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Dynamical analysis of balance in vestibular schwannoma patients

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ABSTRACT

The analysis of the complexity of postural fluctuations is a recent method for assessing postural control. Complexity relates to the irregularity of the center of pressure time series and characterizes the ability of postural control to meet a changing environment. In our study, we used the sample entropy (SampEn) parameter to evaluate the complexity of postural sway velocity time series in patients with vestibular schwannoma ($n = 19$) compared to healthy controls ($n = 20$), using the sensory organization test. Patients performed postural assessments three days before surgical ablation of the tumor, then three times after surgery, at eight, thirty, and ninety days. The control group underwent posturographic tests only once. Our results demonstrated that SampEn values distinguished both groups before surgery only in postural tasks where vestibular afferences significantly contribute to maintaining balance. We also found an immediate decrease of complexity after the surgical resection of the tumor. Our results are in line with the theory of complexity loss of physiological systems stating that reducing the number of their structural components or altering their coupling leads to a decrease in complexity. Finally, our findings showed that progressive restoration of complexity over time was such that no difference was found between the two groups ninety days after surgery, due to the implementation of central adaptive mechanisms and the substitution by other sensory afferences. Thus, the SampEn parameter can highlight the postural effects of vestibular pathology, and complexity analysis appears to be a valuable tool for investigating the temporal structure of CoP time series.

1. Introduction

Postural control relies on feedback from the somatosensory, vestibular, and visual systems [1]. The alteration of one of these systems can lead to increased postural instability. This degradation arises notably in patients with vestibular schwannoma (VS) – a benign tumor affecting Schwann cells surrounding the vestibular nerve – whose slow growth leads to a gradual vestibular dysfunction. This process is progressively compensated by central adaptive mechanisms [2], but the surgical resection of the tumor using a translabyrinthine approach induces unilateral vestibular deafferentation (uVD), leading to a decompensation of the previously compensated situation. Therefore, the uVD results in serious deterioration of balance control, which is progressively restored due to the implementation of central adaptive mechanisms. These could be of vestibular origin and could be the result of learning mechanisms involving neural structures and pathways beyond the vestibular nuclei [3].

In clinical practice, the quantification of center of pressure (CoP) displacement – using classic stabilometric measures such as sway area, sway path or length, mean velocity and variability of CoP fluctuations – is an important outcome to assess balance control [4]. Typically, low values for these parameters are interpreted as indicators of stability [5,6]. The sensory organization test (SOT), a common protocol used to study balance disorders, gives a good knowledge of the time-course of balance compensation in VS [3]. Yet, previous studies highlighted the limitations of the main calculated variable, called equilibrium score (ES), to produce an accurate assessment of balance control. Among these limitations, it was emphasized that the ES computation is based only on the two extreme sway angle values recorded during trial, thus ignoring all other postural fluctuations, and on a 12.5° theoretical range of sway limit of stability without taking into account individual differences (see [7] for a review). These limitations questioned the validity of this method for analyzing postural fluctuations to

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distinguish between individuals presenting different health status, and capture accurately the balance compensation in VS patients following the ablation of the tumor.

Moreover, conflicting results were reported in the literature concerning the effectiveness of stabilometric measures to highlight the effects of disease [8], as well as to distinguish between populations of various ages [9], and between various experimental conditions [10]. Thus, the assumption of an association between stability of posture and variability of classical parameters is currently debated [11,12]. Newell et al. [12] were the first to advocate not to associate these two concepts systematically. Likewise, Woollacott [13] showed that quantity of displacements of CoP is not correlated to the quality of postural control. These discrepancies prevented us from drawing conclusions regarding factors (e.g. aging and disease) that could modulate these measures and suggest that new methods may be necessary to investigate the changes in postural control.

For several decades new methods based on dynamics systems were increasingly used for characterizing the dynamical features of postural sway [14–17]. Among them, some techniques consist in assessing CoP dynamics through the quantification of the complexity of CoP signals. In this context, complexity is related to regularity, predictability and temporal correlations. Authors developed the theory of complexity loss suggesting that advancing in age and disease – hence the deterioration of physiological systems – seems to be associated with a decrease of complexity of CoP trajectories [15,16]. The two basic principles behind this theory are that (i) the output of a healthy system reveals a type of complex variability associated with long-range correlations and nonlinear interactions; (ii) and this complexity breaks down with aging and disease, reducing the adaptive capabilities of the individual. Over the years, various algorithms were developed to better estimate the entropy (i.e. complexity) of a system [14,18,19]. Recently, Richman and Moorman [17] introduced the sample entropy (SampEn) method to quantify the regularity of time series. The more irregular the signal is, the higher the SampEn is. The SampEn acts as a good measurement of complexity in many applications such as heart rate variability [17], EMG recordings [20], and postural sway [21].

