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# Chaotic Synchronization of Respiration and Center of Gravity Sway

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**Abstract:** Thus far, attention has been paid to phenomena wherein respiratory movement and physical movement systems have worked in coordination with one another, which has been studied. On the other hand, the earlier studies have hinted at the importance of considering mental and physical health from a holistic perspective, while taking into consideration the principles that prescribe the chaotic behavior of living organisms. In other words, this raises the issue: The validity of hypothesizing chaos dynamics as a universal principle for living systems that prescribes the chaotic nature of center of gravity sway and respiration. Therefore, the purpose of this study is to focus on center of gravity sway and respiration in order to examine the relationship in the chaotic nature between the two. Consequently, the issue presented above was supported. What this implies is that quantitatively assessing synchronous phenomena for the LLE for center of gravity sway and respiration used in this study is a more highly valid approach for determining people's mental and physical conditions in the field of clinical medicine, and therefore it could potentially be applied as a means of substantially supporting the promotion of health.

**Keywords:** Respiration; Center of Gravity Sway; Chaos; Synchronization

## I. INTRODUCTION

The metabolic (autonomous) respiration system and posture control system are the most fundamental systems underpinning the human body. First is metabolic respiration, the greatest role of which is to transport oxygen to the mitochondria in cells throughout the body. It is possible to suppress metabolic respiration in order to switch over to active (volitional) respiration, but it has been acknowledged that in doing so metabolic respiration is preserved without fail [3].

Conversely, the workings of the posture control system serve as the basis for all physical movement, and this is maintained through the workings of the visual system, vestibular system, somatosensory system, and the central nervous system, which synthesizes the information from these systems [16][24]. Posture control functions are expressed in the form of center of gravity sway, which is measured in order to quantify this. Posturography is used primarily for objectives such as evaluating equilibrium function and localization diagnoses of lesions [36].

Thus far, attention has been paid to phenomena wherein these respiratory movement and physical movement systems have worked in coordination with one another, which has been studied under the name Locomotor-Respiratory Coupling (LRC) [4][5][8][32]. This refers to phenomena wherein physical movement and respiratory movement have a particular rhythm and are in synch with one another during movement. The mechanism for this has yet to be clearly elucidated, but most studies have explained coordination of peripheral movement such as respiratory movement and physical movement as being the result of Central Pattern Generators (CPGs), which are hypothesized to be located in the central nervous system.

However, the degree of freedom the human body has is about 102 at the joint level, 103 at the muscle level, and 1014 at the neuron level. When attempting to determine this large quantity of parameters (degrees of freedom), problems with motor areas of the cerebral cortex loom large, and it becomes difficult to attribute this control to the central nervous system [22]. In response to this, reference [30] have indicated the possibility that the coordinative structure: synergy contributes to reducing the large quantity of parameters (degrees of freedom) the body has.

For example, when thinking about this by transposing a single system with two independent

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elements into a two-dimensional coordinate system, you must indicate the x-coordinates and the y-coordinates for the two elements (four degrees of freedom). However, if we assume that the two elements are firmly interlinked with one another and move in a coordinated manner, then this reduces the degrees of freedom to three. The field that deals with the coordinative structures seen within such dynamic systems is called synergetics [10][11].

It was from this perspective that the HBK model [12], which models the coordinated movement between extremities such as arms and legs as dynamical systems, has been proposed. It has been reported that this model can be applied to physical movement and respiratory movement as well [33]. Moreover, the field of synergistics continues to amass findings that support physically equating the motor systems of living things (regardless of whether this is autonomous movement or volitional movement) with self-organizing systems that follow order parameters (parameters encapsulating the order of systems) and dynamics [35] as a valid approach [19][31]. It also supports the idea that the principles for this coordination are identical, regardless of what types of subordinate systems perform this coordination [2][18]. In other words, there is the possibility that the body's structures coordinate via the same principle at various different levels.

This principle, which is known as "self-organization," is a principle that drives pattern formation in the natural world [6][15][29]. In self-organizing systems, dynamic steady conditions (attractors) that are maintained through the metabolism of energy and materials repeatedly arise and disappear, thus devolving into chaotic conditions [21].

In actuality, fluctuations in living things are chaotic at every observable level. Chaos refers to fluctuations in phenomena, and is observed in most of the phenomena in the natural world, such as chemical reactions and the movement of fluids, as well as in the majority of biological and physiological phenomena, psychological phenomena, and social and economic phenomena. When it comes to biological information and psychological phenomena, it has often been reported that dynamic fluctuations involving chaos are associated with healthy conditions, more so than unchanging static stability is [34][27].

