On a Body Sway Model while Maintaining Upright Posture during Exposure to a Stereoscopic Movie on a Liquid Crystal Display

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***Abstract*— It is known that a mathematical model of the body sway can be developed by a stochastic process. The authors have succeeded in finding the nonlinearity in the potential function. Regarding to the mathematical model, we applied an index, sparse density (SPD), of stationary stabilograms for detecting instability due to the motion sickness (simulator sickness), which occurs when a human attempts to maintain an upright posture. In this study, subjects in a standing position were stimulated by stereoscopic movies on a liquid crystal display (LCD). We also measured the degree of determinism in the dynamics of the sway of the center of gravity of the subjects. The Double-Wayland algorithm was used as a novel method. As a result, the dynamics of the body sway in the presence of the stimulus as well as in its absence were considered to be stochastic. The structural changes in the potential function during exposure to the conventional three-dimensional images could be detected by using the SPD.**

I. Introduction

The human standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism called the righting reflex [1]. In order to maintain the standing posture when locomotion is absent, the righting reflex, centered in the nucleus ruber, is essential. Sensory signals such as visual inputs, auditory and vestibular inputs, and proprioceptive inputs from the skin, muscles, and joints are the inputs that are involved in the body's balance function [2]. The evaluation of this function is indispensable for diagnosing equilibrium disturbances such as cerebellar degenerations, basal ganglia disorders, or Parkinson's disease in patients [3].

Stabilometry has been employed to evaluate this equilibrium function both qualitatively and quantitatively. A projection of a subject's center of gravity onto a detection stand is measured as an average of the center of pressure (COP) of both feet. The COP is traced for each time step, and the time series of the projections is traced on an x-y plane. By connecting the temporally vicinal points, a stabilogram is created, as shown in Fig 1. Several parameters such as the area of sway (A), total locus length (L), and locus length per unit area (L/A) have been proposed to quantitize the instability involved in the standing posture, and such parameters are widely used in clinical studies. It has been revealed that the last parameter particularly depends on the fine variations involved in posture control [1]. This index is then regarded as a gauge for evaluating the function of proprioceptive control of standing in human beings. However, it is difficult to clinically diagnose disorders of the balance function and to identify the decline in equilibrium function by utilizing the abovementioned indices and measuring patterns in the stabilogram. Large interindividual differences might make it difficult to understand the results of such a comparison.

Mathematically, the sway in the COP is described by a stochastic process [4]–[6]. We examined the adequacy of using a stochastic differential equation and investigated the most adequate equation for our research. G(**x**), the distribution of the observed point x, is related in the following manner to U(**x**), the (time-averaged) potential function, in the stochastic differential equation (SDE), which has been considered as a mathematical model of the sway:

$$U(\vec{x}) = -\frac{1}{2}\ln G(\vec{x}) + const. \qquad (1)$$

Actually, G(**x**) is estimated by the histogram of the time series data. The nonlinear property of SDEs is important [7]. There were several minimal points of the potential. In the vicinity of these points, local stable movement with a high-frequency component can be generated as a numerical solution to the SDE. We can therefore expect a high density of observed COP in this area on the stabilogram.

The anterior-posterior direction y was considered to be independent of the mediallateral direction x [8]. Stochastic differential equations (SDEs) on the Euclid space $\mathbf{E}^2 \ni (x, y)$

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x}U_x(x) + w_x(t)$$
$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y}U_y(y) + w_y(t)$$

have been proposed as mathematical models that generate the stabilograms [4]-[7]. In numerical analysis, pseudorandom numbers were generated as white noise terms $w_x(t)$ and $w_y(t)$. Constructing the nonlinear SDEs from the stabilograms (Fig. 1) in accordance with Eq. (1), their temporally averaged potential functions U_x, U_y have plural minimal points, and fluctuations could be observed in the neighborhood of the

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minimal points [7]. The variance in the stabilogram depends on the form of the potential function in the SDE; therefore, sparse density (SPD) is regarded as an index for its measurement.

The analysis of stabilograms is useful not only for medical diagnosis but also for achieving the control of upright standing for two-legged robots and for preventing falls in elderly people [9]. Recent studies suggest that maintaining postural stability is one of the major goals of animals, [10] and that they experience sickness symptoms in circumstances where they have not acquired strategies to maintain their balance [11]. Riccio and Stoffregen argued that motion sickness is not caused by sensory conflict, but by postural instability, although the most widely known theory of motion sickness is based on the concept of sensory conflict [11]–[13]. Stoffregen and Smart (1999) report that the onset of motion sickness may be preceded by significant increases in postural sway [14].

