POSTURE AS A DYNAMIC STABLE STATE OF A BODY

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Abstract

An upright posture is a coordinated stable phenomenon of the whole body relative to its external environment and the task of maintaining posture involves a complex sensorimotor control system. Such a global and complex phenomenon needs to be explained from both macroscopic and microscopic points of view. In an upright posture the body sways. Time variation of the center of pressure (COP) under the feet was used as an index of the macroscopic phenomenon of a swaying body in the upright posture and its dynamic properties were analyzed using dynamical systems theory.

Chaotic swaying was found in the movement of the COP under a subject's feet when standing still and when standing while swinging the upper limbs. Proof of this chaotic swaying was shown by reconstruction of the dynamics in phase space and calculation of the largest Lyapunov exponent. The properties (geometry and dimension) of the chaotic attractor observed when the upper limbs were swinging were similar to that of observed when the subject was standing still. This, result suggests that posture and movement are adaptively and flexibly integrated.

Mathematical techniques from information theory were applied to the analysis of the ability of information processing of the COP chaos. This novel approach led to extracion of the ability of the COP chaos to receive information fed from the outside. As the ability of receiving information of the COP chaos was superior, chaotic swaying was rational from the viewpoint of information processing. Therefore, it was thought that chaotic swaying of the body is a dynamic stable state of the body while receiving information from many segments within the body and its external environment.

keywords: posture, chaos, dynamical systems theory

Introduction

Because posture has been treated as a static stable state of a body, most of the past studies in postural control (Moore et al. 1988; Woolacott et al. 1988; Diener et al. 1988; Horak et al. 1990; Diets et al. 1991) have focused on analyzing the response of the body to various external perturbations. In these past studies, a dynamic characteristic of the center of pressure (COP) under the feet that is known as a stabilogram, (Figure 1b) was ignored and static characteristics of COP, i. e. calculation of the length of the sway path, and the average radial area were studied.

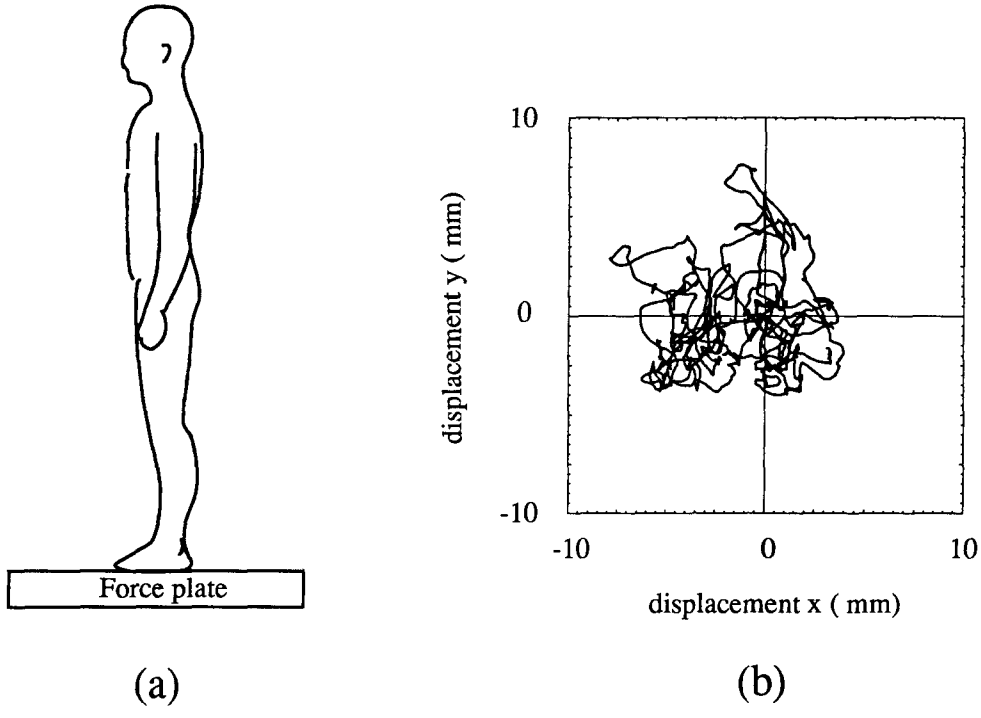

FIGURE 1 (a)Upright posture, (b) Typical 50− s stabilogram for a healthy subject during quiet standing. The COP under the subject' s feet moves relative to a global coordinate system.

