POSTURAL TIME-SERIES ANALYSIS USING EMPIRICAL MODE DECOMPOSITION AND SECOND-ORDER DIFFERENCE PLOTS

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ABSTRACT

This paper presents a new method for analysis of center of pressure (COP) signals using Empirical Mode Decomposition (EMD). The EMD decomposes a COP signal into a finite set of band-limited signals termed as intrinsic mode functions (IMFs). Thereafter, a signal processing technique used in continuous chaotic modeling is used to investigate the difference between experimental conditions on the summed IMFs. This method is used to detect the degree of variability from a second-order difference plot, which is quantified using a Central Tendency Measure (CTM). Seventeen subjects were tested under eyes open (EO) and eyes closed (EC) conditions, with different vibration frequencies applied for the EC condition in order to provide additional sensory perturbation. This study has demonstrated an effective way to differentiate vibration frequencies by combining EMD and second-order difference (SOD) plots.

Index Terms— COP signal, EMD and SOD plots.

1. INTRODUCTION

Parameters extracted from center of pressure (COP) signals are commonly used as indicators of balance and postural control. In order to maintain equilibrium, the central nervous system (CNS) needs to continuously monitor and interpret information from the visual, vestibular and proprioceptive systems [1]. Inadequacy in postural balance in older people increases the risk of falls, which are the leading cause of accidental death and injury [2]. Inadequacy of visual function with age is one of the key risk factor for falls in the elderly [3]. Problems related to other sensory systems would also have an adverse effect on balance. For instance, ankle proprioception plays a key role in maintaining balance. Individuals with lower-leg proprioceptive loss have balance problems, particularly in dynamic tasks [4].

It would be of interest to develop a method to identify differences in balance between individuals with different sensory problems. The two sensory problems that lend themselves most easily to such modifications are the visual and proprioceptive systems. The effect of vision on maintaining D. Hewson, H. Snoussi, J. Duchêne

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balance can be altered simply by requiring subjects to close their eyes, while proprioception can be modified by the use of tendon vibrations. In the latter case, the vibration acts as an artificial simulation that causes erroneous information on the movement of the affected body segment to be sent to the CNS. In the case of balance, vibration applied to the tibialis anterior tendon when subjects are in a static upright position creates an illusion of a backwards tilt of the body in order to correct the perceived tilt [1]. To this point, no studies have assessed the effect of vibration frequency on standing posture.

In order to study static equilibrium, recently, nonlinear methods have been proposed to extract new parameters linked to the underlying physiological systems. Among these parameters, the Hurst exponent provides information about the correlation and the auto similarity of the COP signal, while, the Lyapunov exponent and entropy might also contain precious information about the static equilibrium of the subject. Previous studies have shown that the COP signal is a nonstationary and nonlinear process [5, 6].

In this paper a new technique based on the two successive signal dependent decompositions was employed to detect the differences in the COP time series between EC (with different vibration frequencies) and EO conditions. The first applied decomposition is the empirical mode decomposition (EMD) [7], which extracts local oscillations composing the signal, referred to as the Intrinsic Mode Functions (IMF), as well as the residual representing the local trends. Then, in order to study the rate of variability of the different combinations of the IMFs, a method used in continuous chaotic modelling had been employed. This method measures the degree of variability seen in a second-order difference (SOD) plot, and quantifies it using CTM [8].

2. METHODOLOGY

2.1. Subjects

Seventeen healthy adult subjects were tested (10 males and 7 females). Subjects mean age, height and weight were 22.8 4.0, 174.2 8.5 cm, and 67.1 10.7 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.

2.2. Experimental Protocol

Subjects were tested with their eyes closed in order to increase the contribution of the proprioceptive system on balance control, and thus increase the likelihood of obtaining a modification in balance as a result of the experiment. Vibration was applied bilaterally using the VB115 vibrator (Techno Concept, Cereste, France) to the tibialis anterior tendon for 10 s. At the end of vibration, subjects were given a verbal command to step onto a force plate (4060-80, Bertec Corporation, Colombus, OH, USA). Subjects stood quietly for 10 s with their eyes remaining closed, before stepping down backwards off the force plate after a second verbal command. Measurements were repeated five times for each experimental condition, with a 30-second delay between tests. Subjects were given a 10-min delay between experimental conditions in order to reduce any post-vibratory effect of one frequency on the subsequent experimental condition. Subjects were tested using four different vibration frequencies (0 Hz; 50 Hz; 70 Hz; 90 Hz) which were performed in a random order. The frequencies chosen were based on those reported in previous studies [9, 10].

