RELIABILITY OF NON-LINEAR POSTURAL PARAMETERS DURING STABILOMETRIC ANALYSIS

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Abstract: The study of the reliability of postural parameters is interest for examination the effect of aging on balance. To date, several publications have reported the reliability of temporal, spatiotemporal, and spectral parameters extracted from centre of pressure (COP) signals. Recently, several studies have examined non-linear parameters extracted from COP signals, which are thought to be related to physiological control processes. Of particular interest are estimations of the Hurst exponent, which provides an indication of the degree of auto-similarity in the signal. The aim of this study was to examine the reliability of three methods of estimating the Hurst Exponent extracted from stabilogram signals. The intraclass correlation coefficient (ICC) was used as a measure of reliability. ICC values ranged from The ICC values calculated for non-linear stabilogram analysis ranged from 0.37 to 0.73, which can be considered to be fair to good. Correlations for ML displacement were greater than those for AP displacement. In conclusion, non-linear postural parameters extracted from stabilometric signals are sufficiently reliable to be used for assessment of balance.

Introduction

The study of postural stability is of interest in many fields, including the study of aging and balance disorders. One method of analysing postural stability is to use a force plate to extract measures of centre of pressure (COP) displacement in anteroposterior (AP), mediolateral (ML), and resultant (RD) directions. The stabilogram is a representation of the centre of pressure displacement in AP and ML in function of the time (see Fig. 1).

The classical parameters that are typically extracted from such COP signals (stabilogram) include temporal (mean, RMS), spatiotemporal (surface of the ellipse) and spectral (median frequency, deciles). Such simple measures provide no information about the type of control mechanism used to produce the COP trace. In contrast, non-linear parameters, such as the Hurst Exponent, have been shown to be related to physiological control processes, thus providing a possible tool to follow balance disorders longitudinally [1]. There are several methods by which the Hurst exponent can be estimated, including Stabilogram Diffusion Analysis (SDA), Rescaled Range Analysis (R/S), and Detrended Fluctuation Analysis (DFA) [2]. Despite the potential physiological significance of these parameters, in order to be clinically useful they must provide reliable estimations.

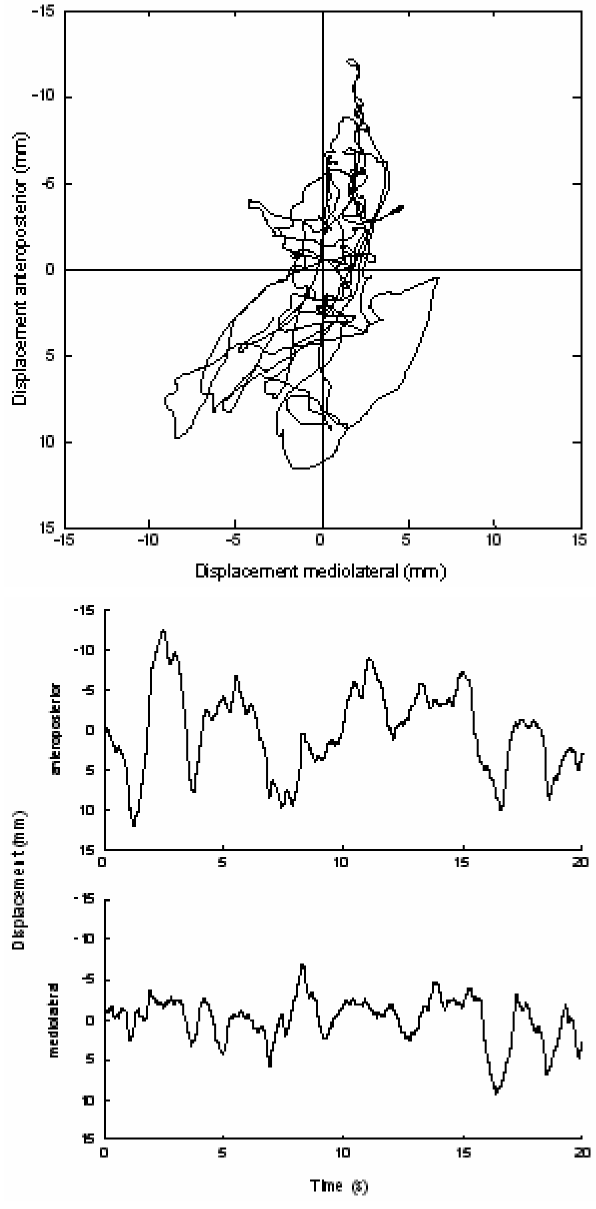

Figure 1: Typical stabilogram of the displacement of the centre of pressure (COP).