On the other hand, Collins and Luca (1993) analyzed the dynamic properties of the COP trajectories using random walk analysis when the subject was standing still. They reported that COP trajectories could be modelled as fractional Brownian motion and that at least two control systems: - a short-term mechanism (open loop control mechanism) and a long-term mechanism (closed-loop control mechanism) - were operating during an undisturbed stance. These results suggest that posture control needs to be analyzed the same way as voluntary movement control and should not only be based upon the input/output characteristics of the simple postural system.

Some doctors and researchers have reported that movement and posture are not separately controlled but tightly integrated. Thelen and Fisher (1982) showed that when 1-month-old and slightly older infants were submerged up to their chests in warm water, stepping patterns were seen which would not normally be seen due to the weight of the limbs. Reed (1989) pointed out that if postural support can yield such a dramatic change in behavior, it would seem unreasonable to limit the effect of posture to that of simply a stabilizing mechanism response to perturbation.

In this study, posture was considered to be a dynamic stability of a continuously moving body. In the hypothesis, we did not divide human movement into a static state (commonly called posture) and a dynamic state (commonly called movement). We considered posture and movement to be adaptively and flexibly integrated. To test this hypothesis dynamical systems theory was applied to analysis of dynamic behavior of

the stabilogram. The theory has provided many new tools with which to analyze non-linear phenomena in physical systems.

Methods

Experimental methods

Five healthy subjects, aged 21-34 years, were used in this study. The subjects had no evidence or known history of a gait, postural or skeletal disorder. Postural stability was evaluated by using a force platform (AMTI model OR6-5) to measure the time-varying displacements of the COP under a subject's feet. Each subject was instructed to stand in an upright posture in a standardized stance on the platform for two different experimental conditions. The experimental system is depicted schematically in Figure 2. In the first experiment, the subjects stood barefoot with their arms comfortably at their sides and their eyes open and fixed on a point in front of them. In the second experiment, the subjects stood barefoot while swinging their upper limbs like they were walking in time to a periodical sound from an oscillator, and with their eyes open and fixed on a point in front of them. The frequency of the oscillator was 1.5 Hz, then 1 period, during which they swung their arms, was 0.75 Hz. Each experiment lasted for a period of 200 seconds and the force platform data were digitized to a resolution of 12 bits, sampling at 100Hz.

