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Dynamical and stabilometric measures are complementary for the characterization of postural fluctuations in older women

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ABSTRACT

We investigate the complementarities of several measures extracted from center of pressure (COP) recordings during quiet standing, in older women. The selected variables include classical stabilometric measures (SMs) and several dynamical measures (DMs). The computed DMs quantify various features of the temporal structure of COP signals, including predictability, regularity and smoothness of the trajectories. The postural fluctuations of a group of 101 healthy older women were recorded by means of a force platform. After estimating the SMs and DMs from the COP data, we used principal components analysis (PCA) to quantify the contribution of each measure. The results suggest that SMs and DMs are complementary. In addition, the different DMs are globally not redundant. This finding is a reinforcement argument in favor of the use of DMs as postural signatures.

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1. Introduction

Since decades, many studies have aimed to understand the mechanisms of postural control in humans. One of the main variables that have been used to quantify postural sway during quiet standing is the center of pressure (COP). The COP is simply the point location of the vertical ground reaction resultant force vector. It can be easily measured by using a force platform.

The stabilometric variables extracted from COP fluctuations, such as length (or mean velocity), area and variability, are often used as global indices to evaluate postural control [1,2]. Good "stability" is generally associated with small displacements of the COP and slow postural oscillations [1]. Authors have demonstrated that older adults are characterized by an increase of the area of COP sway and a concomitant increase of the length of these fluctuations [2]. The speed of COP displacement has been exploited to investigate the role of sensory reintegration in the elderly [3]. However, analyses and results based on stabilometric parameters should be interpreted with caution since many studies and reviews have shown that no general conclusions can be made concerning the effects of several functionally relevant factors on the evolution of these parameters or their potentially predictive power regarding the risk of falls (see for instance the review [4]).

Since approximately 20 years, new methods derived from nonlinear dynamics and statistical physics [5] offered new possibilities for the analysis and interpretation of COP measures [6,7]. From a conceptual point of view, these techniques consider the postural control system as a complex dynamical system. The measures obtained from these methods are generally scale-independent: they do not depend on the magnitude or the variance of the data. These dynamical measures describe the temporal structure of the COP signals and their complexity [5].

In a more general context, Goldberger et al. have proposed the theory of "loss of complexity" to explain some of the effects of age and disease on physiologic systems [8]. The two main ideas of this theory are given in [8]: (i) the output of a healthy system reveals a complex variability that relates to long-range correlations and nonlinear interactions, and (ii) this complexity is broken down by aging and disease, reducing the adaptive capabilities of the organism. Among the new techniques that have been applied to COP fluctuations, recurrence quantification analysis (RQA [9]) has been used to quantify the changes in the dynamics of the posture when vision is removed [10], with aging [11] or with disease [12]. Different entropy measures have been calculated from COP time series to investigate the effects of visual feedback [13], aging [14] or frailty [15] on the complexity of postural data. Some studies have combined various techniques [14,15] and a recent paper [16] included a principal components analysis (PCA) to verify that three COP variables (velocity, area and one complexity measure) are not loaded on the same components. Another previous study [17] also used PCA as the basis of a feature selection process to analyze

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traditional stabilometric (kinematical and frequency-domain) measures obtained from young and healthy subjects.

In this paper, we used PCA to explore the relative contributions and potential redundancies of four different dynamical variables and three stabilometric parameters extracted from COP time series, recorded from a group of 101 older women. We selected dynamical measures that are related to the complexity of COP fluctuations in terms of predictability (measures provided by RQA), regularity (sample entropy denoted SEN) and smoothness (Central tendency measure denoted CTM). These measures were chosen among several statistics because they do not require deterministic underlying dynamics [13,14]. In addition, as it will be detailed in the methods section, they can be applied to non-stationary data, directly or by including a simple preprocessing of the COP time series.

2. Methods

2.1. Subjects and protocol

101 older women (age: 68.4 ± 4.2 years; height: 162.1 ± 6.5 cm; mass: 67.8 ± 12.2 kg) were recruited and tested with eyes open. These subjects were selected after a medical visit to ensure that they were free from muscular, neurological or cardiovascular diseases. Participants had to maintain quiet stance with arms rested alongside their body while standing on a force platform (Médicapteurs®). The signal processing was done with a 16-bit A/D converter. The recordings started 5 s after the beginning of each test, and lasted for 51.2 s. The sampling frequency was 40 Hz, yielding 2048 points time series in both anteriorposterior (AP) and mediolateral (ML) directions. An institutional review board approved this study (CPP Sud Méditerranée III, Number 2008.07.04).

2.2. Data analysis

2.2.1. Stabilometric measures (SMs)

The key dependant variables of the COP's displacement are: its length, *L*, its surface area, *S*, taken as the surface of the confidence ellipse enclosing 90% of COP sway, and its standard deviation, SD, in the ML and AP directions.

