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RESEARCH ARTICLE

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Role of visual input in nonlinear postural control system

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Abstract. Stabilometry signals involve irregular and unpredictable components. The purpose of the present study was to investigate these signals with a nonlinear technique to examine how the complexity of the postural control system breaks down under altered visual conditions. We evaluated the dynamical similarities of the postural control system when the eyes were open or closed, or when there was optokinetic stimulation (OKS). A similarity index was calculated by the cross-correlation integral between the two dynamics: eyes open and eyes closed, or eyes open with OKS. Using this technique, dynamical changes were not observed between eyes-open and eyes-closed conditions. This result suggests that the nonvision condition does not produce any striking effect on the postural control system; instead, the eyes-open condition causes a decrease in the stochastic activity of the postural control system, which may originate mainly from the stiffness of the musculoskeletal systems. In contrast, the visual input of OKS affected the dynamics of the postural control system in nearly half of the subjects (group 2) despite showing no significant differences between the eyes-open condition and the other conditions for area as the conventional parameter. However, the other half of the subjects (group 1) did not experience any influence of OKS on their postural dynamics, despite showing significant differences between eyes-open and the other conditions for all traditional parameters. From the results for group 2, we hypothesize that OKS may induce the striking effect on dynamics properties of the multilink network system involving visual and vestibular cortex related to self-motion perception, which acts to decrease the stochastic activity in order to correct disturbed posture.

Keywords Chaos · Complexity · Balance · Optokinetic · Vection · Human

Introduction

The control of human balance during upright standing depends upon the integration of afferent information from the vestibular, somatosensory and visual systems. The importance of vision in the maintenance of postural control has been well documented, for example, in static conditions the visual afferences reduce the self-generated body sway by 50% (Edward 1946).

Traditionally, the postural control mechanism of orthostatic posture has been analyzed by measurement of the center of pressure (COP) with a stabilometer. Body stabilization has been estimated by measuring the magnitude of displacement, the area, and the power spectrum (Kapteyn et al. 1989). The most popular protocol for the visual system is the Romberg test, which makes the comparison of postural sway under eyes-open (EO) and -closed (EC) conditions by using the these parameters. However, the human postural control system is highly complex, consisting of multiple sensory systems, motor components, and central integration. These postural stabilization systems interact with each other through feedback loops, constituting a multilink network around the neck, hip, and ankle joints (Allum et al. 1992), so small changes in one input can have striking and unanticipated effects. Hence, the stabilometry signals can be assumed to arise from a nonlinear control system (Sasaki et al. 2001).

Given the complexity of the postural control system, it is conceivable that the changes of the visual information

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involve a transition of postural control dynamics through requiring adjustments to the weights given to each sensory system. From the viewpoint of the control system, the physiological insights obtained from the conventional measurements in stabilometry, including displacement, area, or power spectrum, are limited in providing meaningful findings of how the complex integration changes. Nonlinear analysis offers an alternative way to characterize qualitative changes in the dynamics of the complex system and promises to be important in clinical practice. A promising field for the application of nonlinear analyses is electroencephalography. In particular, the application of this analysis to epileptic seizure makes it possible to detect dynamical changes of brain activity several minutes prior to seizure, which cannot be detected by linear methods (Martinerie et al. 1998; Le Van Quyen et al. 1999). Furthermore, a similar approach has led to promising results in the analysis of heart rate variability, i.e., nonlinear analysis can be used to predict the risk of sudden death in cardiac patients, contrary to time domain analysis (Woo et al. 1992). On the other hand, the first application of nonlinear analysis to posturolography by Collins and De Luca (1994) suggested that the postural control system should not be modeled as a chaotic process and is better represented as a stochastic one. These findings thus offer significant advantages over more traditional linear procedure. The fundamental idea in nonlinear analysis is that the dynamics of a system are studied in a phase space, and a point in this space characterizes the state of the system at any moment in time. In order to reconstruct the trajectory from a single time series, the time-delayed method is usually employed (Takens 1981).

In our earlier study using the nonlinear technique for stabilometry signals, we examined whether the visual input and the vestibular lesion cause the qualitative changes in the dynamics of the control network (Sasaki et al. 2001). These analyses revealed the significant reduction of a similarity index (Sim), which reflects the dynamical closeness between two states, quantifying the extent to which the dynamics differed between the EO and EC conditions in the patients with vestibular lesions. Moreover, nonlinear measurement can detect finer vestibular compensation processes than conventional measurements. The purpose of the present study was to further investigate the stabilometry signals with nonlinear techniques in order to examine how the complexity of the postural control system breaks down under altered visual conditions.

