Multi-evaluation Method of Visual Fatigue and Motion Sickness While Viewing 2D/3D Video Clips on a Liquid Crystal Display

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Abstract. It is physiologically known that the vestibular system and the autonomic nervous system interact with each other. The motion sickness can affect both these systems, and severity of the motion sickness is expected to be measured by dysfunction of the equilibrium system. We have proposed a new index, sparse density (SPD), of stationary stabilograms for detecting the metamorphism in the (temporally averaged) potential function of stochastic differential equations, which occurs when a human attempts to maintain an upright posture. 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. Subjects in a standing position were stimulated by a movie scrolling from left to right on a liquid crystal display (LCD) in measurement 1 and a stereoscopic video clip on an LCD in measurement 2. 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 metamorphism in the potential function during exposure to blurred images and a stereoscopic video clip could be detected by using the SPD.

Keywords: Visual Fatigue, Visually Induced Motion Sickness (VIMS), Blurred Images, Stereoscopic Images, Stabilometry.

1 Introduction

The human standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism [1]. 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]. Even when a young, healthy individual attempts to stand still, the centre of gravity of his/her body and the centre of pressure (COP) under his/her feet move relative to a global coordinate system [3], which is induced by the complex sensorimotor control system. A plot of time-varying coordinates of the COP is known as a stabilogram.

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The COP could be measured in accordance with stabilometry in which many of the earlier studies limited the analysis of the plots to summary statistics, i.e., calculation of the length of sway path, average radial area, etc. [3].

With respect to the body sway, the anterior-posterior direction y was considered to be independent of the mediallateral direction x [4]. Stochastic differential equations (SDEs) forced by white noise w_z on the Euclid space $\mathbf{E}^2 \ni (x, y)$

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x} U_x + w_x(t) \tag{1}$$

$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y} U_y + w_y(t) \tag{2}$$

have been proposed as mathematical models that generate stationary stabilograms for z = x, y [3],[5]-[7]. Based on the Stratonovich's rule, a correspondence has been obtained between their temporally averaged potential functions U_z and distributions of the time series G_z as follows [7];

$$U_z = -\frac{1}{2} \ln G_z + const \cdot \tag{3}$$

Due to the nonlinear SDEs constructed from the stabilograms, the potential functions Ux, Uy 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.

Motion sickness brings about abnormality in the stabilograms. Stoffregen and Smart argued that motion sickness is not caused by sensory conflict, but by postural instability [8], although the most widely known theory of motion sickness is based on the concept of sensory conflict [9]. The blurred images on the LCDs sometimes induced "image sickness" in viewers, which is an unpleasant feeling that is similar to the motion sickness. Significant increases in the postural sway were observed during the image sickness induced by simulator [8]. On the other hand, optokinetic stimulation is known to trigger motion sickness [10]. In particular, anterior displacement of the COP remarkably increased during the body sway when random dots were rotated vertically at a speed of 40-60 deg/s as optokinetic stimulation to the subjects. The conventional LCD would aggravate symptom of the motion sickness. Furthermore, the equilibrium function in humans deteriorates when viewing three-dimensional (3D) video clips [12]. A disagreement between convergence and visual accommodation has been pointed out as a cause of this visually induced motion sickness (VIMS) while viewing 3D video clips.

As mentioned above, most of previous investigations ignored the dynamic characteristics of stabilograms. Using our Double-Wayland algorithm [11], [12], we herein examine hypothesis that the VIMS was occurred by viewing blurred images on the conventional LCD and a stereoscopic video clip, and the postural control system might drastically change by the VIMS.

2 Material and Methods

The objective and contents of the study and consideration of protection of personal information were explained to all subjects before the experiment, and written informed consent was obtained. The measurement was performed in a dimly lit room (about 260 lx) air-conditioned at 25°C.

The subjects stood without moving on the detection stand of a stabilometer (G5500, Anima Co., Ltd.) in the Romberg posture [13] with their feet together for 1 min before the sway was recorded. A centre of pressure (COP) was measured as a projection of the centre of gravity on to a force plate. Each sway of the COP was then recorded with a sampling frequency of 20 Hz. With regard to each component of the stabilograms, translation errors E_{trans} [14] in the following states were estimated in m dimensional embedding space ($1 \leq m \leq 10$) by the Double-Wayland algorithm [11], [12]. In addition, we calculated indices for stabilograms such as "total locus length [13]" and "SPD [15]". Statistical comparison was employed by the Wilcoxon matched-pair signed-rank test in which the level of significance was set to be 0.05.