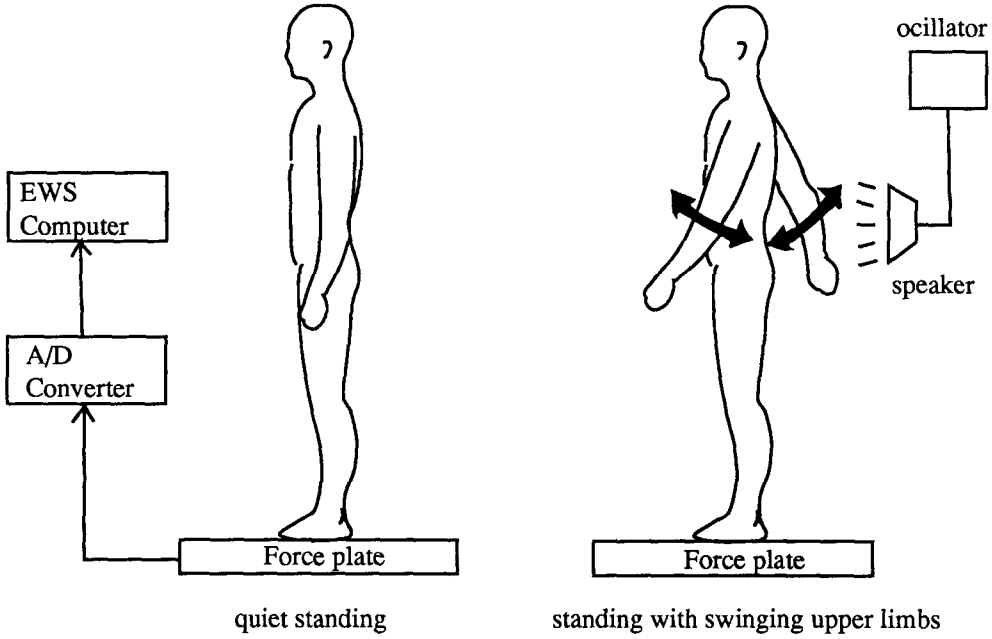

FIGURE 2 Schematic diagram of the experimental system. Five healthy subjects stood barefoot on a force platform with their arms comfortably at their sides and the subject's eyes were open and fixed on a point in front of them (experiment 1). In the second experiment, the subjects stood barefoot while swinging their upper limbs as if walking in time to a periodical sound from an oscillator. The time-varying displacememts of the COP over the plane of support were measured using the force platform.

Data analysis

COP time series

The COP trajectories were studied as a distance from the initial position. The COP data were filtered with a low-pass filter (cut-off 5 Hz). The COP data can be treated as one index for a swaying body.

Embedding and correlation dimension

The time evolution of a single degree of freedom, the COP time series, was used to reconstruct the attractor utilizing an embedding by time-delayed coordinates (Takens; 1981). A dimension of the attractor was calculated as a correlation dimension using an algorithm similar to that of Grassberger and Procaccia (1983). (Chaos Attracting System developed by Tsuda, Tahara, and Iwanaga (1992) was used. This software was also used to compute the largest Lyapunov exponent and mutual information.)

Lyapunov exponents

The exponential divergence of nearby trajectories underlies the sensitivity to initial conditions in the chaotic system. The Lyapunov exponents can be defined by studying the development of the initial conditions on an infinitesimal n-dimensional hypers-