Furthermore, it is well known that optokinetic stimulation (OKS) induces an increase in postural sway (Lee and Lishman 1975; Dichgans et al. 1976; Lestienne et al. 1977) and an illusion of self-motion, called "circular vection" (CV). These visual stimuli create a sensory conflict, requiring the postural control system to increase dependence on proprioceptive and vestibular cues. Although it is not clear which cortical areas are involved in the visual perception of self-motion, a recent PET activation study (Brandt et al. 1998) has pioneered new functional interpretations of CV. However, it is not known how the neural network of postural control changes during OKS in order to maintain balance. Therefore, the second aim of this investigation was to obtain quantitative data regarding the change of postural control dynamics during OKS.

Materials and methods

Experimental methods

Twenty-three healthy subjects (3 women and 20 men, aged 24–45 years), who had no history of dysequilibrium, participated in this study. All subjects were volunteers who gave their informed consent prior to participation.

Stabilometry was performed by means of a force platform (AFP40/16; Midi Capteurs, France) with a construction based on the strain gauge principle. This platform can measure a difference in force of ±0.2 N, which corresponds to a movement of the COP of ±0.1 mm. The COP signals were sampled for 51.2 s at a frequency of 40 Hz by a microcomputer.

The subjects stood barefoot with their arms relaxed comfortably at their sides under standardized conditions determined by the Association Française de Posturologie (Gagey et al. 1988). The visual target was placed 90 cm away, illuminated with 2,000 lux.

Horizontal OKS consisted of random dots projected on a screen (Jung type) which rotated at a constant speed of 60°/s to the right for 60 s. The subjects were instructed to stare straight ahead at the stimuli without attempting to follow their course. All subjects experienced the illusion of self-motion in this condition.

In order to examine the contribution of visual input to the postural stabilization system, the subjects performed 3 sets of two 51.2-s, consecutive balance tasks: (a) with the eyes open in both tasks, (b) with the eyes open and closed, and (c) with the eyes open and with OKS. The first EO task constructed a reference dynamic, which was compared with the reconstructed dynamics in the successive task. The order of the 3 sets of trials was randomized and a 10-min rest was given after each set trial. To maintain their alertness, subjects were required to do mental arithmetic during the tests.

Conventional measure

The conventional measure was performed in terms of the total length, the total distance of the lateral component (X length), the total distance of the anteroposterior component (Y length), and the area of the 90% confidence ellipse (surface; Takagi et al. 1985), which contains 90% of the COP positions sampled.

Nonlinear measure

We employed a new nonlinear analysis method, which was applied to the anticipation of epileptic seizures by Le Van Quyen et al. (1999). A measure of similarity was here used to quantify the extent to which the dynamics differ between distant pairs of time windows. The utility of relative measures between different parts of long, nonstationary signals has been discussed in a number of recent theoretical works (Manuca and Savit 1996; Schreiber and Schmitz 1997). Relative measures show a greater discriminatory power than other current nonlinear techniques and a validity that is not dependent on the dynamical nature of the system. The algorithm for quantifying the extent to which the underlying dynamics differ between pairs of segments follows.

We define here a time series during 51.2 s of stabilometry signals, with the reference segment of the EO task and the successive task given as S_{op} and S_{ss}, respectively. The standard way