The equilibrium function in humans deteriorates when viewing 3-dimensional (3D) movies [15]. It has been considered that this visually induced motion sickness (VIMS) is caused by the disagreement between vergence and visual accommodation while viewing 3D images [16]. Thus, stereoscopic images have been devised to reduce this disagreement [17]–[18].

VIMS can be measured by psychological and physiological methods, and the simulator sickness questionnaire (SSQ) is a well-known psychological method for measuring the extent of motion sickness [19]. The SSQ is used herein for verifying the occurrence of VIMS. The following parameters of autonomic nervous activity are appropriate for the physiological method: heart rate variability, blood pressure, electrogastrography, and galvanic skin reaction [20]–[22]. It has been reported that a wide stance (with midlines of the heels 17 or 30 cm apart) significantly increases the total locus length in the stabilograms of individuals with high SSQ scores, while the length in those of individuals with low scores is less affected by such a stance [23]. We wondered if noise terms vanished from the mathematical model (SDEs) of the body sway. Using our Double-Wayland algorithm [24], we evaluate the degree of visible determinism for the dynamics of the sway.

We propose a methodology to measure the effect of 3D images on the equilibrium function. We assume that the high density of observed COP decreases during exposure to stereoscopic images [15]. The SPD would be a useful index in stabilometry to measure VIMS. In this study, we verify that reduction in body sway can be evaluated using the SPD during exposure to a new 3D movie on an LCD.

II. Material and Method

A. Participants

Ten healthy subjects (age, 23.6 ± 2.2 years) voluntarily participated in the study. We ensured that the body sway was not affected by environmental conditions. Using an air conditioner, we adjusted the temperature to 25 °C in the exercise room, which was kept dark.

B. Material

The subjects stood without moving on a detection stand of a stabilometer (G5500; Anima Co. Ltd.) with their feet together. The subjects were positioned facing an LCD monitor (S1911- SABK, NANAO Co., Ltd.) on which three kinds of images were presented in no particular order: (I) visual target (circle) whose diameter was 3 cm; (II) a new 3D movie that shows a sphere approaching and going away from subjects irregularly; and (III) a conventional 3D movie that shows the same sphere motion as in (II) which was created using the Olympus power 3D method [25]. The new stereoscopic images (II) were constructed by Olympus Power 3D method. The distance between the wall and the subjects was 57 cm.

C. Design

The subjects stood on the detection stand in the Romberg posture for 1 min before the sway was recorded. Each sway of the COP was then recorded at a sampling frequency of 20 Hz during the measurement; subjects were instructed to maintain the Romberg posture for the first 60 s and a wide stance (with the midlines of heels 20 cm apart) for the next 60 s. The subjects viewed one of the images, i.e., (I), (II), or (III), on the LCD from the beginning till the end. The SSQ was filled before and after stabilometry.

D. Calculation Procedure

We calculated several indices that are commonly used in the clinical field [26] for stabilograms, such as “area of sway,” “total locus length,” and “total locus length per unit area.” In addition, new quantification indices that were termed “SPD”, “total locus length of chain” [27] and the translation error [28] were also estimated. The translation error (E_{trans}) is calculated in order to evaluate the degree of determinism for dynamics that generate a time series. E_{trans} represents the smoothness of flow in an attractor, which is assumed to generate the time series data.

III. Results

The results of the SSQ are shown in Table 1 and include the scores on nausea (N), oculomotor discomfort (OD), disorientation (D) subscale and total score (TS) of the SSQ. No statistical differences were seen in these scores among images presented to subjects. However, increases were seen in the scores for N and D after exposure to the conventional 3D movie, (II) *Cross-point 3D*. In addition, the scores after exposure to the new 3D images were not very different from those after exposure to the static one, (I) *Pre*. Although there were large individual differences, sickness symptoms seemed

Table 1 Subscales of the SSQ after exposure to 3D movies

Movies	(II) *Cross-Point 3D*	(III) *Power 3D*
N	8.6±2.6	14.3±4.8
OD	17.4±3.4	16.7±4.0
D	16.7±6.2	22.3±9.3
TS	16.4±3.7	19.8±5.8

