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Rotary Spectra Analysis Applied to Static Stabilometry

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***Abstract*—Static stabilometry is a technique aimed at quantifying postural sway during quiet standing in the upright position. Many different models and many different techniques to analyze the trajectories of the Centre of Pressure (CoP) have been proposed. Most of the parameters calculated according to these different approaches are affected by a relevant intra- and inter-subject variability or do not have a clear physiological interpretation.**

In this study we hypothesize that CoP trajectories have rotational characteristics, therefore we decompose them in clockwise and counter-clockwise components, using the rotary spectra analysis. Rotary spectra obtained studying a population of healthy subjects are described through the group average of spectral parameters, i.e., 95% spectral bandwidth, mean frequency, median frequency, and skewness. Results are reported for the clockwise and the counter-clockwise components and refer to the upright position maintained with eyes open or closed. This study demonstrates that the approach is feasible and that some of the spectral parameters are statistically different between the open and closed eyes conditions. More research is needed to demonstrate the clinical applicability of this approach, but results so far obtained are promising.

I. Introduction

STATIC stabilometry [1]-[3] is a technique aimed at characterizing the performance of the postural control system quantifying body sway during quiet standing. By means of a force platform, the trajectories of the Centre of Pressure (CoP) on the platform surface are recorded. CoP trajectories can be directly related to the centre of mass sway, therefore they provide information about the postural control system [3].

In literature, several techniques have been proposed to analyze the CoP trajectories. The traditional approach consists of considering the CoP time series from the geometrical and statistical points of view, in the time and frequency domains [3], [4]. Collins et. al [5], [6] proposed to consider the CoP time series as fractional Brownian motion and defined a new set of stabilometric parameters based on the fractal model. An alternative model based on chaos theory was proposed to describe the postural sway [7]-[9]. Most of the parameters calculated according to these different approaches are affected by relevant intra- and inter-subject variability or do not have a clear physiological interpretation [1].

In the present study, the problem of characterizing CoP trajectories is approached from a new perspective. Hypothesizing that CoP trajectories on the platform surface have rotational characteristics, the rotary spectra technique is introduced to analyze posturographic data.

Rotary spectrum analysis is a well known technique developed in the meteorological and oceanographic fields by Gonella and Mooers [10]-[12] as a method for the interpretation of geophysical data exhibiting inherent rotational characteristics.

We analyzed the CoP trajectories of a group of healthy subjects during quiet standing according to rotary spectra techniques and obtained the group average of a set of spectral parameters for the clockwise and counter-clockwise components.

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II. Materials and Methods

A. Subjects

The postural control was investigated on a group of 43 healthy subjects, 26 females (age 18.0 - 28.0 years, mean 23.6 years, height 158.0 - 175.0 cm, mean 167.0 cm, weight 44.0 - 72.0 kg, mean 56.7 kg) and 17 males (age 20.0 - 40.0 years, mean 26.6, height 169.0 - 196.0 cm, mean 179.9 cm, weight 55.0 - 94.0 kg, mean 75.6 kg), who did not suffer from orthopedic, neurologic or visual problems.

B. Acquisition Protocol

The acquisition protocol consisted of two different trials with the subject in upright position with eyes open (OE) and closed (CE). Trials were randomized to avoid learning and fatigue effects. At the beginning of each trial, the subject was asked to stand quietly on a force platform, arms at the side, and to look straight ahead at a visual target. The inter-malleolar distance was fixed at 4 cm and the feet opening angle was 30°. The experimental setup consisted of a Kistler 9286A (Kistler, Switzerland) force platform and of the acquisition system STEP32 (DemItalia, Italy). Each acquisition lasted 60 s. The signal was recorded with a sampling frequency of 2 kHz and down-sampled to 100 Hz.

C. Rotary spectra theory

The rotary spectral analysis implicate the representation

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of a random time series w(t) in complex form and its decomposition into two polarized counter-rotating components. The different frequency components of the vector w(t)=u(t)+jv(t) are represented in terms of clockwise and counter-clockwise rotating vectors, with amplitudes A^-, A^+, and relative phases θ^-, θ^+, respectively. The counter-clockwise component is considered to be rotating with positive angular frequency ($\omega \geq 0$) and the clockwise component with negative angular frequency ($\omega \leq 0$). Thus, instead of dealing with two Cartesian components (u, v) we deal with two circular components (A^-, θ^- ; A^+, θ^+).

The vector addition of the two oppositely rotating circular vectors causes the combined vector to trace out an ellipse over one complete cycle. The eccentricity ε of the ellipse is determined by the relative amplitudes of the two components. Motions at frequency ω are circularly polarized if one of the two components is zero; motions are rectilinear if both circularly polarized components have the same magnitude.