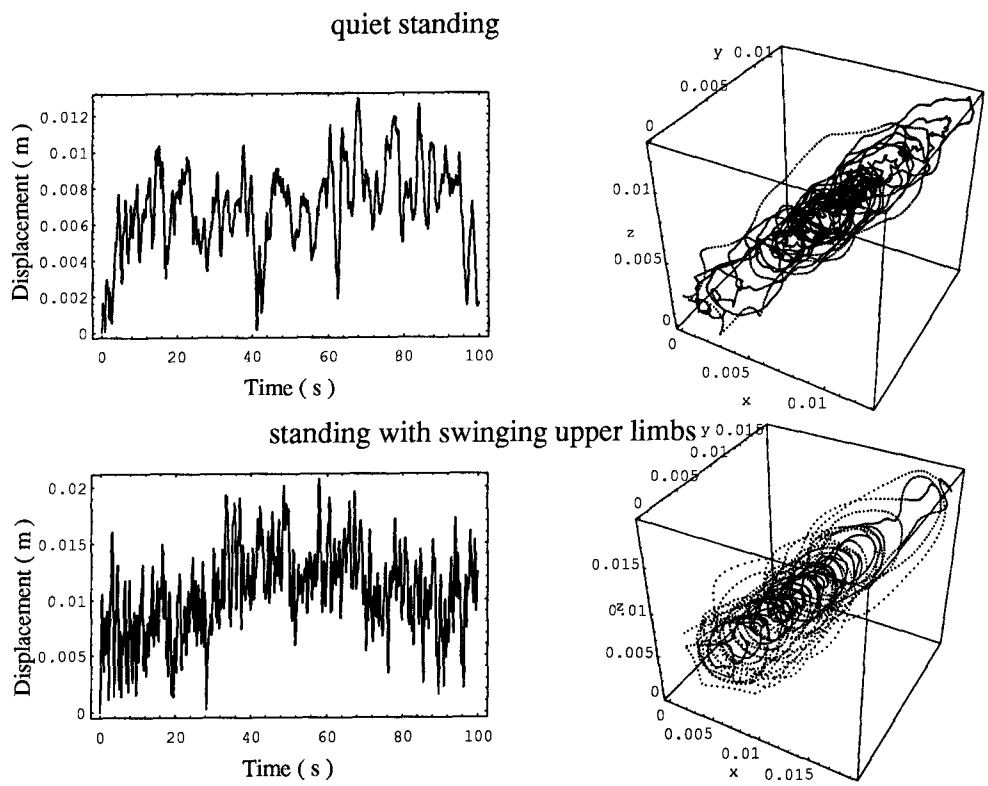

FIGURE 3 Typical time series of the COP data (left) in the case of standing still and when standing while swinging the arms, and the phase portraits (right) in the case of embedding into three—dimensions of the data.

phere. A system is chaotic if at least one of its Lyapunov exponents is positive. To determine whether the dynamics on the attractor of the COP data are chaotic or not, the largest Lyapunov exponent was calculated. To compute the exponent, an algorithm similar to that of Wolf (1985) was used.

Spectrum analysis

Spectrum analysis was often used for analyzing the chaotic system. Because a chaotic state is non-periodic, it contains a broadband spectrum. The Cooley-Tukey fast Fourier transform algorithm was used to calculate the power spectral density for the time series of the COP data.

Results

Figure 3 shows the typical time series of the COP data (left) when the subject is standing still and when standing while swinging the arms, and the phase portraits (right) in the case of embedding into three-dimensions of the data. As seen in Figure. 3, the geometries of the attractors for the two experimental conditions were similar. The first Lyapunov exponents and the correlation dimensions for the COP data from two experiments are summarized in Table 1. Correlation dimensions of the attractors for both experiments of all subjects were between 2.1 and 2.5. The first Lyapunov exponents for both experiments of all subjects were positive, and the exponent for the experiment of swinging the arms was 0.5-1.5 larger than the exponent for the experiment when the subject was standing still.

Figure 4 shows the typical power spectra of the COP data when the subject was standing still (left) and when standing with swinging the arms (right). The spectra of the COP data when the subject was standing still contained a broadband spectrum. The spectral profile was almost flat over the frequency range of 0.01-0.3 Hz. However, the power spectrum over this range showed a curve approximately inversely proportional to the frequency (1/f spectrum). The spectrum of the COP data in the swinging

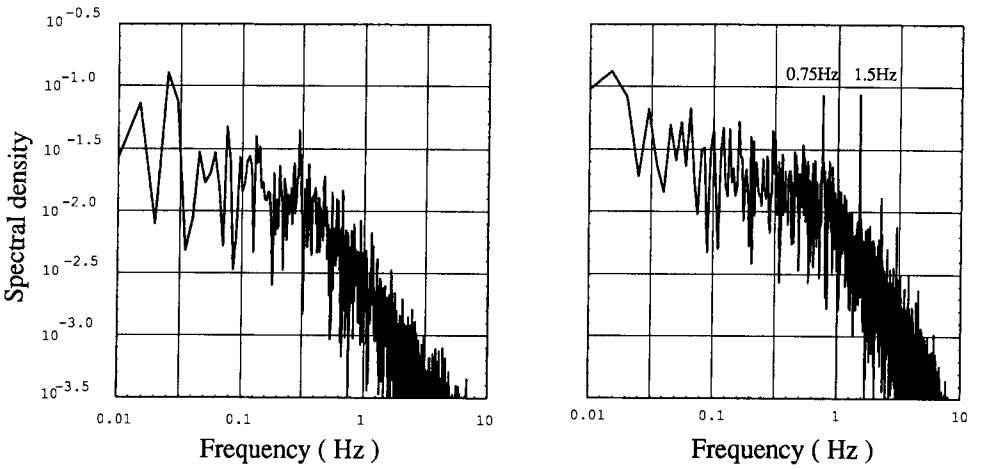

FIGURE 4 Typical power spectra of the COP data in the case of standing still (left) and when standing while swinging the arms (right).