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To date, reliability studies have tended to analyse only classical COP parameters with the intraclass correlation coefficients (ICC) reported varying from 0.22 to 0.94 [3-5]. As part of the testing protocol, investigators typically trace the position of each subject's feet in order to use the same foot position in subsequent testing sessions. However, such a technique is not practical for a large scale longitudinal study of postural stability.

The aim of this study, therefore, is to compare the reliability of non-linear COP parameters over different testing sessions with no constraint over subjects' foot position.

Materials and Methods

Subjects: Ninety healthy young adults (57 male, 33 female). Subjects' mean age, height and weight were 19.7 ± 0.8 y, 174.9 ± 9.5 cm, and 67.0 ± 11.1 kg, respectively. All subjects who participated gave their written informed consent. No subjects reported any musculoskeletal or neurological conditions that precluded their participation in the study.

Experimental protocol: Subjects were instructed to look straight ahead, with their arms placed at their sides in a comfortable position, and were tested either barefoot or wearing socks. Upon a verbal command, subjects stepped onto a force plate (4060-80, Bertec Corporation, Colombus, OH, USA) with no constraint given over foot position and stood quietly for 45 s with their eyes open (EO), after that a verbal command was given to close their eyes (EC) for 30 s. While their eyes are opened, subjects are instructed to looking at a target of a 10-cm cross fixed on the wall two meters in front of the force-plate. Each subject was tested four times: twice per testing session, with a 5-min pause between tests, with two testing sessions performed two weeks apart. Subjects were allowed to select their own foot position for each test.

Centre of pressure data acquisition: Data were acquired with a NIDAQ card (6036E, National Instruments, Natick, USA) at 100 Hz with a low-pass Butterworth filter (8th order, cut-off frequency 10 Hz). The initial COP signals were calculated with respect to the centre of the force-plate before normalization by subtraction of the mean. All calculations of COP data were performed with Matlab (Mathworks Inc, Natick, MA, USA).

Estimation of the Hurst exponent: Estimates of the Hurst exponent were calculated using the three methods outlined below:

Rescaled Range Analysis: The original method used to estimate H for a non-linear time series was Hurst's Rescaled Range Analysis (R/S), which was initially used to analyse water levels in the Nile [6]. When applying Hurst's method, a time series is first divided into a series of equal intervals, each of which is then integrated to produce X(t,n), defined by the following equation:

$$X(t,n) = \left\{ \sum_{i=1}^{t} (x_i - \langle x \rangle_n) \right\} \tag{1}$$

where $\langle x \rangle_n$ is the mean of the interval of n data points.

The range R of each interval $X(t,n)$ is then calculated as:

$$R = \max_{1 \le t \le n} X(t,n) - \min_{1 \le t \le n} X(t,n) \tag{2}$$

The range is then normalized by dividing by the local standard deviation S of the original time series:

$$S(n) = \left\{ \frac{1}{n} \sum_{t=1}^{n} \left[x_t - \bar{x}_n \right]^2 \right\}^{1/2} \tag{3}$$

This procedure is repeated for all possible interval lengths, and the average calculated to produce:

$$R / S = (\alpha n)^H \tag{4}$$

where α is a constant, and H is the Hurst exponent, hereafter indicated as HR/S.

Detrended Fluctuation Analysis (DFA): Peng and colleagues [7] introduced another method of estimating the Hurst exponent specifically for biological time series data, which they termed Detrended Fluctuation Analysis (DFA). The first step is to subtract the mean from the original series, which is then integrated:

$$y(k) = \sum_{i=1}^{k} \left[x(i) - \langle x \rangle \right] \tag{5}$$

This series is then divided into n equal length intervals. If the total length N is not divisible by n, the length N is adjusted to the largest multiple of n < N. The local trend of each window y_n is obtained and subtracted from the summed series, using a line of least-squared fit to obtain the detrended fluctuation F(n) as:

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left\{ y(k) - y_n(k) \right\}^2} \tag{6}$$

The slope of the regression line for F(n) on a log scale is calculated (α) and used as an estimation of the Hurst exponent, hereafter indicated as HDFA. The estimation HDFA is always greater than HR/S , with HDFA = HR/S +1 for fractional Brownian motion [8].