Data were recorded using the ProTags TM (Jean-Yves Hogrel, Institut de Myologie, Paris, France) program developed under Labview (National Instruments Corporation, Austin TX, USA). Data were sampled at 100 Hz, using an 8th-order low-pass Butterworth filter with a cut-off frequency of 10 Hz.



Fig. 1. Second-order difference plots anteroposterior (AP) time series: (a) EO and, (b) EC with vibration of 90 Hz

2.3. Empirical Mode Decomposition

The principle of the EMD technique is to decompose a signal x(t) automatically into a set of the band-limited functions $D_p(t)$ called IMFs [7]. Each IMF satisfies two basic conditions: (i) in the complete data set, the number of extrema and the number of zero crossings must be the same or differ at

most by one, (ii) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The first condition is similar to the narrow-band requirement for a stationary Gaussian process and the second condition is a local requirement induced from the global one, and necessary to ensure that the instantaneous frequency will not have redundant fluctuations as induced by asymmetric waveforms. The nonstationary signal x(t) is then represented as a linear sum of IMFs and the residual compo-

nent: $x(t) = \sum_{p=1}^{M} D_p(t) + r_M(t)$, where *M* is the number of IMFs and $r_M(t)$ is the final residue. The number of IMFs varied between experiments and between subjects. The minimum number of IMF was 4.



Fig. 2. CTM of AP and mediolateral (ML) signals for the different value of radius: (a) r=0.362, (b) r=0.276, (c) r=0.198. \star Significant difference from EO; \dagger Significant difference from 90 Hz condition.

2.4. Second-Order Difference Plot and CTM

In the SOD plot, [x(n+2)-x(n+1)] is plotted against [x(n+1)-x(n)]. It is a plot of successive rates against each other and gives a graphical representation of the rate of variability [x(n+2)-x(n+1)] versus [x(n+1)-x(n)]. It shows the rate of variation of successive rates. For continuous data as the sampling interval decreases, the rates scale appropriately and approach the result of continuous data. Therefore, provided the sampling interval is small, the difference will approach a scaled rate of the continuous function where the scaling factor is the sampling frequency. In this study the same frequency is used for all conditions.

The CTM quantifies the variability seen in the SOD plot. It is computed by selecting a circular region of radius r, around the origin, counting the number of points that fall within the radius, and dividing by the total number of points [8]. For each radius r, CTM provides the fraction of the total number of points lie within it. Figure 1 shows the SOD plots of the COP signal in the EO and EC (with vibration of 90 Hz). In the EC condition the plot is more elongated than when the eyes are open. There is more variability when eyes are closed than when open.

2.5. Statistical Analysis

Statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). Multivariate repeated measures analysis of variance was used to compare results between conditions, with CTM as the dependent variable and the experimental condition as the independent variables. Separate analyses were performed for AP and ML signals. Analysis of contrasts were undertaken to identify differences between configurations, with Bonferroni adjustments used to reduce type I error rates. Alpha level was set at p < 0.05.



Fig. 3. CTM of AP signals for the different combinations of the IMFs (upwards):(a) All IMFs, (b) Summation of the second IMF to the maximum IMF (IMF2m), (c) Summation of the third IMF to the maximum IMF (IMF3m), (d) Summation of the fourth IMF to the maximum IMF (IMF4m). * Significant difference from EO; † Significant difference from 90 Hz condition; \$ Significant different from 70 Hz condition.

3. RESULTS

Figure 2 shows the CTM plots for AP and ML signals for the values of radius r, when the CTM reaches values 0.95, 0.90, 0.80 respectively for the EO condition. The plot shows that for a given value of radius r, the CTM clearly distinguishes the two conditions EO and EC (p < 0.05). There is more variability when eyes are closed than when open. The CTM value corresponding to 0.90 for EO gives the best separation between the EO and EC conditions (Figure 2; p < 0.05). It is also clear that differences for AP signals vary accordingly to r, with the best results, in terms of separation between vibration frequencies, obtained for the CTM value corresponding to 0.90 for EO conditions (p < 0.05). The CTM also separates the EO and EC conditions for ML signals corresponding to the CTM 0.90 and 0.95 for EO condition (Figure 2; p < 0.05).