arms experiment was characterized as follows:
1) The spectrum consists of two fundamental frequencies, 0.75Hz and 1.5 Hz, 0.75 Hz was the frequency of the swinging arms, and they were an integer combination.
2) The spectrum contains broadband frequencies that were observed when the subject was standing still besides the sharp components of 0.75Hz and 1.5Hz.

Discussion

Posture as a component of voluntary movements

As can be seen in Figure. 1, we could obtain attractors from the COP time series of two experimental conditions using the embedding tachnique and the geometries of the attractors were similar. This qualitative similarity of the attractors was confirmed by calculating the dimensions of the attractors, which is one of the most widely used methods to characterize attractors. As seen in Table 1, the dimensions of the two attractors from the two different experimental conditions were similar too. An attractor shows an order or a constancy over the time of the phenomena that means a dynamic structure of the observing system. In this case, the attractor we obtained shows the structure of the dynamic system of the body swaying. The similarity of this structure implies that properties of the dynamic systems for the two experimental conditions were also similar. In the experimental condition of swinging the upper limbs, the body is obviously moving. In such a situation, the properties (geometry and dimension) of the attractor of the COP were almost the same as those of attractor for the case when the subject was standing still. Therefore, it is thought that there is a role for stabilizing the body dynamically in a voluntary movement. This hypothesis was also confirmed by spectrum analysis. The spectrum of the COP in the case of swinging the arms contains broadband frequencies that were observed in the case where the subject was standing still, besides the sharp components 0.75Hz and 1.5Hz that originated from the arms movements. By this stabilizing work in a voluntary movement when

TABLE 1 The first Lyapunov exponents and the correlation dimensions for the COP chaos from both experimental conditions.

Sub. /Condition	First Lyapunov exponent	Correlation dimention
A/quiet standing	0.91	2.3
standing with swinging upper limbs	1.70	2.2
B/quiet standing	0.98	2.5
standing with swinging upper limbs	2.07	2.4
C/quiet standing	0.57	2.3
standing with swinging upper limbs	1.70	2.2
D/quiet standing	0.60	2.2
standing with swinging upper limbs	1.92	2.4
E/quiet standing	0.51	2.1
standing with swinging upper limbs	2.06	2.5

there is a functional task beyond that of quiet standing, the postural patterns undergo task-specific reorganizations of an intricate nature. For this reorganization, it is thought that the chaotic swaying of the body is useful. We analyze this chaotic swaying of the COP further in the next section.

Why swaying of COP is chaotic ?

Comparing the two results from different experimental conditions, it is thought that the chaotic swaying of the COP, obserbed when the subject was standing still, plays an important role for the adjustment of posture. In this section, we analyze the role of chaotic swaying using mathematical techniques.

Sensory signals from muscles which are produced by each movement of the body, (hand, head, and so on) in turn produce specific spatio-temporal patterning of neural activities throughout the central nervous system. Therefore, it is worth studying the information capacity of the observed COP chaos, especially its ability for the transmission of information fed from the outside. In order to study this from experimental data, we used a new algorithm proposed by Matsumoto and Tsuda (1989). They considered a dynamical system as an information channel. The amount of information transmitted from initial condition i to the next condition at time j through the dynamical system can be computed using the mutual information:

$$I(i;j) = -\sum_{i} P(i)\log P(i) + \sum_{i,j} P(i)P(j/i)\log P(j/i)$$

where p(j/i) is the conditional probability.