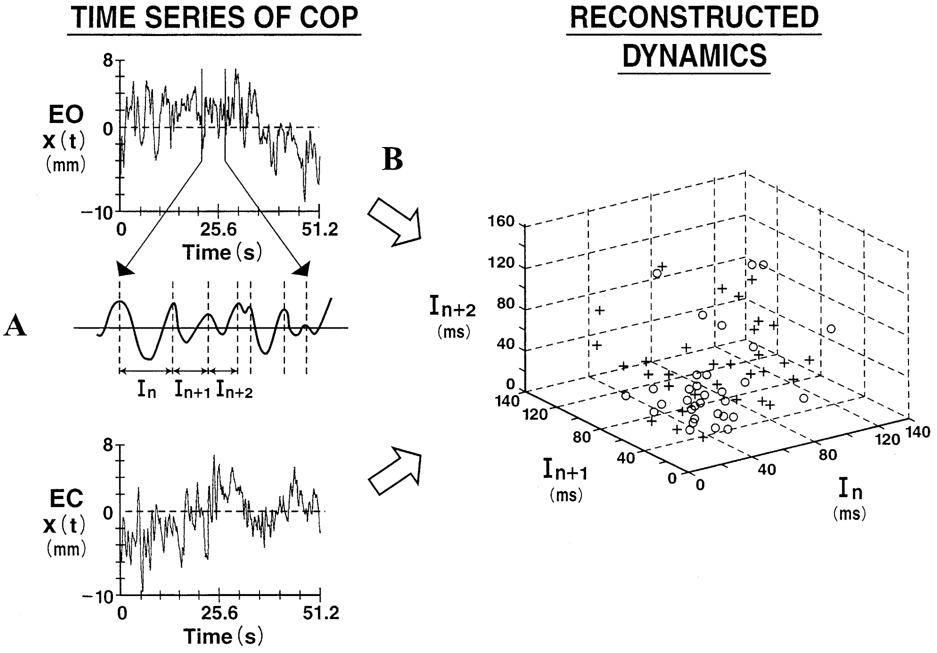

Fig. 1a, b An example of the quantification of the dynamic similarity between eyes open (EO) and closed (EC) in *x*-axis ($x(t)$) recording. **A** is the sequences of time intervals, which are derived from successive maximums of signal. From the each time interval between two successive maximums, the delayed vectors are formed. **B** defines a multidimensional reconstruction of the dynamics by a time-delay embedding of the intervals (I_n, I_{n+1}, I_{n+2},...I_{n+m-1}), where m=8 in our study, but here m=3 for a schematic representation. Here, the *open circles* and the *crosses* show the dynamic clouds with eyes open and closed, respectively. Next, the comparison of the dynamics between eyes open and closed in phase space is made by calculation of the similarity index (*COP* center of pressure)

of reconstructing the underlying dynamics is given by a time-delay embedding of the amplitudes. However, this reconstruction is computationally troublesome for practical applications and requires a large data set. Hence, we adapted another way to reconstruct the qualitative dynamics. The time series was prefiltered between 0.02 and 2.5 Hz then reduced to pure phase information by generating the sequence of time intervals between successive maximums of the signal (Fig. 1A). From a theoretical standpoint, the reason for this is that time intervals can be interpreted as the phase of the system's flow in a Poincaré section (Pikovski et al. 1997). This method makes it possible to obtain a pure dynamical component while avoiding loss of important dynamical information as a result of the reduction of noise components induced by variations in signal amplitudes such as spiking activity. If T_n shows the times of maximums, then $I_n=T_{n+1}-T_n$ is the time interval between two successive maximums. First, we constructed the delay vectors forming $A_n=(I_n, I_{n+1},..., I_{n+m-1})$, which is defined as an m-dimensional embedding space. We chose m=8 because, at more than 8, the calculated Sim showed the same value as m=8 and, at below eight, it showed decrease. Hence, the optimal value of the embedding dimension in this study could be taken to be m=8.

Next, in order to further reduce the noise, a single value decomposition (SVD; Albano et al. 1988) of this 8-dimensional embedding space was employed. Let $A(S_{op})$ be the trajectory matrix of a reference time series with eyes open S_{op} (i.e., the matrix whose rows are the embedding vectors S_n), then a SVD can be calculated with conventional algorithms by the transformation $A(S_{op})\rightarrow X(S_{op})=A(S_{op})V$, where $X(S_{op})$ is the trajectory matrix projected onto the basis V defined by the eigenvectors of the covariance matrix $A(S_{op})^T \cdot A(S_{op})$. The dynamics in the space defined by the largest singular values are identical to those in the original embedding space.

In order to allow comparisons between two dynamics, a basic skeleton of a dynamics built by a random selection of a sub-set of points is considered. This produces an adapted picture $Y(S_{op})$ of the reconstruction, which extracts the most frequent occupations of the phase-space flow. The dynamic similarities are estimated between the dynamics with eyes open $Y(S_{op})$ and the projection $X(S_{ss})$ of an 8-dimensional reconstruction of S_{ss} on the principal axes of the dynamics, with eyes open as the reference dynamics (i.e., $X(S_{ss})=A(S_{ss})\cdot V$, where V is the eigenvector matrix of the reference window; Fig. 1B). Thereby, the statistical measurement of the similarity based on the cross-correlation integral is calculated as follows:

$$C(S_{op}, S_{ss}) = \frac{1}{N_{op}N_{ss}} \sum_{i=1,Nop} \sum_{j=1,Nss} T(||Y_i(S_{op}) - X_j(S_{ss})|| - r)$$

where Θ is the Heaviside step function, || || represents the euclidian norm, and N_{op} (and N_{ss}) means the number of elements in each set. This equation yields the probability of finding points within a neighborhood "r" in the reconstruction of S_{op} close to points in that of S_{ss}, where r is the distance at 30% of cumulative neighborhood distribution of the S_{op} set. In order to further improve the discriminatory power between two dynamics, we modified this measure with the cross-correlation ratio Sim:

$$Sim(S_{op.}S_{ss}) = C(S_{op,}S_{ss}) / \sqrt{C(S_{op.}S_{op})\ C(S_{ss,}S_{ss})}$$

The Sim value ranges from 0 to 1 and yields the degree of similarity between two dynamics. When the similarity of the two dynamics becomes close, the value is approximately 1. Inversely, changes of dynamical state produce a reduction in the value to less than 1.

By means of this procedure, we compared the dynamical similarity between the stabilometry signals with two successive tasks of each set trial: (a) EO-EO, (b) EO-EC, and (c) EO-OKS, in the lateral direction (*x-axis*), called similarity *X*, and in the anteroposterior direction (*y-axis*), called similarity *Y*. This computation can be performed with the aid of MATLAB (Math Works) on a PC.