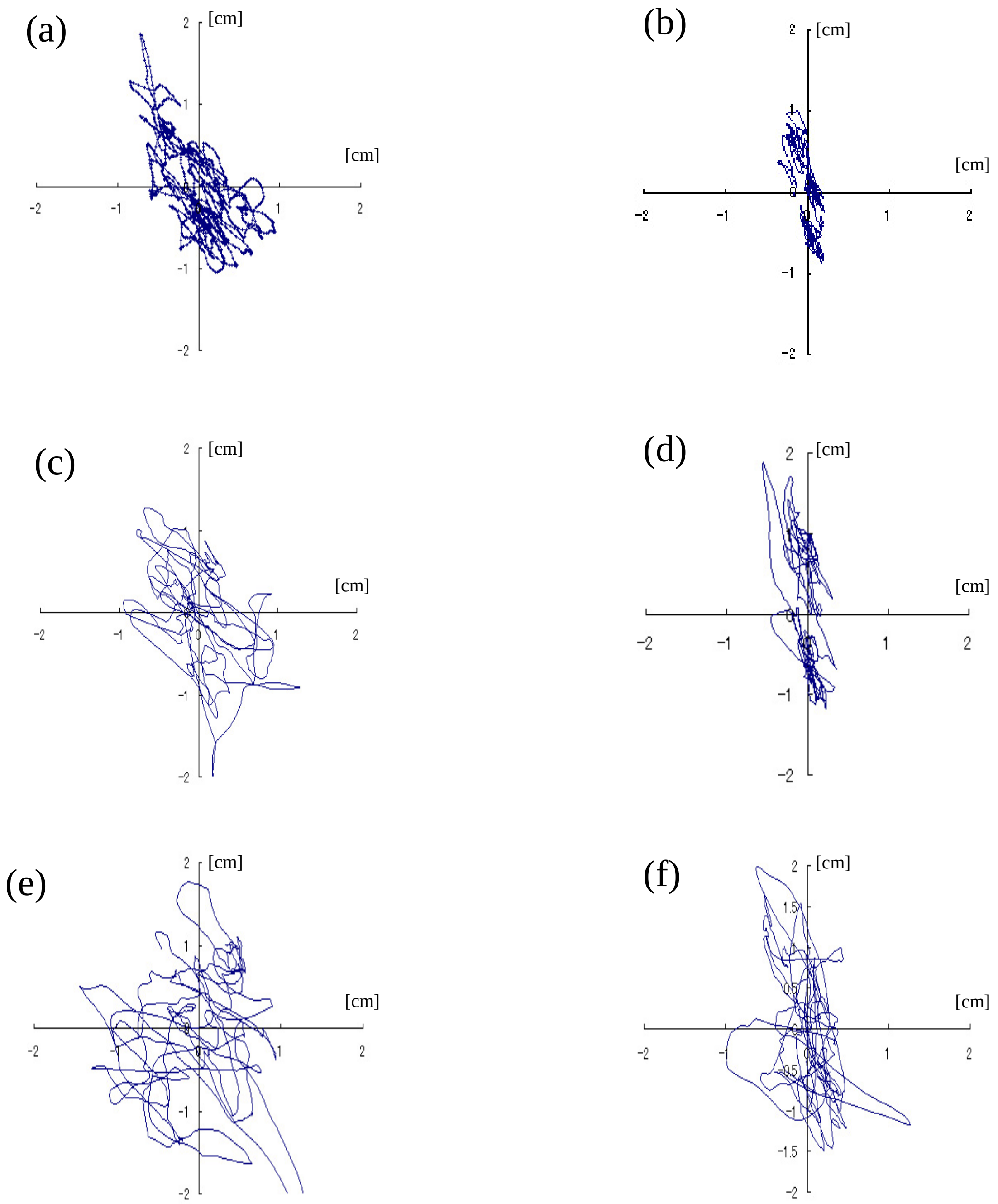

Fig. 1. Typical stabilograms (sway of the COP) observed when subjects viewed a static circle (a-b), the new stereoscopic movie (c-d), and the conventional 3D movie (e-f) [29].

to appear more often with the conventional 3D movie.

Typical stabilograms are shown in Fig. 1. In these figures, the vertical axis shows the anterior and posterior movements of the COP, and the horizontal axis shows the right and left movements of the COP. The amplitudes of the sway that were observed during exposure to the movies (Fig. 1c–1f) tended to be larger than those of the control sway (Fig.1a-1b). Although a high density of COP was observed in the stabilograms (Fig. 1a–1b, 1e–1f), the density decreased in stabilograms during exposure to the conventional stereoscopic movie (Fig. 1c–1d). Furthermore, stabilograms measured in an open leg posture with the midlines of heels 20 cm apart (Fig. 1b, 1d, 1f) were compared with stabilograms measured in the Romberg posture (Fig. 1a, 1c, 1e). COP was not isotropically dispersed but characterized by much movement in the anterior-posterior (y) direction (Fig. 1b, 1f). Although this trend is seen in Fig. 1d, the diffusion of COP was large in the lateral (x) direction and had spread to the extent that it was equivalent to the control stabilograms (Fig. 1a).