The amount of transmitted information is assumend to be the source information mimus the missing information during transmission. The mehod was expanded by Tsuda et al. (1992) to a calculation of amount and direction of the transmitted informa-

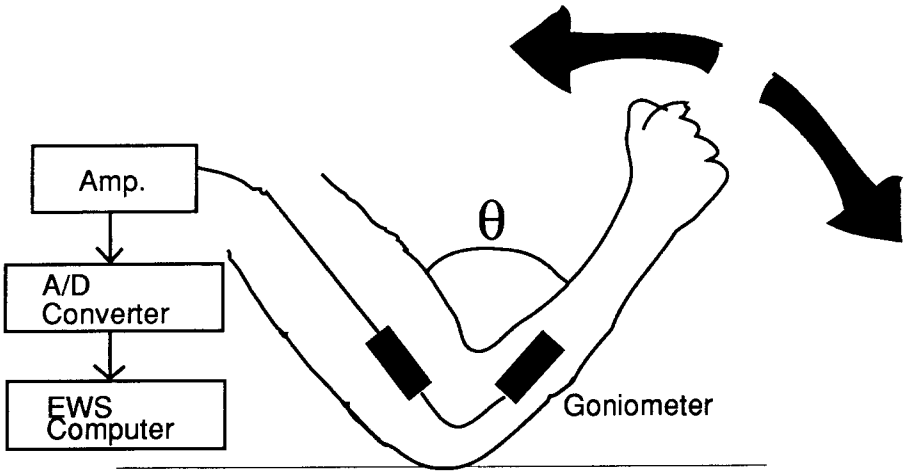

FIGURE 5 Schematic diagram of the experimental system for rhythmic and unrhythmic movements in the elbow joint. The subjects sat on a chair comfortably with their right arm on a desk. A goniometer was attached to the subject's elbow joint to measure the fime vaiation of the elbow angle. During testing, the subjects extended and flexed their elbow joint with a constant rhythm (exp. 3). In experiment 4, the subjects extended and flexed their elbow joint irregularly.

tion relatively between two dynamical systems. They calculated the information ability of a capillary chaos found by them through the use of this method. Two time series were prepared to evaluate the information capacity of the observed COP chaos. Figure 5 shows the new experimental systems (Exp. 3 and Exp. 4) schematically to get the time series. The same subjects were instructed to sit on a chair comfortably with their right arm on a desk. During testing, the subjects extended and flexed their elbow joint in a constant rhythm (exp. 3). On the other hand, under the other condition (exp. 4), the subjects extended and flexed their elbow joint irregularly. A goniometer was attached to the subject's elbow joint to measure the time variation of the elbow angle. Each experiment lasted for a period of 20 seconds and the data of the goniometer were digitized to a resolution of 12 bits, sampling at 100 Hz. Figure 6 shows the typical time series of the angular data (left) for exp. 3 and exp. 4 and phase portraits (right) in the case of embedding into three-dimensions of the data. As can be seen from Figure 6, it seems likely that the phase portrait for the first experimental condition (exp. 3) is similar to a limit cycle attractor, and the phase portait for the second experimental condition, (exp. 4) is similar to a chaotic attractor. Information ability of the COP chaos was calculated using the two time series.