2.1 Measurement 1

The test subjects were six persons from 20 to 27 years of age with no history of equilibrium function problems. The subjects first stood with their eyes open for 1 min (resting state); they then viewed a moving map on a 32-inch display of the previous model with a contrast ratio of 600:1 for the next 1 min (testing state).

The map of a fictitious city was scrolled from left to right (or right to left). The subjects had to read the name of a place from the moving map as a moving map task. The scroll speed of the moving map was 20 dots/s. The viewing distance was 1 m.

2.2 Measurement 2

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. They provided informed consent prior to participation. The following subjects were excluded from the study: subjects working in the night shift, those dependent on alcohol, those who consumed alcohol and caffeine-containing beverages after waking up and less than 2 hours after meals, those who had been using prescribed drugs, and those who may have had any otorhinolaryngologic or neurological diseases 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. The subjects stood without moving on a detection stand of a stabilometer (G5500; Anima Co. Ltd.) with their feet together. Two kinds of stimuli were presented in random order: (I) a static circle with a diameter of 3 cm (resting state); and (II) a conventional 3D video clip that showed a sphere approaching and moving away from the subjects, irregularly (Olympus Memory Works Co. Ltd.). Stimuli (I) and (II) were presented on an LCD monitor (S1911- SABK, NANAO Co., Ltd.). The distance between the LCD and the subjects was 57 cm. The subjects viewed one of the video clips, i.e., (I) or (II) from the beginning until the end. The SSQ was filled before and after stabilometry.

3 Results

3.1 Measurement 1

A stabilogram shows the result when a subject viewed the conventional LCD. The amplitudes of the sway as well as the right-left movement tended to be larger when the subjects viewed the display than when they were in the resting state (RS).

We statistically compared the RS among the testing states using the values of the indices that were used to evaluate the stabilograms (Fig. 1). It was found that the values of indices were significantly larger when the subjects viewed the display of the previous model than when they were in the RS ($p<0.05$). These statistical results indicated that visually induced motion sickness was affected by the display of the previous model.

Most E_{trans} values estimated by the Double-Wayland algorithm [11], [12] were larger than 0.5 for each embedding space. There appeared to be no differences between the E_{trans} values derived from the time series data of the lateral and anterior/posterior directions. $0.8 \leq E_{trans} \leq 1$ was obtained from the temporal differences of these time series.

3.2 Measurement 2

After the exposure to a 3D video clip (II), scores for SSQ-N (nausea), SSQ-OD (eyestrain), SSQ-D (disorientation), and SSQ-TS (total score) were 8.6 ± 2.6, 17.4 ±

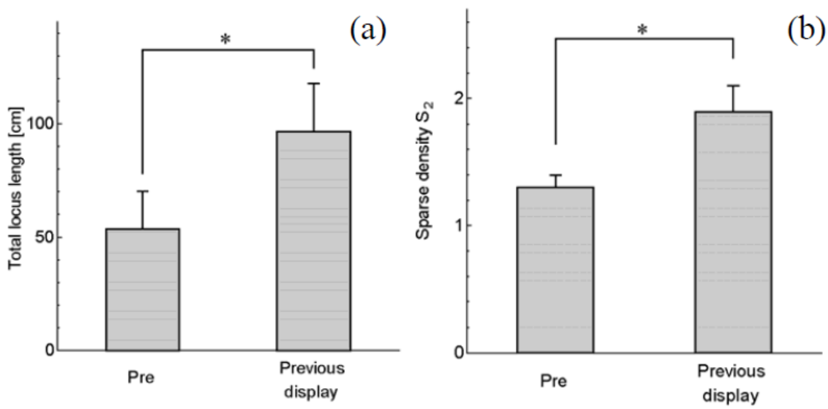

Fig. 1. The sway value in the RS (Pre) was compared with that in the testing states (Previous display). Using indices that evaluated the stabilograms: (a) total locus length and (b) SPD S_2.