The Largest Lyapunov Exponent (LLE) derived from a chaotic analysis of biosignals was used as the indicator for people's mental and physical health in this study in order to quantitatively assess the chaotic nature inherent in these signals. For example, regarding respiration reference [37] reported that the LLE for respiration in panic disorder patients in a standing position was higher than with the healthy control group, while reference [38] pointed out that serotonin reuptake inhibitors are effective at decreasing overly-high LLE in panic disorder patients. With center of gravity sway, on the other hand, it was reported that LLE is effective as an indicator of center of gravity sway changes associated with illnesses in cases of unilateral labyrinthine dysfunction [25]. Furthermore, in an examination of learning to maintain a standing posture on an unstable balance, it was reported that learning altered the intrinsic dynamic dimensions of the motion and reduced LLE [26].

In other words, these studies have hinted at the importance of considering mental and physical health from a holistic perspective, while taking into consideration the principles that prescribe the chaotic behavior of living organisms. In other words, this raises two issues: (1) The validity of hypothesizing chaos dynamics as a universal principle for living systems that prescribes the chaotic nature of center of gravity sway and respiration, and (2) The need to explore the potential that describing and controlling chaos dynamics has to contribute to determining the status of and controlling living systems as a whole.

In conventional synergistics, the parameters that describe the order of a system are called order parameters, while parameters that have an effect on these are called control parameters [10][11], and the dynamics of people's coordinated movements have been examined. The majority of these studies have examined the dynamics of order parameter $\varphi$ by using the relative phase ($\varphi$) generated between two oscillating motor systems as the unit for coordination, and manipulating the two control parameters of the oscillating frequency of two coordinated systems and the difference between the natural frequencies of the subordinate components constituting them $\measuredangle\omega$.

If we were to assume that the dynamics of living systems are accompanied by chaotic rhythms, then presumably it would be highly valid to observe the synchronous phenomena of the chaotic nature inherent in biosignals. However, we could not find any reports focusing on the relationships between biosignals in studies on chaos in living organisms. Therefore, the purpose of this study is to focus on center of gravity sway and respiration in order to examine the relationship in the chaotic nature between the two. In

other words, its objective is to examine: (1) The validity of hypothesizing chaos dynamics as a universal principle for living systems that prescribes the chaotic nature of center of gravity sway and respiration, which was one of the issues described above.

## II. METHODOLOGY

### A. Experiment time and location

This experiment was conducted between July 7 and 21, 2006 using a conference room as a laboratory at University A in Tokyo.

### B. Experiment participants

This experiment was conducted on a total of 31 university students (average age: 20.50 years old, SD=2.21 years, 10 males and 21 females).

### C. Experiment equipment

The stabilograph used was a SYNAPACK EN-ER series EN2102 (made by NEC), and the respiration meter used (1) was a portable Respitrace unit (made by AMI) comprised of a respiband, oscillator, connecting cable interface, and a retainer. One of the respiration and center of gravity sway meters (2) used was a Mac Lab/8s (made by Bio Research Center), and the other respiration and center of gravity sway meter (3) was a Macintosh (PC) LC5220 (made by Apple). A Lyspect 3.5 (made by Chaos Technology Research Laboratory) was used for center of gravity sway and respiration LLE detection, while a Macintosh M5343 (made by Apple) was used for the data analysis.

### D. Physical and physiological indicators

The center of gravity sway and respiration were each measured over 210 seconds using a sampling period of 10Hz, and then a chaotic analysis was performed on this. For the various set values used during the chaotic analysis, we referred to the methods and wisdom regarding fingertip pulse waves that have been conventionally proposed [1][14][34], while making some adjustments. The delay time was set as the time when the autocorrelation function initially reached zero, while the evolution time was set at 50 ms, the size of the hypersphere was set as 0.05 (equivalent to approximately 5% of the average chaos attractor), the time constant as 1 second, and the embedding dimension as the fourth dimension. Furthermore, in order to truly reflect the factors that have an impact on the various set values, we used a Lyspect (made by Chaos Technology Research Laboratory) to reduce noise and used a CHORUS (made by Computer Convenience) to perform ten-dimensional spline interpolation processing.

### E. Experiment Procedure

1) Explanation of the content measured: The following explanation was given to the experiment participants. “This experiment is a study related to the relationship between physical strain and the mind. If you experience any physical abnormalities, discomfort, or unpleasant feelings you can stop the experiment at any time. You will not suffer any adverse effects whatsoever for stopping the experiment. All of the information obtained from this experiment will be kept strictly confidential”. After delivering the explanation above, the subjects’ physical condition was checked (to see if they had any colds, fevers, or any other mental or physical ailments or disorders). Once they had consented to take part in the experiment and it was found that there were no problems with their physical condition, the experiment was carried out.

