} s_{DBOX}}}$$

and this comparison yielded a statistically significant difference ($p<0.05$) between the areas so that the DBOX performed better, provided that the samples were drawn from the population described above (Table 1).

The analysis allowed a choice of a cut-off point for the test studied, so we chose the points of the ROCs to be as close as possible to the upper left corner, obtaining the following: for the SEA test, a cut-off point of 173.45, corresponding to a sensitivity of 79.17% and a specificity of 75.00%, with 77.08% of subjects correctly classified, and for the DBOX, a cut-off point of 1.63 with a sensitivity of 75.00% and a specificity of 87.50%, with a 81.25% correct classification.

FIGURE 3

BOX-COUNTING DIMENSION DISTRIBUTION WITH EO AND EC

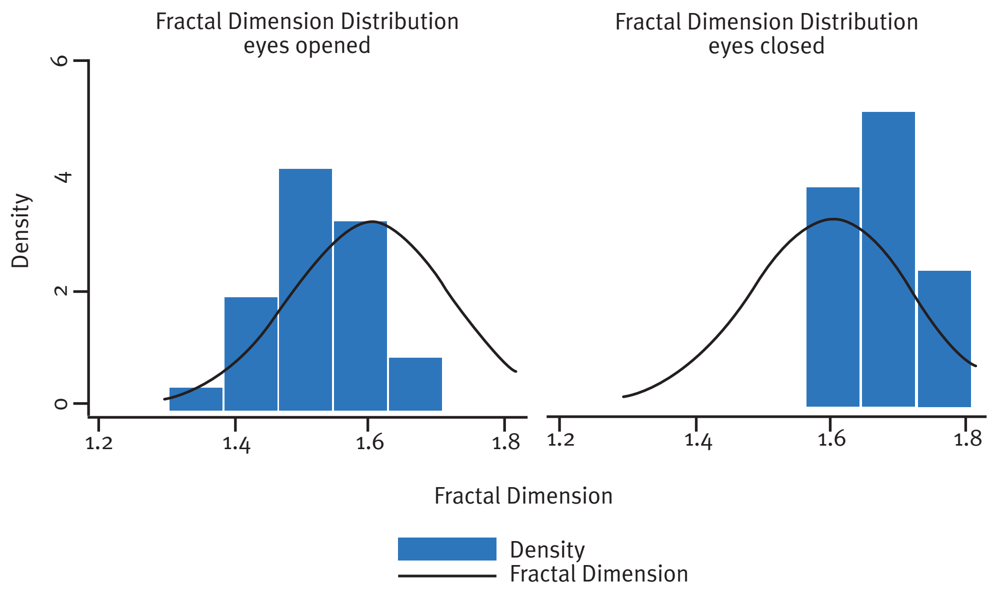


FIGURE 4

SEA DISTRIBUTION WITH EO AND EC

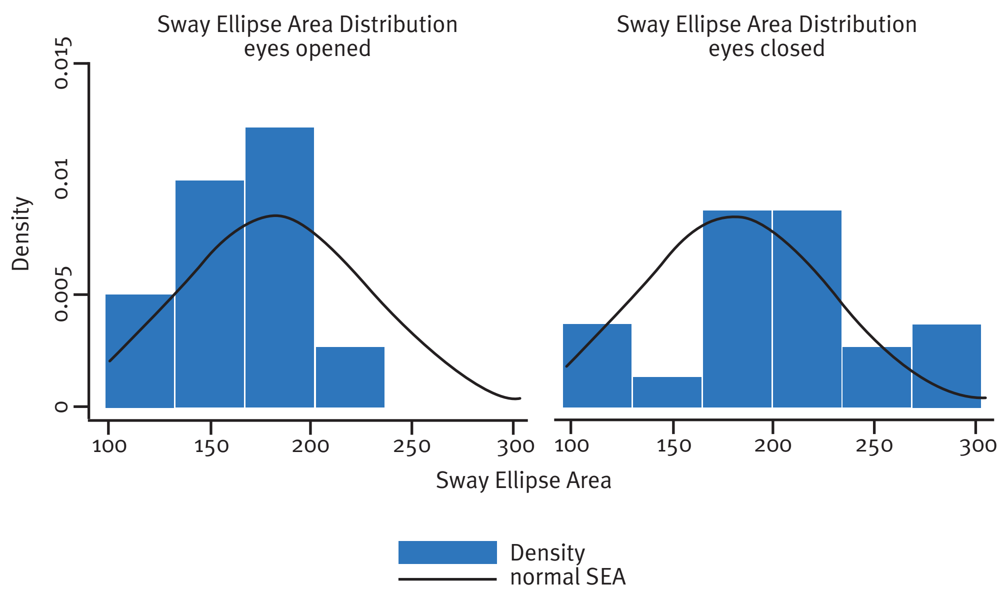


FIGURE 5

ROC COMPARISON OF THE SEA TEST AND THE DBOX TEST, ACCOUNTING RESPECTIVELY FOR EO AND EC

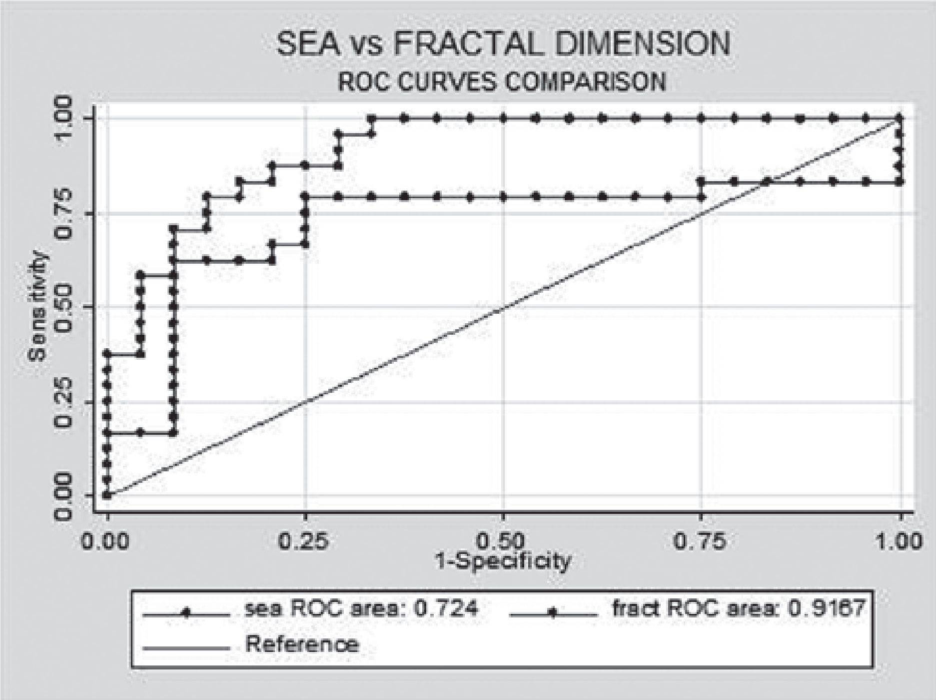


TABLE 1

MEAN VALUES OF SEA (SWAY ELLIPSE AREA) AND DBOX (BOX-COUNTING DIMENSION), WITH EYES OPENED AND EYES CLOSED, AND THE ROC COMPARISON OF THE CORRESPONDING AUCS

	SEA (mm^2)		DBOX			
	SEA_{EO}	SEA_{EC}	$DBOX_{EO}$	$DBOX_{EC}$	AUC_{SEA}	AUC_{DBOX}
Mean (SD)	166.18 (6.20)	198.55 (11.28)	1.52 (0.02)	1.68 (0.01)	0.72 (0.08)	0.92 (0.04)
NULL HYPOTHESIS H_0	T-TEST			PROB > |T|		
$\mu(SEA_{EO}) = \mu(SEA_{EC})^{(*)}$	-2.68			0.01		
$\mu(DBOX_{EO}) = \mu(DBOX_{EC})^{(*)}$	-5.35			0.00		
$AUC_{SEA} = 0.5$	13.19			0.00		
$AUC_{DBOX} = 0.5$	52.48			0.00		
ROC COMPARISON	χ^2			Prob > χ^2		
$AUC_{SEA} = AUC_{DBOX}$	4.53			0.03		

(*) Two tailed matched-pairs t-test

DISCUSSION