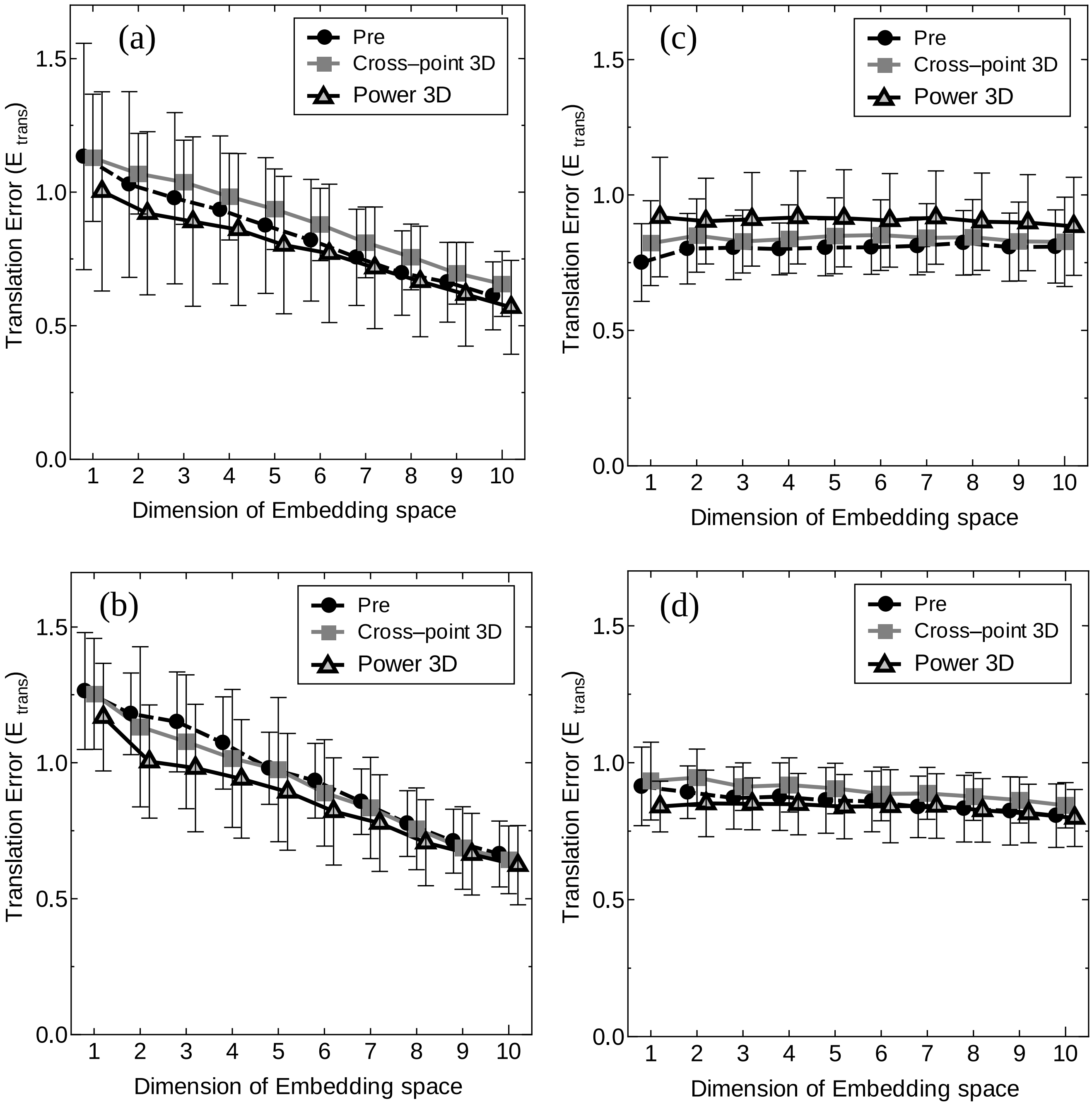

Fig. 2. Mean translation error (E_{trans}) for each embedding space. Translation errors were estimated from a lateral component of stabilograms (a)–(b), and temporal differences of the time series (c)–(d). Subjects maintained the Romberg posture (a), (c), and a wide stance (b), (d).

Results of the Double-Wayland algorithm are shown in Fig. 2 and Fig. 3. Whether subjects was exposed to the 3D movies or not, E_{trans} derived from the temporal differences of those time series x, y was approximately 1. These translation errors in each embedding space were not significantly different from the translation errors derived from the time series x, y although E_{trans} derived from the time series y is less than 1 for any embedding space without exposure to any of stereoscopic movies.