2.2.2. Dynamical measures (DMs)

We refer to dynamical measures as quantities describing the temporal structure of the analyzed data. We define (x_i) as the time samples of the COP signals in the AP and ML directions. The time series describing the velocity dynamics were obtained from the first differences of x_i: $\nu_i = x_{i+1} - x_i$. Fig. 1 shows a recorded COP signal and the corresponding differenced time series.

The use of the differenced time series (ν_i) for the computation of some dynamical measures was motivated by the non-stationarity [18] and long-range correlations [19] observed in COP time series. Indeed, these specific properties are generally obstacles to the application of nonlinear analyses [5]. Differencing the original data allows to remove the trend and reduce correlations [13,14,20]. In the following subsections, for each DM and method used to estimate it, we will specify the use of the position (x_i) or differenced (ν_i) time series.

The methods described below are based on phase space reconstruction and time delay embedding [5]. The first step of the procedure is to construct delayed vectors. For instance, if the original time series is given by the samples (x_i), such vectors $X_i(m)$ are defined by $X_i(m) = (x_i, x_{i+\tau}, x_{i+2\tau}, \ldots, x_{i+(m-1)\tau})$, where τ is an integer called the time delay and m is the dimension of the vectors. The dimension m and the time delay τ are selected according to a specific procedure, which depends on the computed measure.

- Recurrence quantification analysis (RQA)

RQA is a tool for studying the temporal dynamics of a time series. This method provides quantitative information on the properties of the underlying dynamical process of a time series (see [9] and references therein). RQA does not require a normal distribution or stationary data.

Here, we apply RQA to the COP position samples (x_i). After defining delayed vectors $X_i(m)$ defined previously and computing the distances between the associated points, RQA is based on the construction of a recurrence plot (RP) [21] from which quantitative measures are extracted, such as the percentage of recurrence, which quantifies the density of recurrence points. Another important measure, named the percentage of determinism and

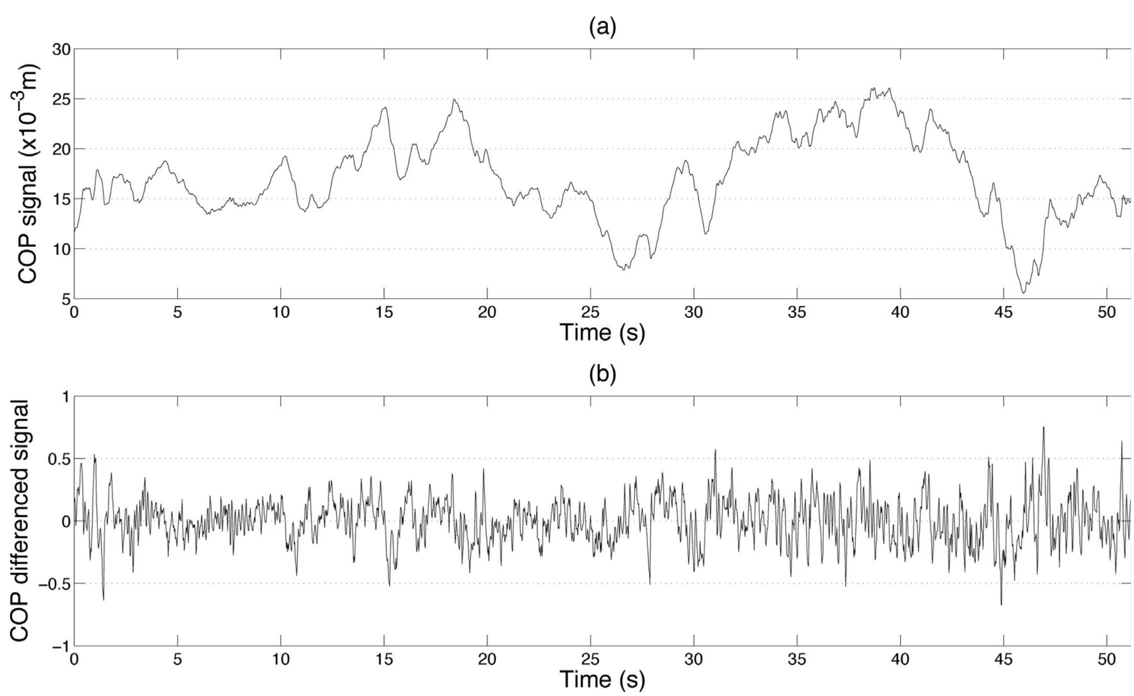

Fig. 1. An AP COP signal of an older woman (a) and the corresponding differenced time series (b).

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