Therefore, the purpose of this study was to use SampEn (i) to evaluate the effect of vestibular dysfunction on the complexity of CoP trajectories and (ii) to assess the time-course of this complexity (pre- and post-uVD). According to the theory of loss complexity, we assumed that SampEn values decrease with VS compared to controls; and we predict a decrease of complexity in VS patients early after uVD, which will be progressively restored over time.

2. Methods

2.1. Participants

Nineteen patients (Table 1) with unilateral VS who were scheduled for surgical ablation using translabyrinthine approach took part in the protocol. Patients were compared to a healthy control group ($n = 20$). The patients performed postural assessment three days before surgery (BS) and three times after surgery, at eight (AS_8), thirty (AS_{30}), and ninety days (AS_{90}). Participants enrolled in the control group underwent posturographic tests only once. Each participant provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee and complied with the Declaration of Helsinki.

Table 1
Participants' characteristics (Mean ± Standard Deviation).

Variables/groups	VS patients; $n = 19$	Healthy controls; $n = 20$	p
Age (yrs)	53.4 ± 11.5	50.9 ± 12.0	0.21
Height (cm)	169.3 ± 11.2	173.4 ± 8.8	0.78
Weight (kg)	74.6 ± 15.8	73.2 ± 13.5	0.51

The p value is based on Student's t-test for groups.

2.2. Sensory organization test (SOT)

The SOT was performed on a computerized dynamic balance platform (Equitest®, NeuroCom System®, Natus Medical Inc., Pleasanton, CA, USA). The testing consisted of three 20 s trials in six conditions that combined three visual conditions with two platform support conditions: (Condition 1–C1) patient's eyes were open, or (C2) closed with fixed surrounding and support; (C3) the support was fixed and patient's eyes were open within a sway-referenced surrounding (i.e. the visual surround follows the anteroposterior sways of the patient's center of gravity); for conditions 4–6, somatosensory information is disrupted by a sway-referenced support (i.e. the support surface follows the anteroposterior sways of the patient's center of gravity) while patient's eyes were open (C4), or closed (C5), or open within a sway-referenced surrounding (C6). Participants were instructed to maintain an upright stance, as stable as possible, and to keep their arms held alongside their body.

The CoP time series was extracted from the Equitest® software at a sampling rate of 100 Hz. The recording lasted 20 s so that the obtained time series had 2000 samples length. Data were low-passed filtered using a 4th-order Butterworth with a 20 Hz cutoff frequency. As previously suggested in the literature, we used the CoP velocity signals to explore the dynamical features of postural sway [9,21]. CoP velocity was calculated in the anteroposterior (AP) and mediolateral (ML) directions using the first difference of the original data (x_i): $v_i = x_{i+1} - x_i$. Differenced (v_i) time series allow reducing temporal correlations and non-stationarity that usually characterize COP time series and constitute obstacles for the application of nonlinear analysis [22,23].

2.3. Sample entropy (SampEn)

Formally, the calculation of *SampEn* was based on the following equation used by previous authors [24]:

$$SampEn(m, r, N) = -\log\left(\frac{A(r)}{B(r)}\right),$$

where each coarse-grained time series was calculated using the negative natural logarithm of the conditional probability that a time series of length N, having repeated itself for m samples within a tolerance r, will also repeat itself for $m + 1$ samples, excluding the selected on itself (i.e. self-matches). $A(r)$ and $B(r)$ were the total number of template matches of length $m + 1$ and m, respectively, within a tolerance r. Parameters for the analysis were set at $m = 3$ and $r = 0.30$ for both AP and ML directions [21,24]. The PhysioToolkit-PhysioNet SampEn software was used for the estimation of the SampEn values [25].

2.4. Statistical analysis

All trials were used for subsequent analysis. All data were examined for normality and homogeneity of variance using Skewness, Kurtosis and Brown-Forsythe tests. To determine the healthy profile of complexity of CoP trajectories, a one-way repeated measure ANOVA was used to test for any significant effect of conditions (C1, C2, C3, C4, C5, C6) on the changes in SampEn values in the control group. Two repeated measures ANOVA with