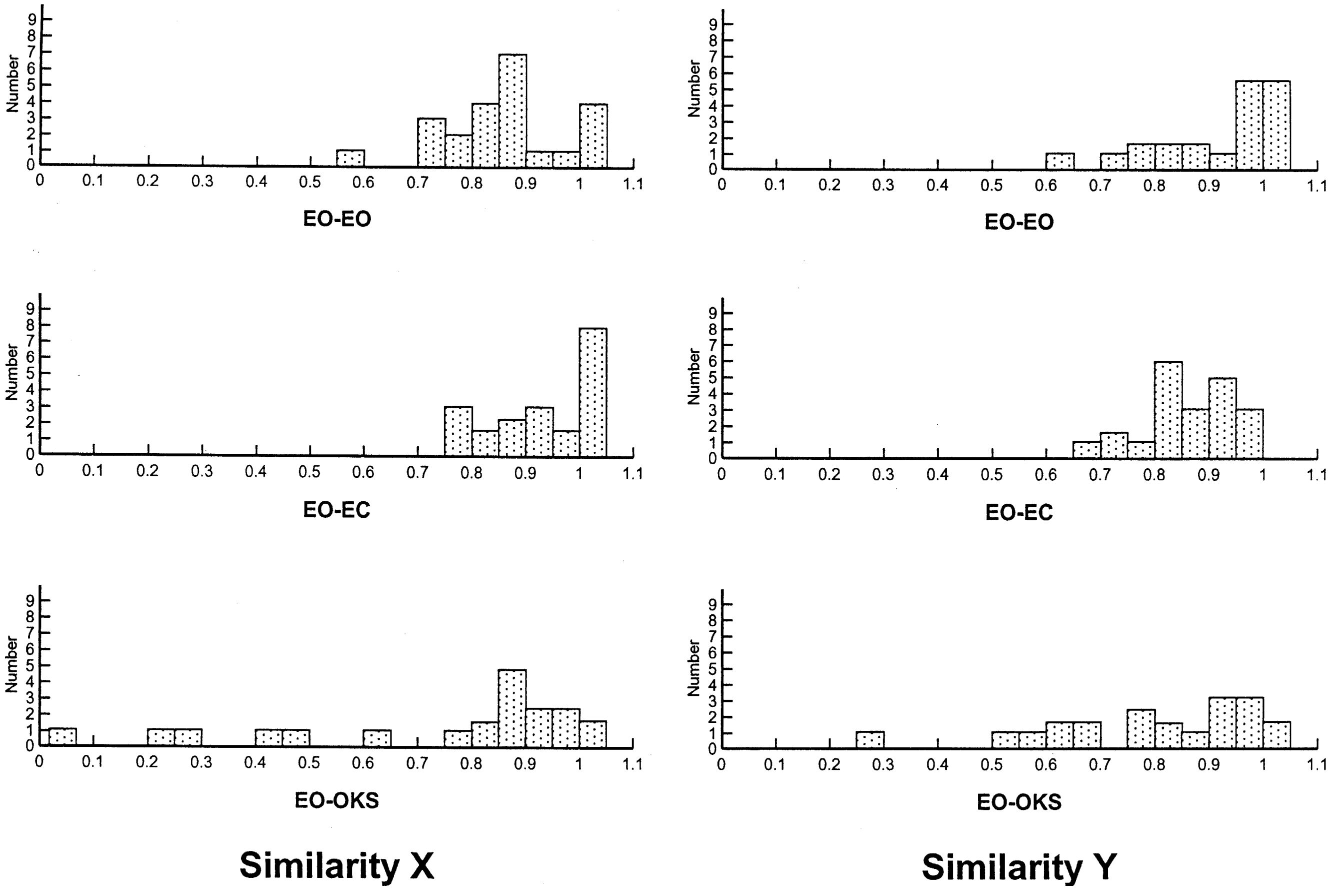

Fig. 2 The distribution of the similarity indexes for all subjects (*N*=23) under each compared set trial

Statistical analyses

Comparisons of the similarity indexes among the three visual conditions were made using a repeated-measures one-way ANOVA, and a post-hoc test (Steel-Dwass's test) was used to determine the source of the significant effect. For the statistical analyses of the two classified groups by the results of the similarity index, Wilcoxon signed-ranks test was used to make comparisons with the traditional parameters.

Table 1 Similarity index (EO eyes open, *EC* eyes closed, *OKS* optokinetic stimulation)

	Similarity *X*	Similarity *Y*
EO-EO	0.859±0.121	0.926±0.123
EO-EC	0.929±0.100	0.892±0.101
EO-OKS	0.755±0.272	0.804±0.197*

*Significant difference between EO-EO and EO-OKS: P<0.05

Results

The means and standard deviations of the calculated similarity index, which imply the dynamical closeness between EO and each successive task, are given in Table 1. There was a significant difference between EO-EO which is the reference trial for this study, and EO-OKS in similarity *Y* (ANOVA; F=5.99, P<0.05). Since this result reflects that the dynamical closeness between the EO condition and the successive EO trial is statistically different from that between EO and the successive OKS condition, OKS could induce the striking effect on dynamical properties of the postural control system in the anteroposterior direction. However, in the lateral direction, the statistical difference between the aforementioned comparison caused by a large standerd deviation cannot be seen. Regarding the influence of the nonvision condition on dynamical properties, it should be noted that there were no significant differences between EO-EO and EO-EC. This result reflects that the removal of visual information does not provide any changes of the postural control dynamics.

Since there were large variances of similarity index in EO-OKS, a histogram of similarity index in each set trial is given in Fig. 2. The distribution of these data showed that the variances of similarity index in EO-OKS trials increase compared with that of either EO-EO or EO-EC. On the basis of this result, we divided the subjects into two subpopulations, compared by the results of the standard trial of EO-EO: group 1, where the values of similarity index in both *X* and *Y* are within the mean of the value in EO-EO −2 SD, i.e., similarity X>0.617 and

