Evaluation of Body Sway and the Relevant Dynamics While Viewing a Three-Dimensional Movie on a Head-Mounted Display by Using Stabilograms

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Abstract. The viewers of three-dimensional (3D) movies often complain of blurring and bleeding. They sometimes experience visually induced motion sickness (VIMS). In this study, the effect of VIMS on body sway was examined using stabilograms. We measured the sway in the center of gravity before and during the exposure to images projected on a head-mounted display (HMD). While viewing, the subjects were instructed to remain in the Romberg posture for the first 60 seconds and maintain a wide stance (midline of the heels, 20 cm apart) for the next 60 seconds. Employing Double-Wayland algorithm, we measured the degree of determinism in the dynamics of the sway in the center of gravity with respect to viewing 3D movies on HMD. As a result, the dynamics of the sway during and before the exposure was considered to be stochastic. Thus, exposure to 3D movies would not change the dynamics to a deterministic one.

Keywords: Three-dimensional (3D) movie, Visually induced motion sickness, Stabilogram, Degree of determinism, Double-Wayland algorithm.

1 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].

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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 V(x), the (temporal averaged) potential function, in the stochastic differential equation (SDE), which has been considered as a mathematical model of the sway:

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

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 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 [8]. Recent studies suggest that maintaining postural stability is one of the major goals of animals, [9] and that they experience sickness symptoms in circumstances where they have not acquired strategies to maintain their balance [10]. 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 [10]–[12]. Stoffregen and Smart (1999) report that the onset of motion sickness may be preceded by significant increases in postural sway [13].

The equilibrium function in humans deteriorates when viewing 3-dimensional (3D) movies [14]. 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 [15]. Thus, stereoscopic images have been devised to reduce this disagreement [16]–[17].

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 [18]. The SSQ is used herein for verifying the occurrence of VIMS. The following parameters of autonomic nervous activity is appropriate for the physiological method: heart rate variability, blood pressure, electrogastrography, and galvanic skin reaction [19]–[21]. 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 [22]. We wondered if noise terms vanished from the mathematical model (SDEs) of the body sway. Using our Double-Wayland algorithm [23], 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 [14]. Sparse density (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 HMD.

2 Material and Methods

Ten healthy subjects (age, 23.6 ± 2.2 years) voluntarily participated in the study. All of them were Japanese and lived in Nagoya and its surroundings. They provided informed consent prior to participation. The following subjects were excluded from the study: subjects working the night shift, those dependent on alcohol, those who consumed alcohol and caffeine-containing beverages after waking up and less than 2 h after meals, those who had been using prescribed drugs, and those who may have had any otorhinolaryngologic or neurological disease in the past (except for conductive hearing impairment, which is commonly found in the elderly). In addition, the subjects must have experienced motion sickness at some time during their lives.

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. All subjects were tested from 10 a.m. to 5 p.m. in the room. The subjects wore an HMD (iWear AV920; Vuzix Co. Ltd.) on which 3 kinds of images were presented in random order: (I) a visual target (circle) whose diameter was 3 cm; (II) a conventional 3D movie that shows a sphere approaching and moving away from subjects irregularly; and (III) a new 3D movie that shows the same sphere motion as that shown in (II). The last movie was created using the Olympus power 3D method [24].

2.1 Experimental Procedure

The subjects stood without moving on the detection stand of a stabilometer (G5500; Anima Co. Ltd.) in the Romberg posture with their feet together 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 HMD from the beginning till the end. The SSQ was filled before and after stabilometry.

2.2 Calculation Procedure

We calculated several indices that are commonly used in the clinical field [25] 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” [26] and the translation error [27] were also estimated.

3 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 images (II). In addition, the scores after exposure to the new 3D images were not very different from those after exposure to the static ones (I). Although there were large individual differences, sickness symptoms seemed 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, 1e). 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).

Representative results of the Double-Wayland algorithm are shown in Fig. 2. 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.

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 of chain, a main effect was seen in the both factors (Fig. 3).

Table 1. Subscales of the SSQ after exposure to 3D movies [28]

Movies	(II)	(III)
N	11.4±3.7	10.5±4.4
OD	18.2±4.1	17.4±4.9
D	23.7±8.8	19.5±6.6
TS	19.8±5.3	18.0±4.9