In rotary spectral format, the vector w(t) can be written as the Fourier series

$$w(t) = \overline{u(t)} + \sum_{k=1}^{N} U_k \cos(\omega_k t - \varphi_k) + j(\overline{v(t)} + \sum_{k=1}^{N} V_k \cos(\omega_k t - \phi_k)) =$$
$$= (\overline{u(t)} + j\overline{v(t)}) + \sum_{k=1}^{N} [U_k \cos(\omega_k t - \varphi_k) + jV_k \cos(\omega_k t - \phi_k)], \quad (1)$$

in which $(\overline{u(t)} + j\overline{v(t)})$ is the mean velocity, ω_k (k = 1,…, N) is the angular frequency, t (=nΔt) is the time and (U_k, V_k) and (φ_k, ϕ_k) are the amplitudes and phases, respectively, of the Fourier constituents for each frequency for the real and imaginary components. Subtracting the mean velocity and expanding the trigonometric functions, we find:

$$w'(t) = w(t) - (\overline{u(t)} + j\overline{v(t)}) =$$
$$= \sum_{k=1}^{N} [U_{1k} \cos\omega_k t + U_{2k} \sin\omega_k t + jV_{1k} \cos\omega_k t + jV_{2k} \sin\omega_k t], \quad (2)$$

where

$$U_{1k} = U_k \cos\varphi_k;\ U_{2k} = U_k \sin\varphi_k;$$
$$V_{1k} = V_k \cos\phi_k;\ V_{2k} = V_k \sin\phi_k. \quad (3)$$

It is possible to separate each k^{th} component into clockwise and counter-clockwise components

$$w'(t) = w^+(t) + w^-(t) = A_k^+ e^{j\varepsilon_k^+} e^{j\omega_k t} + A_k^- e^{j\varepsilon_k^-} e^{-j\omega_k t}, \quad (4)$$

where the clockwise and the counter-clockwise rotary component amplitudes are

$$A_k^+ = \frac{1}{2}\sqrt{(U_{1k} + V_{2k})^2 + (U_{2k} - V_{1k})^2}$$
$$A_k^- = \frac{1}{2}\sqrt{(U_{1k} - V_{2k})^2 + (U_{2k} + V_{1k})^2} \quad (5)$$

and the corresponding phase angles at time t=0 s are

$$\varepsilon_k^+ = \tan^{-1}\left\{\frac{V_{1k} - U_{2k}}{U_{1k} + V_{2k}}\right\} \text{ and } \varepsilon_k^- = \tan^{-1}\left\{\frac{V_{1k} + U_{2k}}{U_{1k} - V_{2k}}\right\}. \quad (6)$$

The one side spectra S_k^+ and S_k^- for the two oppositely rotating components for frequencies $f_k = \omega_k / 2\pi$ are

$$S^+(f_k) = \frac{(A_k^+)^2}{N\Delta t} \qquad f_k = 0,\ldots,\frac{1}{2\Delta t};$$
$$S^-(f_k) = \frac{(A_k^-)^2}{N\Delta t} \qquad f_k = -\frac{1}{2\Delta t},\ldots,0. \quad (7)$$

D. *Rotary spectra implementation*

The aim is to apply rotary spectra analysis to the CoP trajectories obtained with the force platform. The rotary spectra analysis is applied to

$$\overrightarrow{CoP} = \overrightarrow{CoP_x} + \overrightarrow{CoP_y}, \quad (8)$$

where CoP_x and CoP_y are the orthogonal components on the force platform surface.

We removed spectral components with frequency lower than 0.05 Hz from CoP_x and CoP_y, and we computed the one side spectra S^+ and S^- for the two oppositely rotating components. A second order moving average filter was then applied.

E. *Data Analysis*

For each clockwise and counter-clockwise component we estimated the bandwidth as the width of the frequency band in which 95% of the signal power is located.

Moreover, we estimated the following spectral parameters: mean frequency (the ratio between the first and the zeroth spectral moments), median frequency (the frequency which divides the spectrum in areas of equal power), and skewness (the ratio between the third spectral moment and the second spectral moment with exponent 1.5).

III. Results

Fig. 1a) and 1b) show clockwise and counter-clockwise components for a specific subject in the open and closed eyes trials, respectively. This is a representative result of the rotary analysis applied to the CoP trajectories.

It is possible to observe that both for the clockwise and the counter-clockwise components there is a main peak.

In fig. 1a) the counter-clockwise component has a main peak at 8 rotations per minute (rpm). For what concerns the clockwise component, we observe that, in this specific case, the main peak is smaller than the counter-clockwise one.