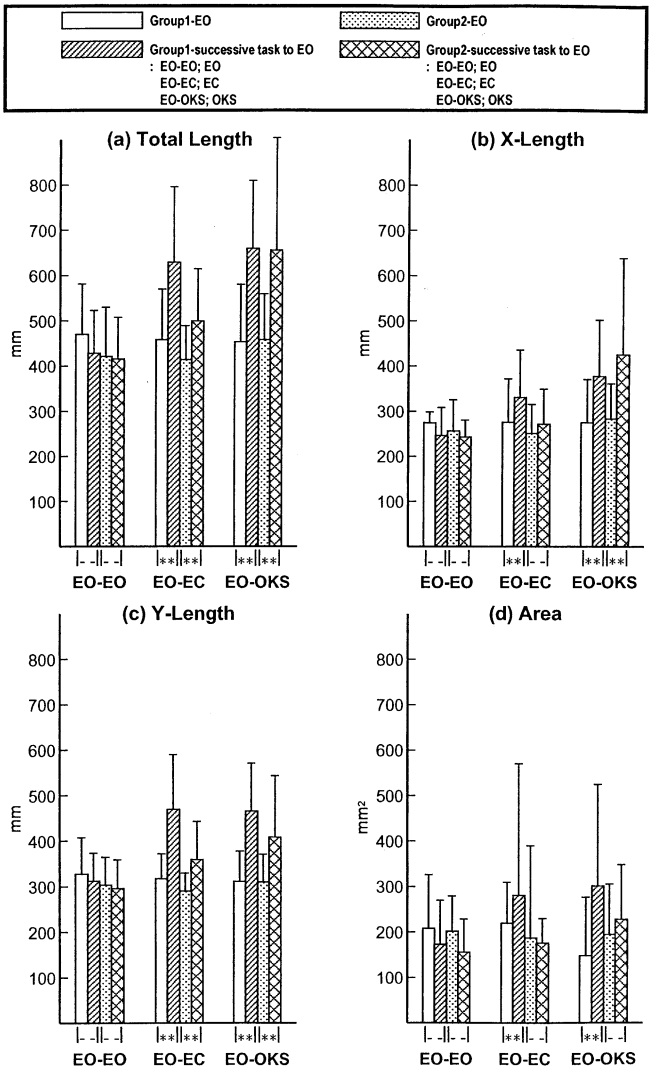

Fig. 3a–d Group means and standard deviations for conventional parameters: **a** total length; **b** *X* length; **c** *Y* length; and **d** the area of the 90% confidence ellipse. **Statistically significant differences at *P*<0.05; *minus sign* statistical comparisons were not significant

similarity *Y*>0.680, respectively; and group 2, where the values in either *X* or *Y* are below the abovementioned limits. According to this division, group 1 consisted of 12 subjects (3 women and 9 men, aged 24–45 years, mean 31.5 years) and group 2 consisted of 11 men (aged 24–40 years, mean 31.5 years).

To examine the characteristic differences between the two groups, comparisons were made of traditional parameters. The group means and standard deviations of traditional parameters for the two groups are presented in Fig. 3. For group 1, all of the EO parameters were significantly smaller than those of the other trials (*P*<0.05). On the other hand, for group 2, there were significant differences between the EO and the OKS condition trials for all parameters except for area. Moreover, in regard to the comparison with EO and EC trials, although significant differences were shown for total length and *Y* length, none were found for either *X* length or area.

Discussion

Our first observation was that the nonlinear analysis of orthostatic posture provided a hidden postural control mechanism, i.e., the similarity index reflected the clinical course of the vestibular compensation process in patients with vestibular neuronitis; also various pathological changes were included in benign paroxysmal positional vertigo which could not be detected by conventional analysis (Sasaki et al. 2001). In the present study we found that visual input affects the postural control system by means of two different patterns. The visual input of OKS affects the dynamics of the postural control system in nearly half of the subjects (group 2) despite showing no significant differences between EO and the other conditions for area as the conventional COP parameter. In contrast, the other subjects (group 1) did not experience any influence on their postural dynamics from lack of vision or OKS; however, they did show significant differences between EO and the other conditions for the all traditional parameters.

The first important finding of our analysis reveals that no postural dynamical changes were observed between EO and EC conditions. As is well known, vision significantly affects postural balance; for example, when in the static condition for EC the body sway is always larger than in EO (Paulus et al. 1984; Gagey et al. 1988). In the field of posturography, which deals with nonstationary signals, a number of statistical tests have been proposed in the literature. Most of these tests are applications of linear time-series analysis, implying that the stationarity is defined on the basis of the second moments such as the mean, variance, or power spectrum. Indeed, it is a general test in clinical practice to evaluate the vestibular-spinal reflex with the patient's eyes closed, in order to eliminate the role of vision (Romberg's test). However, our findings showed that the complexity of the postural control system did not change, suggesting that the nonvision condition did not produce any striking effect on the postural control system. Instead, the EO condition caused a decrease in the stochastic activity of the postural control system, which may have originated mainly from stiffness in the musculoskeletal system. This observation is strengthened by previous works; e.g., De Luca et al. (1982) have demonstrated that fluctuations are always present in mechanical output of skeletal muscles, and Collins and De Luca (1995) have reported that visual input principally causes a decrease in the level of muscle activity across the joints of the lower limbs, which produces a decrease in the effective stochastic activity of the open-loop control mechanism.