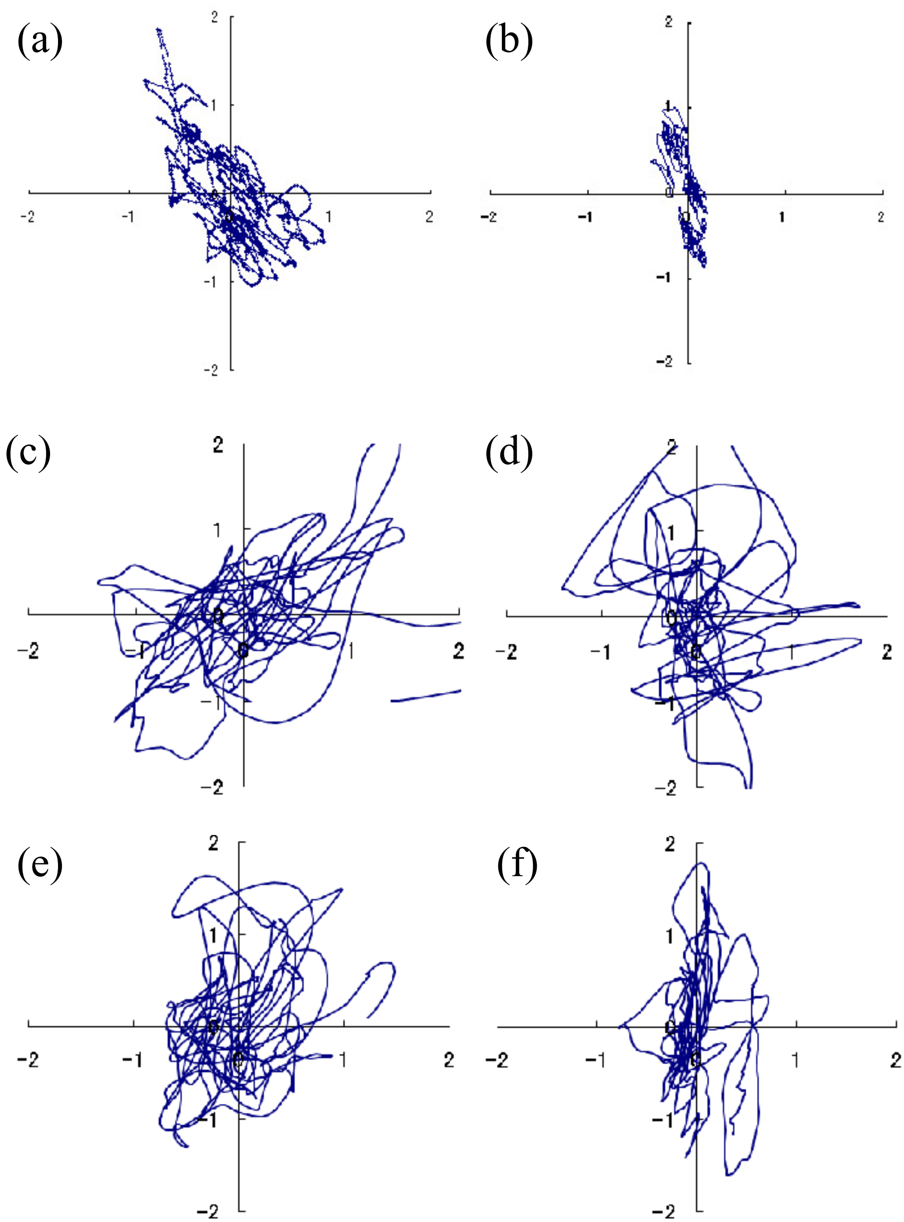

Fig. 1. Typical stabilograms observed when subjects viewed a static circle (a)–(b), the conventional 3D movie (c)–(d), and the new stereoscopic movie (e)–(f) [28]