According to the two-way analysis of variance (ANOVA) with repeated measures, there was no interaction between factors of posture (Romberg posture or standing posture with their feet wide apart) and images ((I), (II), or (III)). Except to the total locus length per unit area and the total locus length of chain, main effects were seen in the both factors (Fig. 4). On the other hand, any indicators could find a main effect in the postural factor ($p < 0.01$).

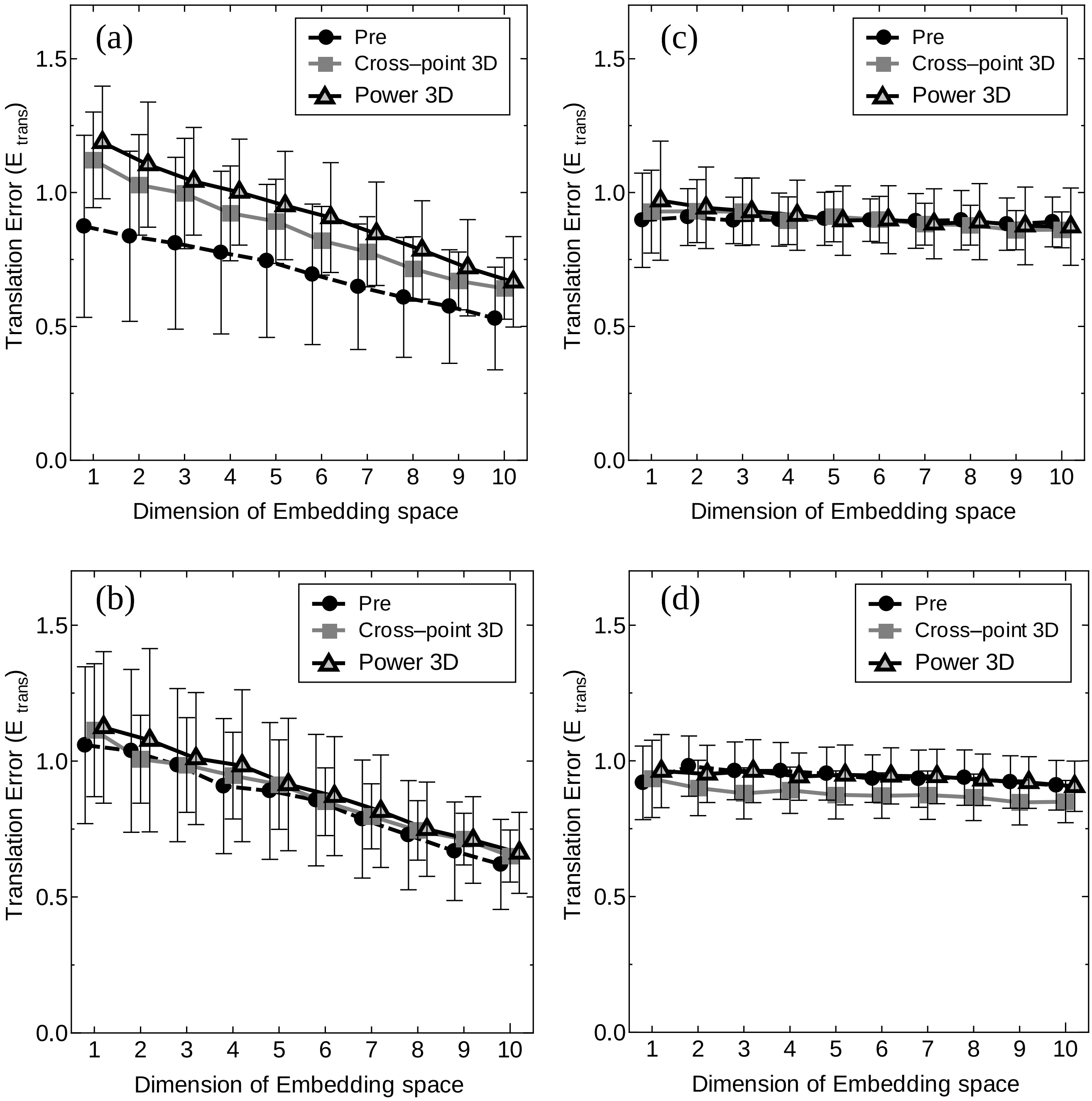

Fig. 3. Mean translation error (E_{trans}) for each embedding space. Translation errors were estimated from a anterior/posterior component of stabilograms (a)–(b), and temporal differences of the time series (c)–(d). Subjects maintained the Romberg posture (a), (c), and a wide stance (b), (d).