In fig. 1b) the clockwise component shows a main peak at 6 rpm, followed by a smaller peak. The counter-clockwise component shows two adjacent smaller peaks, the first at 4 rpm and the second at 10 rpm.

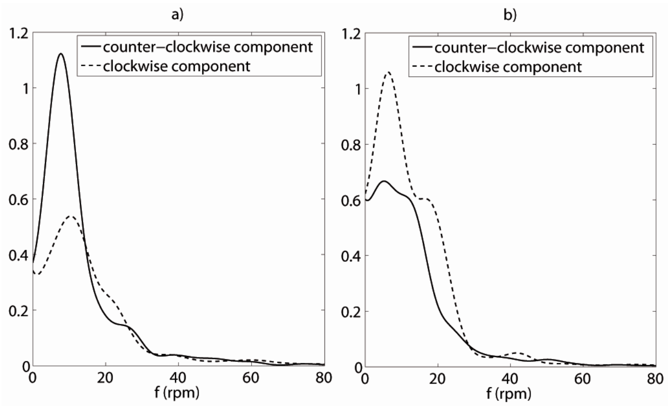

Fig.1. Clockwise and counter-clockwise components of the CoP trajectories. (a) Trial with open eyes; (b) trial with closed eyes.

Table I reports mean and standard deviation for the estimated spectral parameters, for the clockwise and the counter-clockwise components, in both open and closed eyes trials.

After verifying the gaussianity of the distributions, we compared values of the spectral parameters obtained for the two components in the closed eyes trials with the ones obtained with open eyes by means of a two-sample t-test. Moreover, we compared parameters characterizing the clockwise and the counter-clockwise components obtained from the same trial.

It is possible to observe that, for both rotational components, the bandwidth at the 95% of the signal power is about 60 rpm. There are no significant differences between clockwise and counter-clockwise components, both evaluated with open and closed eyes.

Comparing open and closed eyes conditions, we found that there are significant differences in the counter-clockwise component, but no statistically significant difference is present in the clockwise component. More specifically, in the closed eyes trials mean and median frequencies have greater values than in open eyes trials.

The estimated skewness have positive values for both components, in all the trials. Skewness is a measure of the asymmetry of the spectrum. A positive skew means that the power of the spectrum is concentrated in the lower frequencies.

TABLE I
SPECTRAL PARAMETERS (MEAN ± STANDARD DEVIATION).

		Bandwidth (rpm)	Mean frequency (rpm)	Median frequency (rpm)	Skewness
OE	Counter-clockwise	63 ± 18	16.0 ± 4.8*	13.2 ± 4.2*	1.4 ± 0.4
	Clockwise	62 ± 19	16.0 ± 4.8	13.8 ± 4.2	1.3 ± 0.4
CE	Counter-clockwise	68 ± 19	18.6 ± 4.8*	15.0 ± 3.0*	1.3 ± 0.4
	Clockwise	67 ± 20	18.6 ± 5.4	15.6 ± 3.6	1.2 ± 0.4

* Significant difference between open and closed eyes trials ($p < 0.05$).

IV. Discussion

In this study, we hypothesized that CoP trajectories on the platform surface could be decomposed into rotating components.

We applied rotary spectra analysis to obtain clockwise and counter-clockwise components of the CoP trajectories. This approach was never used before by others to analyze stabilometric signals.

We characterized each rotary spectrum calculating its bandwidth, mean and median frequency, and skewness. Spectral parameters calculated for the 43 subjects show a small inter-subject variability. This is an encouraging result since traditional stabilometric parameters usually show high inter-subject variability [1]. Moreover, we did not find significant differences between the parameters describing the clockwise and the counter-clockwise rotating components.

Comparing open and closed eyes conditions, we found that there are differences for the mean and median frequencies, but these differences are statistically significant for the counter-clockwise component only. The differences between open and closed eyes conditions, when evaluating balance performance, are well documented in literature [3][4][16]. This finding is confirmed by the new approach we adopted.

It is plausible to hypothesize that the CoP signal is not stationary, therefore with our analysis we obtained the frequency marginals of the signal during the 60 s of the test. To analyze the CoP trajectories as non-stationary random signals, it would be necessary to extend the classical rotary spectra theory to deal with non-stationary signals. This problem has been faced with wavelet transform [13], Short Time Fourier Transform [14], and time-frequency analysis [15].

V. Conclusion

The application of rotary spectra analysis to stabilometry gives a new perspective in describing and interpreting CoP trajectories. The hope is that this approach will better highlights the physiological mechanisms underlying postural control than traditional approaches.

This study demonstrates that the described procedure is feasible. More research is needed to demonstrate the clinical applicability of this methodology, but results so far obtained are promising.

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