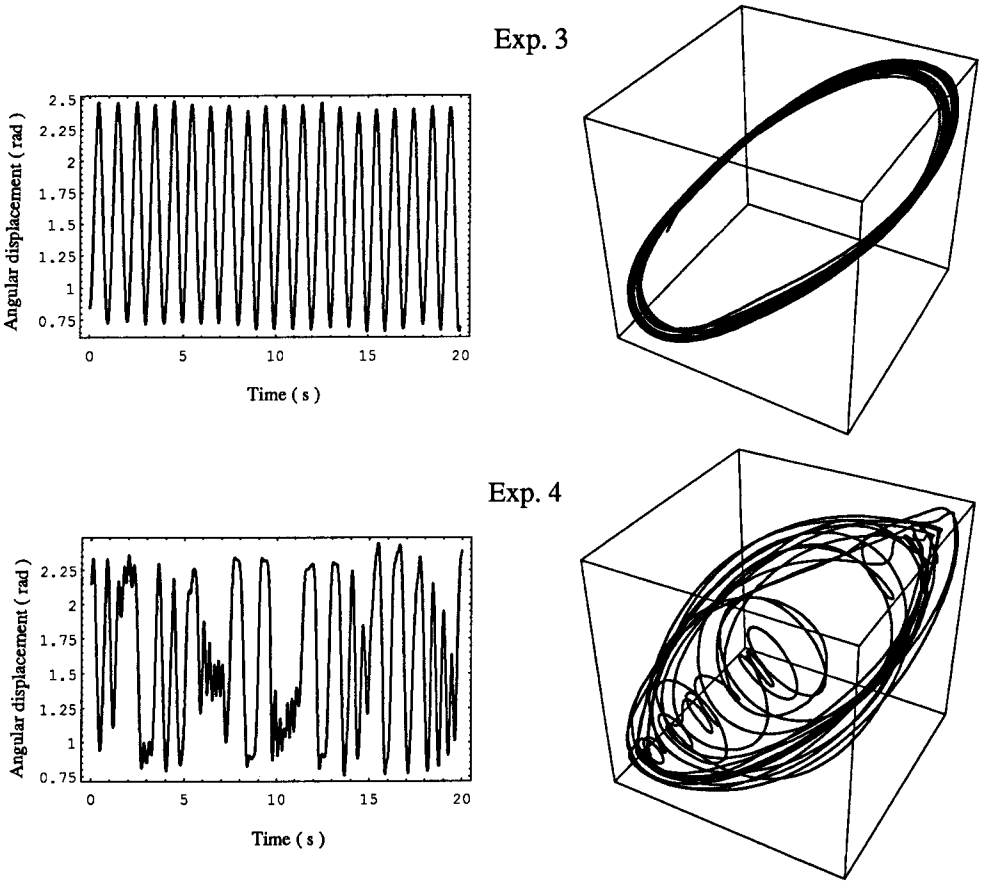

FIGURE 6 Typical time series of the elbow's angular data (left) for exp. 3 and exp. 4 and phase portraits (right) in the case of embedding into three-dimensions of the data.

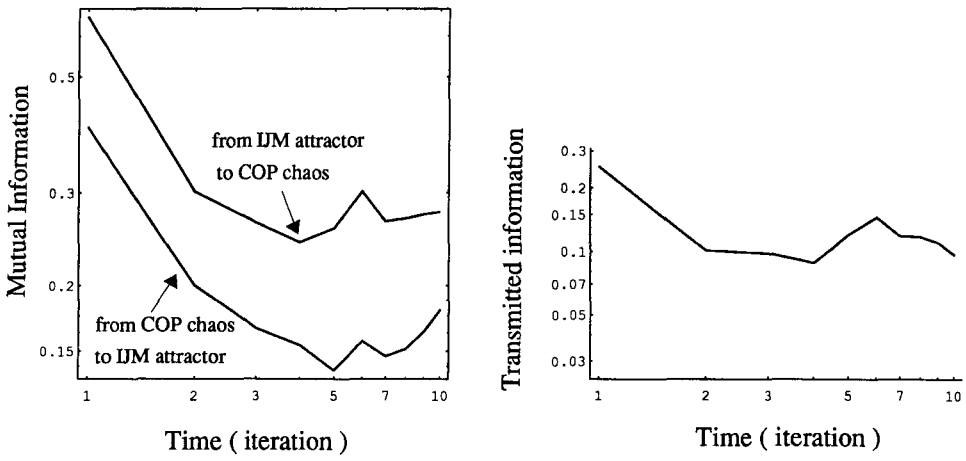

FIGURE 7 Typical time series of mutual information between the COP chaos in the case of standing still and the attractor constructed from irregular joint motion (IJM)(left). Time series of transmitted information from the IJM attractor to the COP chaos in the case of standing still (right).