2) Center of gravity sway / respiration measurement (3 minutes and 30 seconds): A Respiband (made by AMI) for measuring respiration was attached to the participants, and they were made to get on a SYNAPACK EN-ER series EN2102 stabilograph (made by NEC). They were then instructed to, “Face forward, close your eyes, drop your hands at your side, and do not open your eyes, speak, or move your body until the experimenter has given you the signal.” The data measurement began as soon as signals were received from the participant.

3) Confirmation of physical condition: It was confirmed that the subjects did not have any physical abnormalities, and an overview of the experiment was explained to those who wished to hear it.

### F. Ethical considerations

In carrying out the study, we explained the study’s purpose, privacy protections, the fact that there were no adverse effects from not cooperating, and that the subjects themselves could stop the experiment immediately at their request. We also explained that if they requested that the researchers not use their data in the study, even after the measurements had concluded, that their data would absolutely not be used. We also confirmed the subjects’ physical condition, confirmed the total hours spent in the study, and announced when it was over. These explanations were strictly observed

in an effort to strictly safeguard the rights of the subjects and uphold research ethics.

### G. **Analytical method**

We examined the waveform correlation using the cross correlation function on the raw data and LLE for center of gravity sway and respiration. Since the types of data for center of gravity sway and respiration differ, examining the correlation on the raw data as is would cause problems. As a result, the raw data was converted to a Z-score, following which the cross correlation function was calculated (Fig. 1 and Fig. 2).

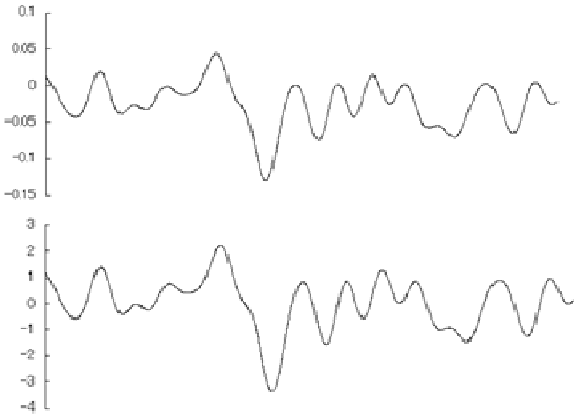

Fig. 1 Center of gravity sway data sample (the raw data is above, data that has been converted to a Z-score is below)

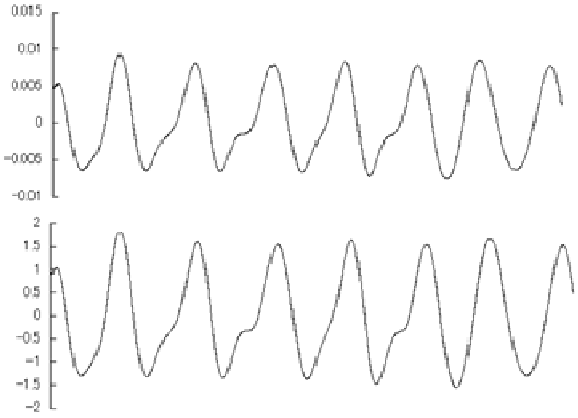

Fig. 2 Respiration data sample (the raw data is above, data that has been converted to a Z-score is below)

The definitional equation for the cross-correlation function is (1):

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y(t+\tau)dt \qquad (1)$$

Since the data that we can actually measure is discrete data of a finite length, we devised several ways to estimate the cross-correlation function. The most basic approach was a method of calculating this from a correlogram, and for this study we estimated this using a Fast Fourier Transform (FFT), which is commonly used. More specifically, FFT was used to calculate a cross spectrum for dual-variable time series data, and the cross-correlation function was estimated by performing an inverse Fourier transform on this. In addition, $\tau$ is 1/100 of a second, which was the time interval for the data, and this was estimated for the interval between 0 and 210 seconds. Since this cross-correlation function data is to be analyzed as single data points, in this study the highest cross-correlation values in the interval from which 20% of the latter half of lag values for the cross-correlation function had been excluded were subject to analysis. The reason that 20% of the latter half of the lag values were excluded was to remove pseudo-correlated values.

## III. RESULTS

A weak correlation was observed in the raw data for center of gravity sway and respiration (maximum value for the cross-correlation function = .29±.07: Fig.3). A strong correlation was observed in the LLE for center of gravity sway and respiration (maximum value for the cross-correlation function = .74±.12: Fig. 4).