Stabilogram Diffusion Analysis (SDA): Collins and De Luca [9] hypothesized that the trajectory of the COP could be modeled as a correlated random walk. They proposed a simple method to calculate the scaling exponent H of a stabilogram, whereby the square of the displacement for a given time interval Δt is calculated for all possible pairs of points separated by Δt, and the average calculated as:

$$\left\langle \Delta x^{2} \right\rangle_{\Delta t} = \frac{1}{N-m} \sum_{i=1}^{N-m} (x_{i+\Delta t} - x_{i})^{2} \qquad (7)$$

where N is the number of points in the vector x, and m is the interval between two values expressed as the number of data.

Estimations of the Hurst exponent are then obtained from the graph of Δt by $<\Delta x>^2$ in log scale by calculating the slope of the short-term (HS) and long-term (HL) regions of the curve. The equations used by Collins and colleagues to estimate HS and HL contain several assumptions. The second derivative of the Δt by $<\Delta x>^2$ data is used to locate four times (T1, T2, T3, T4) between which the slopes HS (T1, T2) and HL (T3, T4) are calculated. The first time, T1, is always taken as zero, while T2 is the first maximum that occurs before 1 s. The slope HS is then calculated between these points. Similarly, the slope HL is calculated between T3 and T4, where T3 is calculated as the second maximum, and T4 as the first maximum occurring after the first minimum when the signal is analyzed backwards from 9 s. If no maximum is found before 7 s, T4 is taken to be 9 s. [1]

Data analysis: Estimates of the Hurst exponent were calculated over 20 s between 20-40 s for EO and between 55-75 s for EC AP and ML displacement. All statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). The intra-class correlation (ICC) was used as a measure of reliability [10].

Results

The results of the ICC analysis for EO and EC experimental conditions across all four tests for AP and ML displacement directions are presented in Table 1.

Table 1: Intra-class correlation coefficients of non-linear postural parameters.

Method	Direction	Eyes open	Eyes closed
DFA	AP	0.55	0.60
	ML	0.72	0.63
RS	AP	0.42	0.37
	ML	0.60	0.61
SDA	AP	0.46	0.54
	ML	0.73	0.70

Discussion

The ICC values calculated for non-linear stabilogram analysis ranged from 0.37 to 0.73. In respect of their level of repeatability, such values are considered to be fair to good using Fleiss's interpretation [11]. The correlations for ML displacement were greater than those for AP, which is not surprising, given that subjects' displacement varies more in an AP than in an ML direction due to the constraints on the system imposed by the ankle and knee joints.

In respect to the reliability observed in previous studies, the present values are broadly in agreement. Lafond and colleagues reported ICC values for temporal, spatiotemporal, and spectral parameters that ranged from 0.22 to 0.87 for 30-s recordings [5]. However, only those ICC for COP velocity exceeded 0.5. In keeping with these results, the ICC values reported by Du Pasquier and colleagues for COP velocity was 0.79 for both displacement directions [12]. In one study in which the reliability of SDA parameters was assessed, Chiari and colleagues reported ICC values ranging 0.41 to 0.79, in keeping with the values reported in the present study [13].

There were major methodological differences between the studies cited above, and the present study in relation to foot position, recording duration, the time between tests, and the total number of tests. In all of the studies cited above, each subject's foot position was noted for the first trial, and all subsequent tests performed using an identical foot position. In contrast, subjects in the present study were left free to choose their foot position. It would have been expected that the freedom given to subjects in the present study to choose their own foot position, would have adversely affected the ICC reported. However, the ICC values reported were of a similar magnitude, irrespective of foot position. In respect to the duration of measurement, the present study used 20-s segments obtained from a 75-s recording time. Such a duration was lower than that used previously, whereby ICC values were calculated for 30 s [5,12], 50 s [13], or even 120 s [4].

An additional difference concerned the time taken between measures, which was 14 days between the first and last test in the present study. In contrast, only the study of Corriveau and colleagues left a similar (up to 7 days) time period between tests. Other studies used rest periods up to three minutes between tests [5,12,13]. Finally, the number of tests used to obtain the ICC estimation varied from two [4,12] to 9-10 [5,13], in contrast to the four tests used in the present study. It is a well-known property of ICC values, that an increased number of tests will produce an increase in the value observed.

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[1] A copy of the Matlab program, as well a detailed explanation is available at www.isbweb.org/software/movanal/stamp.

Conclusion

The non-linear parameters examined in the present study appear to be as reliable as those classical parameters for which reliability has been previously reported. Such parameters are sufficiently reliable to be used for a longitudinal assessment of balance.

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