IV. Discussion

A theory has been proposed to obtain SDEs as a mathematical model of the body sway on the basis of the stabilogram. According to Eq. (1), there were several minimal points of the time-averaged potential function in the SDEs (Fig. 1). The variance in the stabilogram depends on the form of the potential function in the SDE; therefore, the SPD is regarded as an index for its measurement. The movies, especially stereoscopic images, decrease the gradient of the potential function. The new 3D movie (II) should reduce the body sway because there is no disagreement between vergence and visual accommodation. The reduction can be evaluated by the SPD during exposure to the movies on an LCD screen. Performing a one-way analysis of variance for a posture with wide stance, we have succeeded in estimating the decrease in the gradient of the potential function by using the SPD as shown in Fig. 4a ($p<0.05$).

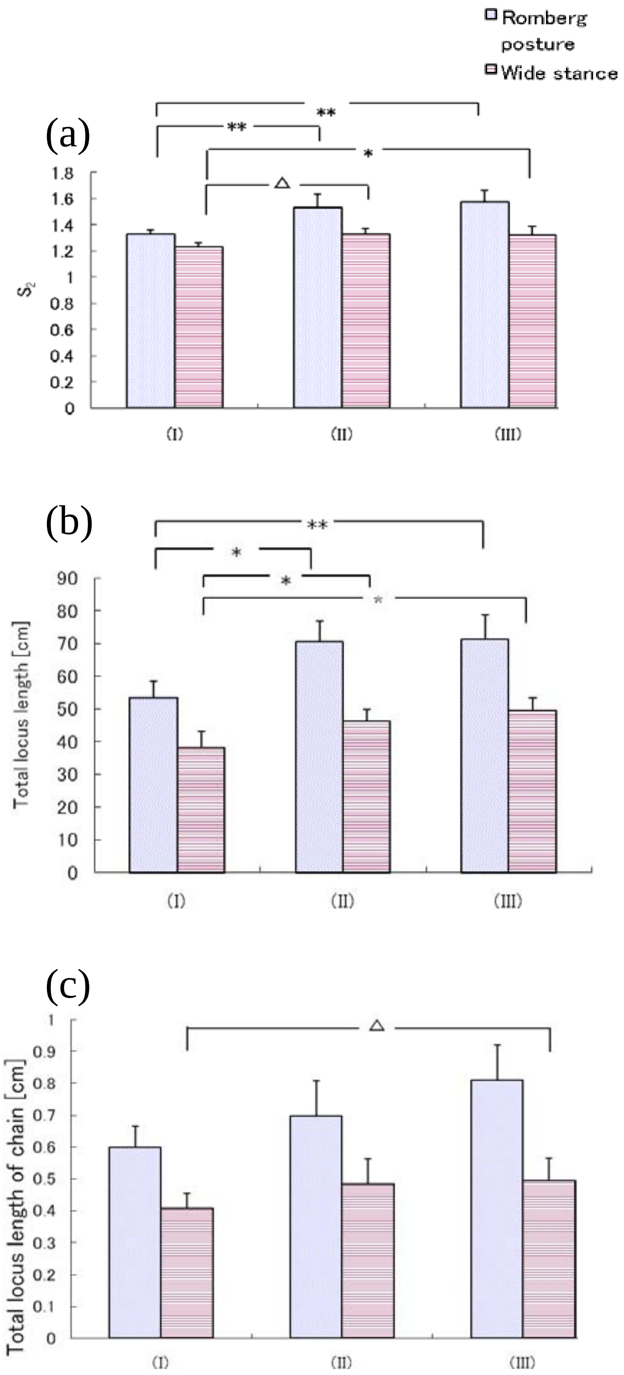

Fig. 4 Typical results of the two-way ANOVA with repeated measures for indicators [29]; the SPD (a), the total locus length (b), and the total locus length of chain (c) (**p < 0.01,*p < 0.05).

In this study, we mathematically measured the degree of determinism in the dynamics of the sway of COP. The Double -Wayland algorithm was used as a novel method. $E_{trans} > 0.5$ was obtained by the Wayland algorithm (Fig. 2-3), which implies that the time series could be generated by a stochastic process in accordance with a previous standard [30]. The threshold 0.5 is half of the translation error resulting from a random walk. The body sway has been described previously by stochastic processes [4]-[7], which was shown with the Double-Wayland algorithm [31]. Moreover, $0.8 < E_{trans} < 1$ obtained from the temporal differences of these time series exceeded the translation errors estimated by the Wayland algorithm, as shown in Fig. 2b. However, the translation errors estimated by the Wayland algorithm were similar to those obtained from the temporal differences, except for Fig. 2b, which agrees with the abovementioned explanation of the dynamics to control a standing posture. The exposure to 3D movies would not change it into a deterministic one. Mechanical variations were not observed in the locomotion of the COP. We assumed that the COP was controlled by a stationary process, and the sway during exposure to the static control image (I) could be compared with that when the subject viewed 3D movies. Indices for stabilograms might reflect the coefficients in stochastic processes although the translation error did not exhibit a significant difference between the stabilograms measured during exposure to the new 3D movie (II) and the conventional 3D movie (III).