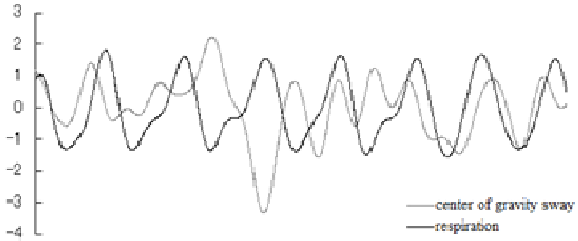


Fig. 3 Sample phase for the raw data for respiration and center of gravity sway

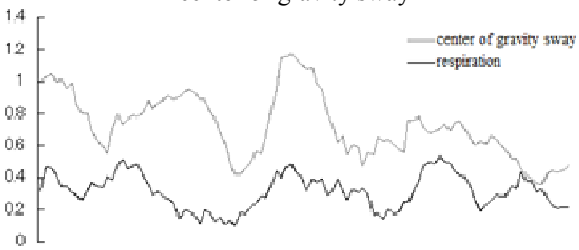


Fig. 4 Sample phase for the LLE for respiration and center of gravity sway

## IV. DISCUSSION

This study used LLE and its cross-correlation function to examine the chaotic relationship between center of gravity sway and respiration. The results revealed a high degree of synchronicity between the LLE for the two signals, while the extent of this synchronicity between LLE was even higher in the raw data. From this the claim could be made that: (1) The results support the validity of hypothesizing that chaos dynamics is a universal principle of living systems.

Moving forward: (2) The possibility that chaos dynamics contributes to determining and controlling the status of living systems as a whole should be pursued by describing and controlling chaos dynamics. This is because with self-organizing systems, the macro-level order that arises in systems due to their order parameter for the degree of freedom has been identified, while conversely it has been revealed that the behavior of subordinate systems also has an impact on macro-level order [20][21].

If we were to consider this in terms of this study, the claim could be made that while the respective behaviors of respiration and center of gravity sway comprising living systems are controlled by the system's macro-level chaos dynamics, they conversely also function to prescribe how chaos dynamics operate. In actuality, this study implied that chaos dynamics for living systems are expressed in synchronous phenomena for the LLE for respiration and center of gravity sway. In the future, attempting to observe and control synchronous phenomena for the LLE for respiration and center of gravity sway could lead to determining the status for living systems as a whole, and perhaps also turn up the possibility that this contributes to promoting the health of living systems.

While the respiratory movement system is controlled autonomously, it can also be controlled voluntarily. Approaches that attempt to promote overall health by using volition to intervene in the autonomically-regulated functions of living things has been used extensively in the fields of physiological psychology and psychophysiology. When it comes to studies that have focused on fluctuations in living things in particular, the heart rate variability biofeedback method (HRV-BF method) in which fluctuations in a person's heart rate are increased by regulating respiration have shown a great deal of results. By way of example, this contributes to treating patients with diseases like asthma [23], heart disease [7], fibromyalgia syndrome [13], major depression [17], and post-traumatic stress disorder [39]. Specifically, it has been reported that for asthma it improves pulmonary function and decreases the required dosage, for heart disease it decreases the postictal case fatality rate, for fibromyalgia syndrome it lowers pain and improves both the depressive states accompanying symptoms as well as sleep, for major depression it considerably reduces the assessed level on the depression scale, and for post-traumatic stress disorder it decreases depressive symptoms associated with this and lowers the impulse to use drugs [39]. On the other hand, center of gravity sway is a biosignal that is essentially autonomously controlled. But when the fact that center of gravity sway is equivalent to the subordinate system of a volitional physical movement system is taken into consideration, then conceivably it would be possible to intervene in the chaotic nature of physical movement systems and posture control systems by voluntarily controlling physical movement. To date, studies focused on chaos in living things pertaining to physical movement have examined the LLE for the motion of the joint when walking [28] and the LLE for the acceleration of three-dimensional movement measured through the use of a tri-axial accelerometer [9]. Based on this, voluntarily changing the tempo of motion or the operation of the joints could potentially serve as an effective means for this.

What this implies is that quantitatively assessing synchronous phenomena for the LLE for center of gravity sway and respiration used in this study is a more highly valid approach for determining people's mental and physical conditions in the field of clinical medicine, and therefore it could potentially be applied as a means of substantially supporting the promotion of health. This not only has a strong possibility of maintaining health using the chaotic nature of living things, but also of having said chaotic nature contribute to maintaining and promoting physical and mental health through the dynamic relationship between physiological phenomena.

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