A second novel finding of our analysis was that, contrary to group 1, in group 2 not only were there no changes of dynamics in the EC condition, but also no differences between EO and EC with area as a conventional parameter, indicating postural blindness, implying that visual information was not used to maintain balance. Under certain conditions (Bizzo 1993), the area measures the precision of the control of orthostatic posture; however, the other parameters, i.e., total length, *X* length, and *Y* length, actually reflect a summation of the body's segmental actions, including stochastic and noise-like fluctuations. The previous report suggests that postural blindness indicates that standardizing visual information is being abnormally integrated into the multimodal system that controls orthostatic posture (Gagey and Toupet 1991). Collins and De Luca (1995), on the other hand, hypothesize that postural blindness causes the visual system to affect the output of the proprioceptive and vestibular system, via gain modulation. We infer that in group 2 the noise-like fluctuations were suppressed by using the gain modulation of the other sensory system, which is not sufficient for the alteration of dynamics.

Furthermore, in group 2, apparent changes of dynamics caused by OKS were exhibited, despite no significant differences in area. Conversely, the subjects in group 1 did not show any dynamical changes during OKS conditions, whereas they did show significant increase in postural sway compared with the EO condition for all conventional parameters. Previous studies (Dichgans et al. 1972; Kapteyn and Bles 1977; van Asten et al. 1988; Previc 1992) have reported that human upright standing perceives a shift of the gravitational vertical and postural change when exposed to roll motion of the visual surroundings. When subjects observe the world to be moving, they perceive themselves to be moving in the opposite direction. The sensation of self-motion during large-field visual motion stimulation, namely CV, is a common visual perception, from which visual-vestibular interaction can be produced.

To further understand CV, a study using new techniques to examine PET activation on visual self-motion perception demonstrated a reciprocal activation-deactivation of visual and vestibular cortical areas during CV, i.e., OKS during CV induces not only activation of bilateral medial parieto-occpital visual areas but also deactivation simultaneously of the parietoinsular vestibular cortex (Brandt et al. 1998). Such a mechanism may protect visual perception of self-motion from potential vestibular mismatches caused by involuntary head accelerations during locomotion (Brandt et al. 1998). Furthermore, since the parietoinsular vestibular cortex not only receives bilateral vestibular input from the vestibular nuclei, but also, in turn, projects it directly down to the vestibular nuclei, corticofugal feedback during OKS must modulate the vestibular brainstem network (Brandt and Dieterich 1999).

Concerning the postural changes induced by a moving visual surround, traditional measurement of postural sway during moving surround in the roll plane recorded a strong deviation in the direction of stimulus motion (Kapteyn and Bles 1977; Lestienne et al. 1977; Previc 1992). But COP measures actually reflect a summation of the body's segmental action. The postural control systems that include multireflex feedback loops constitute the multilink network. Keshner and Kenyon (2000), when examining the body segmental stabilization using a virtual environment, report that large magnitudes of motion in head and trunk, despite small amplitudes and frequent phase reversals in the ankles, are caused by segmental proprioceptive inputs and ground reaction forces rather than by the visual-vestibular signals. Asten et al. (1988) have stated that the texture in the stimulus pattern has a marked effect on the control of postural balance and that the postural responses to a moving surround can be considered as being a linear, 2nd-order low-pass system with a cutoff frequency at approximately 0.5 Hz. Conversely, Dijkstra et al. (1994) have described that postural responses cannot be understood simply in terms of minimization of retinal slip. The recognition of visual stimulation in visual cortex areas is so important for postural changes that the central nervous system generates movement. These movements correspond to nonlinear dynamics that possess limit cycle attractors, which match the visual motion in amplitude and frequency.

We interpret the results of group 1 as suggesting that their increase in postural sway may be due only to increase in the noise-like stochastic activity of the postural control system originating from the network system. In contrast, we hypothesize from the results for group 2 that OKS may induce the striking effect on dynamics properties of the multilink network system involving visual and vestibular cortex related to self-motion perception, which acts to decrease the stochastic activity in order to correct disturbed posture. We also found that the other conventional parameters for group 2, i.e., total length, *X* length, and *Y* length, showed significant differences between EO and the other conditions despite showing no significant increase in area, suggesting that the increase in the other parameters may reflect the increase in stochastic activity of the postural control system.

In future investigations, surrogate data techniques (Theiler et al. 1992) will be needed to confirm the significance of visual effect on the postural control system. Surrogate data sets are obtained by phase randomization of the Fourier transform of the data, then an inverse transform is performed to regenerate a time series. Furthermore, we will concentrate on elucidating the effects of vestibular and proprioceptive input on the nonlinear postural control system. Such studies will be helpful in clarifying the classic basic mechanism of human orthostatic posture.

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