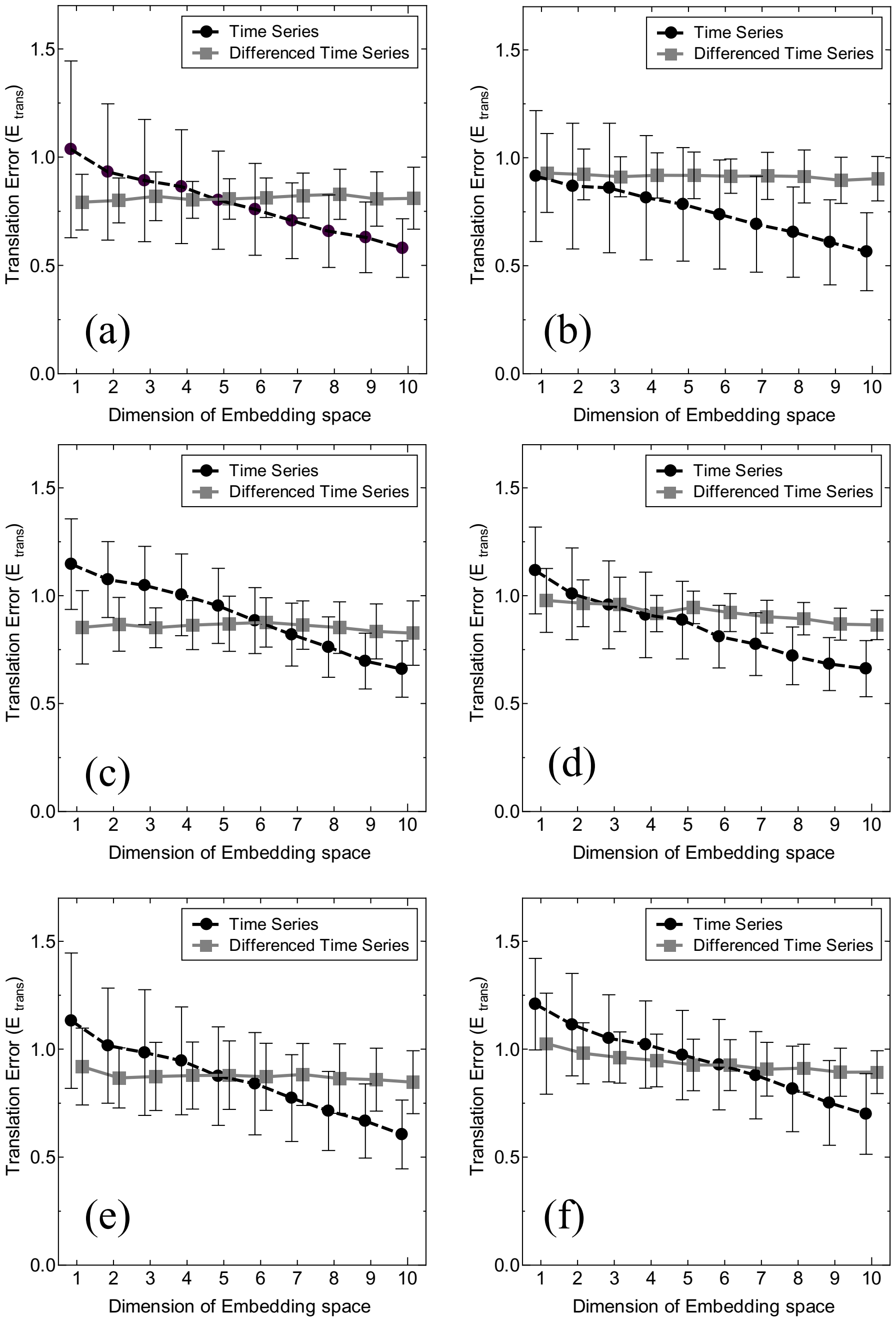

Fig. 2. Mean translation error for each embedding space. Translation errors were estimated from stabilograms that were observed when subjects viewed a static circle (a)–(b), the conventional 3D movie (c)–(d), and the new stereoscopic movie (e)–(f).

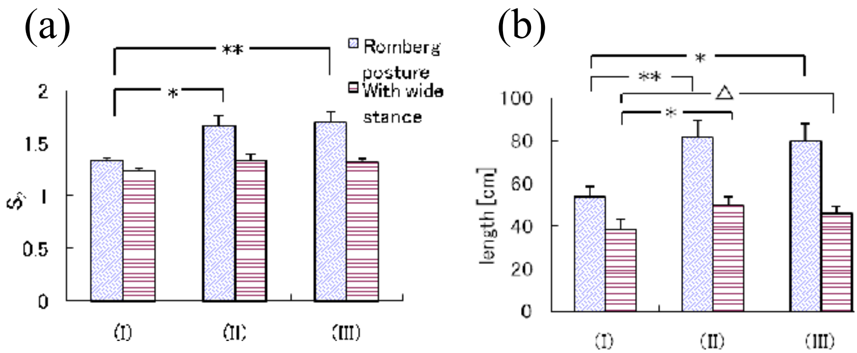

Fig. 3. Typical results of the two-way ANOVA with repeated measures for indicators [28]; the total locus length (a), the SPD (b)

4 Discussion

A theory has been proposed to obtain SDEs as a mathematical model of the body sway on the basis of the stabilogram.

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), which implies that the time series could be generated by a stochastic process in accordance with a previous standard [29]. 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 [30]. 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 conventional 3D movie (II) and the new 3D movie (III).

The anterior-posterior direction y was considered to be independent of the medial-lateral direction x [31]. 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]. Pseudorandom numbers were generated by the 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 minimal points [7]. 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. Although, stereoscopic movies decrease the gradient of the potential function, the new 3D movie (III) 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 HMD screen. We have succeeded in estimating the decrease in the gradient of the potential function by using the SPD by performing a one-way analysis of variance.

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. The same calculation results were also obtained for S_3. 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 [22], whereas, in our study, the degree of sway was found to be reduced significantly when the subjects stood with their feet wide apart than when they stood with their feet close together (Romberg posture). However, the total locus length during exposure to the conventional stereoscopic movie was significantly larger than that during exposure to the control image when they stood with their feet wide apart. As shown in Fig. 1d, 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 conventional 3D movie (II) was significantly greater than that during exposure to the control image (Fig. 3b). Moreover, the total locus length of chain tended to increase when subjects were exposed to the conventional 3D images (II) compared that when they were exposed to (I). Hence, we noted postural instability with the exposure to the conventional stereoscopic images (II) by using these indicators involved in the stabilogram (total locus length and that of chain). This instability might be reduced by the Olympus power 3D method.

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