Indices for stabilograms might reflect the coefficients in stochastic processes although the translation error did not exhibit a significant difference among the exposure to images (I), (II), and (III) as shown in Fig.2-3. With respect to the Romberg posture, the total locus length during exposure to 3-D movies was significantly greater than that to the static one (I) which could not induce the VIMS (Fig. 4b). We considered that the 3-D images on the LCD decrease the gradient of the potential function. Moreover, the new 3D movie (II) might reduce the body sway because there is no disagreement between vergence and visual accommodation. The reduction could be evaluated by the SPD during exposure to the movies on an LCD screen while subjects maintained upright posture with the wide stance (Fig. 4a). We have succeeded in estimating the decrease in the gradient of the potential function by using the SPD. We concluded that the metamorphism in the potential function during exposure to the conventional 3-D images could be detected by using the SPD.

Multiple comparisons indicated that the SPD S_2 during exposure to any of the stereoscopic movies was significantly larger than that during exposure to the static control image (I) when subjects stood in the Romberg posture (Fig.4a). The standing posture would become unstable because of the effects of the stereoscopic movies. As mentioned above, structural changes occur in the time-averaged potential function (1) with exposure to stereoscopic images, which are assumed to reflect the sway in center of gravity.

Scibora et al. concluded that the total locus length of subjects with prior experience of motion sickness increases with exposure to a virtual environment when they stood with their feet wide apart [23], whereas, in our study, the degree of sway was found to be reduced when the subjects stood with their feet wide apart (Fig.1b, 1d, 1f) than when they stood with their feet close together (Fig.1a, 1c, 1e). As shown in Fig. 1d and 1f, a clear change in the form of the potential function (1) occurs when the feet are wide apart. The decrease in the gradient of the potential might increase the total locus length.

Regardless of posture, the total locus length during exposure to the 3D movies was significantly greater than that during exposure to the control image (Fig.4b). However, the SPD during exposure to the conventional stereoscopic movie (III) was significantly larger than that during exposure to the control image (I) when they stood with their feet wide apart (Fig.4a). The total locus length of chain simultaneously tended to increase when subjects were exposed to the conventional 3D images (III) compared that when they were exposed to (I) (Fig.4c). Hence, we noted postural instability with the exposure to the conventional stereoscopic images (III) by using these indicators involved in the stabilogram (SPD and total locus length of chain). This instability might be reduced by the Olympus power 3D method.

REFERENCES

[1] T. Okawa, T. Tokita, Y. Shibata, T. Ogawa, H. Miyata, "Stabilometry - Significance of Locus Length Per Unit Area (L/A) in Patients with Equilibrium Disturbances," Equilibrium Res., vol.55(3), pp.283-293, 1995.

[2] K. Kaga, "Memaino Kouzo: Structure of vertigo," Tokyo: Kanehara, 1992, pp.23-26 [in Japanese].

[3] T. Okawa, T. Tokita, Y. Shibata, T. Ogawa, H. Miyata, "Stabilometry-Significance of locus length per unit area (L/A)," Equilibrium Res., vol.54(3), pp.296-306, 1996.

[4] J. J. Collins, C. J. De Luca, "Open-loop and closed-loop control of posture: A random-walk analysis of center of pressure trajectories," Exp. Brain Res., vol. 95, pp.308-318, 1993.

[5] R. E. A. Emmerrik, R. L. Van Sprague, K. M. Newell, "Assessment of sway dynamics in tardive dyskinesia and developmental disability: sway profile orientation and stereotypy," Moving Disorders, vol.8, pp.305-314, 1993.

[6] K. M. Newell, S. M. Slobounov, E. S. Slobounova, P. C. Molenaar, "Stochastic processes in postural center-of-pressure profiles," Exp. Brain Res., vol.113, pp.158–164, 1997.

[7] H. Takada, Y. Kitaoka , Y. Shimizu, "Mathematical Index and Model in Stabilometry," Forma, vol.16 (1), pp.17-46, 2001.

[8] P. A. Goldie, T. M. Bach, O. M. Evans, "Force platform measures for evaluating postural control: reliability and validity," Arch. Phys. Med. Rehabil., vol.70, pp.510–517, 1989.

[9] K. Fujiwara, H. Toyama, "Analysis of dynamic balance and its training effect-Focusing on fall problem of elder persons," Bulletin of the Physical Fitness Research Institute, vol.83, pp.123-134, 1993.