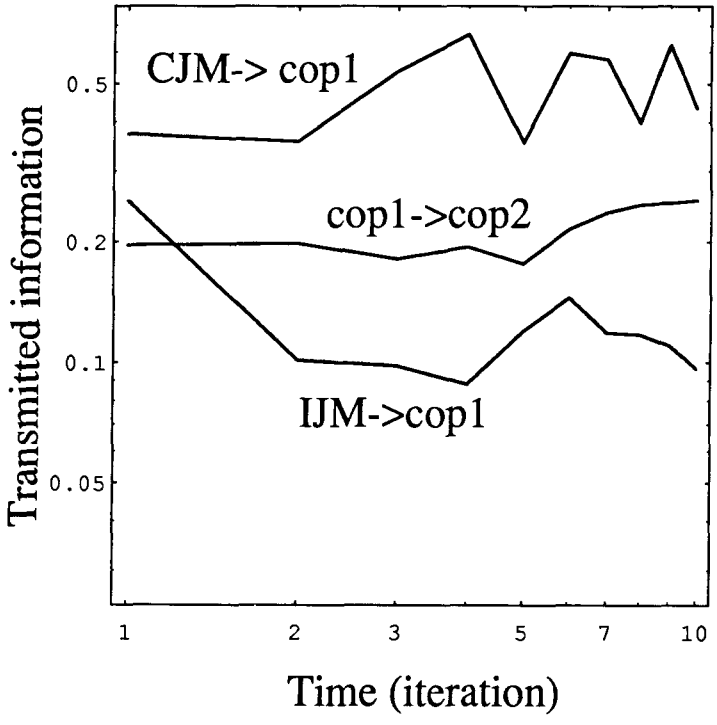

FIGURE 8 Typical time series of transmitted information from the attractor constructed from the joint motion with a constant rhythm (CJM) to the COP chaos in the case of standing still (CJM−>cop1), from the IJM attractor to the COP chaos in the case of standing still (IJM−>cop1), and from the COP chaos in the case of standing still to the COP chaos in the case of swinging the arms (cop1−>cop2).

Figure 7 shows the typical results of the calculation of transmitted information. The left figure in this shows the time series of mutual information between the COP chaos when the subject is standing still and the attractor constructed from irregular joint motion (IJM). The difference in this mutual information represents the amount of transmitted information. When these values are positive, the direction of transmitted information is from the IJM attractor to the COP chaos in the case of standing still. Adversely, if the value is negative, the direction is reversed. The results are shown in the right figure in Figure 7, where information is transmitted from the IJM attractor to the COP chaos in the case of standing still. In this way, transmitted information from the attractor constructed from the joint motion with a constant rhythm (CJM) to the COP chaos in the case of standing still, from the IJM attractor to the COP chaos in the case of standing still, and from the COP chaos in the case of standing still to the COP chaos in the case of swinging the arms are summarized in Figure 8. As can be seen in Figure 8, the ability of receiving information was most superior in the COP chaos in the case of swinging the arms. The order of ability of receiving information, except the COP chaos in the case of swinging the arms, is the COP chaos in the case of standing still, the IJM attractor. Furthermore, the CJM attractor only sent information in comparison with the other dynamical systems. For this reason, the ability of receiving information of the COP chaos is superior. Therefore, the regulating system for the posture composed in a voluntary movement can receive the information from many segments of the body as well as from the outside. If the swaying is regular like a limit cycle attractor or a point attractor instead of chaos, the regulating system for posture can not receive information from irregular movements of the body or from the outside. Finally, it should be noted that swaying of the COP which is chaotic, is rational from the viewpoint of information processing.

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