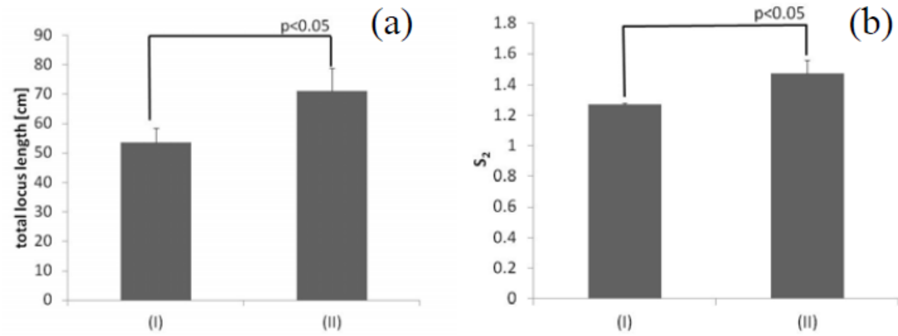

Fig. 2. The sway value in the RS (I) was compared with that in the testing states (II). Using indices that evaluated the stabilograms: (a) total locus length and (b) SPD S_2.

3.4, 16.7 ± 6.2, and 16.4 ± 3.7, respectively. Sickness symptoms seemed to appear with the exposure to the stereoscopic video clips although there were large individual differences. However, increases were seen in the scores for SSQ-N and SSQ-D after exposure to the 3D video clips (II).

Whether subjects was exposed to the 3D video clips 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 video clips.

According to the Wilcoxon matched-pair signed-rank test, indices of stabilograms were enhanced significantly by exposure to a stereoscopic video clips as shown in Fig. 2 ($p<0.05$). The variation in the SPD was remarkably lower than the other indices Fig. 2b.

4 Discussion

A theory has been proposed to obtain SDEs as a mathematical model of the body sway on the basis of the stabilogram. Multiple comparisons indicated that the SPD S2 during exposure to the stereoscopic video clip was significantly larger than that during exposure to the static control image (I) when subjects stood in the Romberg posture. The standing posture would become unstable because of the effects of the blurred movie and a stereoscopic video clip. As mentioned above, structural changes occur in the time-averaged potential function (3) with exposure to the video clips, which are assumed to reflect the sway in center of gravity.

The following SDE could be obtained approximately as a mathematical model for the motion process with substituting an optimal regression polynomial for the first form of the right hand side on Eq. (2)

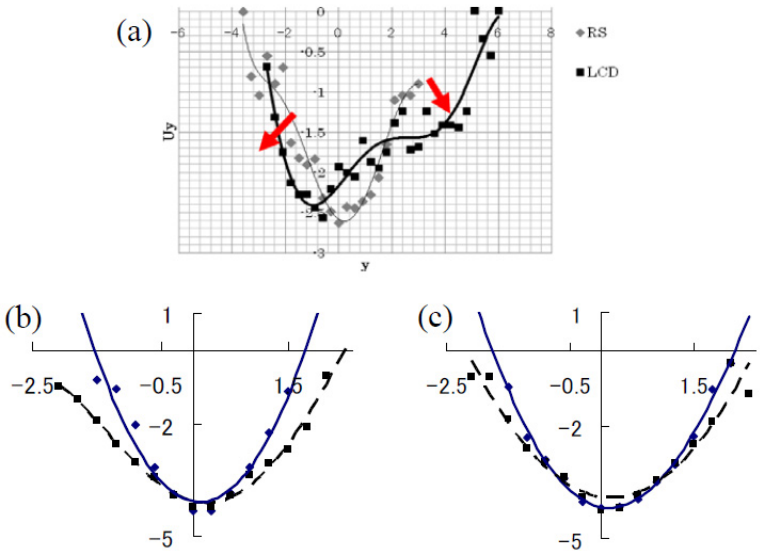

Fig. 3. Typical examples of temporally averaged potential functions. The potential functions are constructed from an anterior/posterior component of the stabilograms in the measurement 1 (a), a lateral component of the stabilograms in the measurement 2 (b), and an anterior/posterior component of the stabilograms in the measurement 2 (c).

$$\frac{dz}{dt} = \frac{1}{2}\sum_{k=1}^{n} k a_k z^{k-1} + W_z(t) \tag{3}$$

a_k are estimated as regression coefficient of the optimal polynomial of degree k (natural numbers) by the least square method (z = x, y). The coefficient of determination R^2 can be estimated to evaluate each regression. The value R^2 shows the suitability for the regression curve and the relative importance on correlations of different magnitudes. The value 0.9 seems to be sufficiently large as a coefficient of determination R^2 because the correlation coefficient R attains to 0.95. Constructing the nonlinear SDEs from the individual stabilograms in accordance with Eq. (2), their temporally averaged potential functions U_x, U_y have plural minimal points (Fig. 3a). However, a parabolic function is appropriate for the potential which are derived from all subjects' distribution when the subjects viewed a static image (◆) and blurred images on a conventional LCD (■) (Fig. 3b-3c). The total locus length was increased during the exposure to the video clips, which might be caused by the diminution of the gradient in the bottom of the parabolic potential function (Fig. 3). We herein note that it is important to focus on form of the potential function. We have also succeeded in estimating the decrease in the gradient of the potential function by using the SPD.