The application of EMD separated the COP signals into different frequency bands (or IMFs). In respect to differences between experimental conditions, the CTM estimates for low frequency bands (IMF4m) were significantly higher for the EO condition than for 70 and 90 Hz conditions (Figure 3; p < 0.05). The 0 Hz and 50 Hz conditions were also significantly higher than the 90 Hz condition (Figure 3; p < 0.05). CTM estimates for medium to low frequency bands (IMF2m) were significantly higher for EO condition than for all other conditions (Figure 3; p < 0.05). The 0 Hz condition was also significantly higher than the 90 Hz and 70 Hz conditions (Figure 3; p < 0.05). CTM estimates for high frequency band (IMF1) were significantly higher for the EO condition than for the 50, 70 and 90 Hz conditions (Figure 4; p < 0.05). The 0 Hz condition was also significantly higher than the 70 and 90 Hz vibrations (Figure 4; p < 0.05).



Fig. 4. CTM of AP signals for the different combinations of the IMFs (downwards):(a) First IMF, (b) Summation of the first two IMFs, (c) Summation of the first three IMFs, (d) Summation of the second and third IMFs. * Significant difference from EO; † Significant difference from 90 Hz condition; \$ Significant different from 70 Hz condition.

4. DISCUSSION

The use of EMD before the second-order difference plot was necessary owing to the nonlinear and nonstationary nature of COP signals [6, 10]. It has been shown in [6] that the EMD enables separation of COP signals into stochastic, chaotic and deterministic components contained in the original signal. The theoretical second-order difference plots derived from the continuous model are effective in visually demonstrating the degree of variability, or chaos, in the data set [8]. This degree of variability provides a powerful approach for summarizing long-duration time series. The CTM is a fast method for summarizing the visual information in the graphs. The optimum value of radius r = 0.276, which gives the best separation between EO and EC conditions, was found for our data base.

In respect to differences between the conditions, without EMD, the CTM can separate only the EO condition from the EC condition. It is not possible to distinguish between the different vibration conditions using the entire signal (Fig. 3(a)). The EMD decomposes a COP signal into a set of IMFs, which can then be analyzed either individually, or after summing. Two different directions of summation were used. Firstly, the highest-frequency IMFs were removed one after the other,

with the sum of remaining IMFs used for CTM analysis. Secondly, the first IMF was used, followed by a summation with the subsequent IMFs until all but the final IMF were included. In the first method, CTM was calculated for the summation of the second IMF to the maximum IMF (IMF2m) present in the signal, thus removing the highest frequency band contained in the first IMF. Although, the performance of the method was similar, it was possible to distinguish the 70 Hz and 90 Hz conditions from 0 Hz. In other words, high frequency vibration was separated from no vibration (0 Hz condition) for eyes closed (Fig. 3(b)); difference of -16% for EO versus 90 Hz condition. When the CTM method was applied on the summation of the third IMF to maximum IMF (IMF3m) present in the signal, thus retaining only the lowest frequency components of the original signal, it was also possible to differentiate between 0 Hz and the 70 and 90 Hz conditions. However, the magnitude of the difference observed was smaller than for IMF2m with a decreased of 10% from EO to the 90 Hz condition (Fig. 3(c)). Finally, when CTM was applied on the summation of the fourth IMF to maximum IMF (IMF4m) present in the signal, no difference was observed between, EO condition was equal to the 0 Hz and 50 Hz conditions, all of which were significantly greater than the 90 Hz condition. The magnitude of this effect was -2 % for EO versus the 90 Hz condition (Fig. 3(d)). Such a finding indicates that the effect of the proprioceptive perturbation (vibration) is primarily contained in the lowest frequency band of COP signals. In the second analysis, starting with the first IMF, CTM was calculated for IMF1. The results show that a good separation was possible between EO condition and EC condition provided vibration was present. In other words, no difference was observed between EO and 0 Hz conditions (Fig. 4 (a)). The magnitude of the difference observed was -2%. This finding suggests that IMF1 is not suited to detecting the effect of visual perturbation. When the CTM method was applied on the summation of the first and second IMFs, the CTM method showed a difference of -10% between EO condition and 90 Hz condition (Fig. 4(b)). When CTM was applied on the summation of first, second and third IMFs, the biggest difference was -15% (EO versus 90 Hz condition) (Fig. 4(c)). When CTM was applied on the summation of second and third IMFs, the biggest difference was -14% (EO versus 90 Hz condition) (Fig. 4(d)).

In terms of the difference observed between experimental conditions, the CTM was generally greater for the eyes open condition than for all other condition. The logical interpretation of this finding is that the greater CTM is due to enhanced postural stability or less variability when subjects could use visual information.

5. CONCLUSION

The use of empirical mode decomposition and the secondorder difference plot to analyze the COP signal is a promising method. Low frequency IMFs are better able to differentiate between the different eyes closed conditions, thus distinguishing between the different vibration frequencies. In contrast, high frequency IMFs are better able to differentiate between EO and EC conditions.

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