[10] T. A. Stoffregen, L. J. Hettinger, M. W. Haas, M. M. Roe, L. J. Smart, "Postural instability and motion sickness in a fixed-base flight simulator," Human Factors, vol.42, pp.458-469, 2000.

[11] G. E. Riccio, T.A. Stoffregen, "An Ecological theory of motion sickness and postural instability," Ecological Physiology, vol.3(3), pp.195-240, 1991.

[12] C. Oman, "A heuristic mathematical model for the dynamics of sensory conflict and motion sickness," Acta Otolaryngologica Supplement, vol.392, pp.1-44, 1982.

[13] J. Reason, "Motion sickness adaptation: a neural mismatch model," J. Royal Soc. Med., vol.71, pp.819-829, 1978.

[14] T. A. Stoffregen, L. J. Smart, B. J. Bardy, R. J. Pagulayan, "Postural stabilization of looking. Journal of Experimental Psychology," Human Perception and Performance, vol.25, pp.1641-1658, 1999.

[15] H, Takada, K. Fujikake, M. Miyao, Y. Matsuura, " Indices to Detect Visually Induced Motion Sickness using Stabilometry," Proc. VIMS 2007, pp.178-183, 2007.

[16] T. Hatada, Nikkei electronics, vol.444, pp.205-223, 1988.

[17] R. Yasui, I. Matsuda, H. Kakeya, "Combining volumetric edge display and multiview display for expression of natural 3D images," Proc. SPIE 6055, 0Y1-0Y9, 2006.

[18] H. Kakeya, "MOEVision:simple multiview display with clear floating image," Proc. SPIE 6490, 64900J, 2007.

[19] R. S. Kennedy, N. E. Lane, K. S. Berbaum, M. G. Lilienthal, "A simulator sickness questionnaire (SSQ): A new method for quantifying simulator sickness," International J. Aviation Psychology, vol.3, pp.203-220, 1993.

[20] S. R. Holomes, M. J. Griffin, "Correlation between heart rate and the severity of motion sickness caused by optokinetic stimulation," J. Psychophysiology, vol.15, pp.35-42, 2001.

[21] N. Himi, T. Koga, E. Nakamura, M. Kobashi, M. Yamane, K. Tsujioka, "Differences in autonomic responses between subjects with and without nausea while watching an irregularly oscillating video," Autonomic Neuroscience Basic and Clinical, vol.116, pp.46-53, 2004.

[22] Y. Yokota, M. Aoki, K. Mizuta, "Motion sickness susceptibility associated with visually induced postural instability and cardiac autonomic responses in healthy subjects," Acta Otolaryngologia, vol.125, pp.280-285, 2005.

[23] L. M. Scibora, S. Villard, B. Bardy, T.A. Stoffregen, "Wider stance reduces body sway and motion sickness," Proc. VIMS 2007, pp.18-23, 2007.

[24] H. Takada, T. Morimoto, H. Tsunashima, T. Yamazaki, H. Hoshina, M. Miyao, "Applications of Double-Wayland algorithm to detect anomalous signals," FORMA, vol.21 (2), pp.159-167, 2006.

[25] T. Nishihara, H. Tahara, "Apparatus for recovering eyesight utilizing stereoscopic video and method for displaying stereoscopic video," US Patent 7404639, 2008

[26] J. Suzuki, T. Matsunaga, K. Tokumatsu, K. Taguchi, Y. Watanabe, "Q&A and a manual in Stabilometry," Equilibrium Res., vol.55(1), pp.64-77, 1996.

[27] H. Takada, Y. Kitaoka, S. Ichikawa, M. Miyao, "Physical Meaning on Geometrical Index for Stabilometly," Equilibrium Res., vol.62(3), pp.168-180, 2003.

[28] R. Wayland, D. Bromley, D. Pickett, A. Passamante, "Recognizing determinism in a time series," Phys. Rev. Lett., vol.70, pp.530–582, 1993.

[29] H. Takada, K. Fujikake, T. Watanabe, S. Hasegawa, M. Omori, M. Miyao, "On a method to evaluate motion sickness induced by stereoscopic images on HMD," Proceedings of the IS&T/SPIE 21st Annual Symposium on Electronic Imaging Science and Technology, pp.72371P-1 2009.

[30] T. Matsumoto, R. Tokunaga, T. Miyano, I. Tokuda, "Chaos and Time Series," Tokyo: Baihukan, 2002, pp.49–64 [in Japanese].

[31] H. Takada, Y. Shimizu, H. Hoshina, Y. Shiozawa, "Wayland tests for differenced time series could evaluate degrees of visible determinism," Bulletin of Society for Science on Form, vol.17(3), pp.301-310, 2005.