The literature on the use of fractal dimensions applied to posturology does not account in a systematic way for the comparison between different procedures of postural sway assessment. This is a major drawback because it does not provide the possibility of deciding on a method, apart from correct but unduly general considerations not supported by a quantitative comparison with the already widely used approaches.

Our main focus was the comparison of the SEA and DBOX, addressing the issue of the choice of an easy parameter for investigating postural conditions, and the status of disorders associated with a major disease. Despite other nonlinear response indexes having been used with some success [21], the geometrical character of the DBOX gives it an intuitive interest that accounts for the additional biomechanical properties of standing, which is reflected in a clinically meaningful score.

The fractal dimension (i.e., the box-counting dimension in our example) seems to fulfil at least 3 requirements close to clinical practice, which distinguishes it from more computationally demanding analysis:

(1) balance disorders are assessed in terms of the complexity of the postural behaviour, rather than the use of any smoothed curves, such as an ellipse;

(2) this parameter can be achieved quickly and at low sanitary expense, with a non-invasive technique;

(3) as discussed in this study, there was an overall better performance of clinical testing associated with the DBOX (or other non-linear outcomes), at least in the context we considered, compared with the common SEA measurement.

This type of testing procedure has the ROC curves dependent on the disease, and it can be investigated in a wider class of conditions of medical interest. In conclusion, we emphasise the potential applications of the fractal dimension approach in posturology, including the role it could play in legal controversies and forensic medicine [22], e.g., providing a tool for assessing the impact of alcohol and drugs consumption on postural behaviour.

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