Information from the vision, vestibule, and somatosensory regions is managed at the centriciput in order to prevent falling down. The most widely known theory of motion sickness is based on the concept of sensory conflict [9]. It was reported that the onset of motion sickness may be preceded by significant increases in postural sway [8]. Instability in the standing posture can also occur due to anomalous eyesight, which exhibits some patterns in stabilograms.

In order to evaluate display devices, a geostationary image and characters were generally used in previous studies [17]-[19]. We have proposed a new method for comparing the standing posture when a subject gazes at an LCD displaying a movie scrolling from the left to the right [20]. By using a stabilometer, a newly developed LCD was also compared with a conventional LCD. In the next step, we should quantitatively investigate effects of a background moving from the left to right without any utilization of a display on the body sway. However, the moving pictures were rotated horizontally at a speed of 25 deg/s or less, which was considered to be sufficiently small optokinetic stimulation. The speed was regarded as half of the maximum speed in order to follow smooth eye movements; therefore, the standing posture would be controlled by a mechanism regardless of whether or not the subjects viewed the moving pictures. This speculation was substantiated by the results in the translation errors.

In the measurement 1, we measured the degree of determinism in the dynamics of the sway of COP. The Double-Wayland algorithm was used as a novel method. $E_{trans} \geq 0.5$ was obtained by the Wayland algorithm, which implies that the time series could be generated by a stochastic process in accordance with a previous standard [21]. The threshold 0.5 is half of the translation error resulting from a random walk. We physiologically consider that the stochastic process to control standing posture originates in kinociliums leaning toward random direction in an otolithic organ.

The translation errors obtained from the subjects viewing the displays were similar to those of subjects in the RS. Moreover, the body sway has been described previously by a stochastic process [3], [6]-[8], which was shown with the Double-Wayland algorithm [11]. $0.8 \leq E_{trans} \leq 1$ obtained from the temporal differences of these time series exceeded the translation errors estimated by the Wayland algorithm. However, it was similar to the latter, except for the RS, which agreed with the abovementioned dynamics to control a standing posture [12]. Knowing that the degree of deter-minism is unchanged, the postural control system can be regarded as a stationary process. Based on this result, we can obtain an assurance of the premise in the time series analysis for stabilograms.

The moving map task would not change it into a deterministic one. Mechanical variations were not observed in the lateral locomotion of the COP. The moving map task was thus regarded as an appropriate stimulus to evaluate the displays. By using several indices for the form of stabilograms [13], [15], some LCDs could be ranked hierarchically [20]. The indices might reflect the coefficients in stochastic processes although the translation error did not exhibit a significant difference between the RS and the conventional LCD. The total locus length during exposure to blurred images was significantly greater than that in the RS. We considered that the blurred images on the conventional LCD decrease the gradient of the potential function. Moreover, we concluded that the metamorphism in the potential function during exposure to the blurred images could be detected by using the SPD.

The moving map task was thus regarded as an appropriate stimulus to evaluate the displays. Some indices for the form of stabilograms are useful for evaluating the LCD displaying the movie. We conclude that our method, where a subject views an LCD displaying a scrolling movie, was effective in evaluating the characteristics of movies being displayed on LCDs.

In the measurement 2, the total locus length and the SPD during exposure to the 3D video clip (II) were significantly greater than that during exposure to the control image (I). We herein noted postural instability with the exposure to the stereoscopic video clips (II) by using the indicators involved in the stabilogram (SPD and total locus length).

5 Conclusion

We quantitatively measured the body sway before and during exposure to 2D and 3D video clips in the measurement 1 and the measurement 2, respectively. For the SSQ sub-scores and each index for stabilograms, we employed the non-parametric test. Moreover, we discussed the metamorphism in the potential functions to control the standing posture during the exposure to video clips. As a result, the system to control the standing posture during exposure to the video clips on an LCD was more instable than that of the RS. Further studies are planned with an increasing number of cases.

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