On a Qualitative Method to Evaluate Motion Sickness Induced by Stereoscopic Images on Liquid Crystal Displays

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Abstract. Visually induced motion sickness (VIMS) is known to be caused by sensory conflict, which is the disagreement between vergence and visual accommodation while observing stereoscopic images. The simulator sickness questionnaire (SSQ) is a well-known method that is used herein for verifying the occurrence of VIMS. We quantitatively measure the sway of the centre of gravity of the human body before and during exposure to several images. During the measurement, subjects are instructed to maintain the Romberg posture for the first 60 s and a wide stance (midlines of the heels 20 cm apart) for the next 60 s. The stereoscopic images decrease the gradient of the potential function involved in the stochastic differential equations as a mathematical model of the body sway. We have succeeded in estimating the decrease in the gradient by using an index called sparse density.

Keywords: stabilometry, Simulator Sickness Questionnair, sparse density, stochastic differential equation, potential.

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, centred in the nucleus ruber, is essential. Sensory receptors such as visual inputs, auditory and vestibular functions and proprioceptive inputs from the skin, muscles and joints are the inputs to 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 equilibrial function both qualitatively and quantitatively. A projection of a subject's centre of gravity onto a detection stand is measured as an average of the centre of pressure of both feet (COP). The COP is traced for each time step, and the time series of the projections is traced on an xy-plane. By connecting the temporally vicinal points, a stabilogram is composed. Several parameters such as the area of sway (A), total locus length (L) and locus

R. Shumaker (Ed.): Virtual and Mixed Reality, LNCS 5622, pp. 254–262, 2009.

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 to evaluate the function of proprioceptive control of standing in human beings. However, it is difficult to clinically diagnose disorders of the sense of balance function and to identify the declines in equilibrial function by utilizing the abovementioned indices and measuring patterns in the stabilogram. Large interindividual differences might make it difficult to understand the results in 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 one for our research. G(x), the distribution of the observed points x, has the following correspondence with V(x), the (temporal averaged) potential function, in the stochastic differential equation (SDE) 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, the SDE shows local stable movement with a high-frequency component. 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 explaining 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 observing 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 observing 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 physiological method for measuring the extent of motion sickness [18]. The SSQ is used herein for verifying the occurrence of VIMS. The physiological methods measures autonomic nervous activity: 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 at 17 cm or 30 cm apart) significantly increases total locus length in stabilograms of the high SSQ score group, while the low score group is less affected by such a stance [22].

This study proposes 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 (Appendix). In this study, we show that reduction of body sway can be evaluated by the SPD during exposure to 3D movies on a Liquid Crystal Display (LCD).

2 Material and Methods

Ten healthy subjects (23.6 ± 2.2 year) voluntarily participated in the study. All of them were Japanese and lived in Nagoya and its surroundings. The subjects gave their informed consent prior to participation. The following were the exclusion criteria for subjects: subjects working the night shift, subjects with dependence on alcohol, subjects who consumed alcohol and caffeine-containing beverages after waking up and less than two hours after meals, and subjects 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 not have been using any prescribed drugs.

Fig. 1. A scene in the movie [23]

Fig. 2. The setup of the experiment [23]

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 am to 5 pm in the room. 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 (Fig. 1): (I) a 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). The new stereoscopic images (II) were constructed by Olympus Power 3D method. The distance between the wall and the subjects was 57 cm (Fig. 2).

2.1 Stabilometry

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 with a sampling frequency of 20 Hz during exposure to one of the images. The subjects viewed a movie (image) on the LCD from beginning to end. SSQ was employed before and after this stabilometry.

2.2 Calculation Procedure

We calculated several indices that are commonly used in the clinical field [24] 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" and "total locus length of chain" [25] were also estimated (Appendix).

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 (III). In addition, the scores after exposure to the new 3D images (II) 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. 3. 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. 3c–3f) tended to be larger than those of the control sway (Fig. 3a–3b). Although a high density of COP was observed in the stabilograms (Fig. 3a–3d), the density decreased in stabilograms during exposure to the conventional stereoscopic movie (Fig. 3e–3f). Furthermore, stabilograms measured in an open leg posture with the midlines of heels 20 cm apart (Fig. 3b, 3e, 3f) were compared with stabilograms measured in the Romberg posture (Fig. 3a, 3c, 3e). COP was not isotropically dispersed but characterized by much movement in the anterior-posterior (y) direction (Fig. 3b, 3d). Although this trend is seen in Fig. 3f, 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. 3a).

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

Movies	(II)	(III)
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

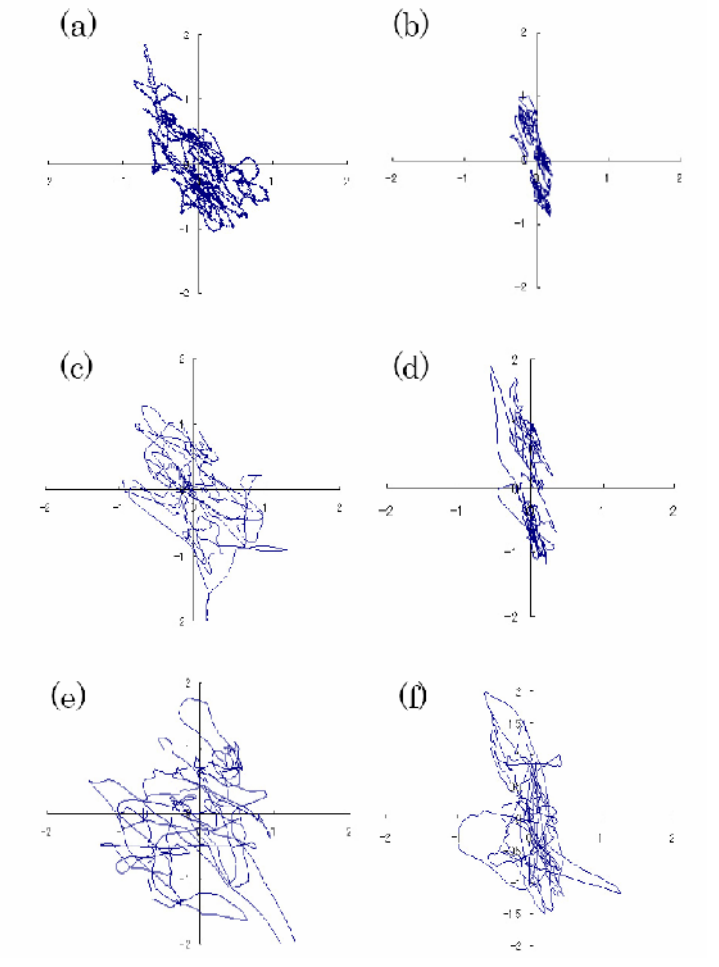

Fig. 3. Typical stabilograms observed when subjects viewed a static circle (a)–(b), the new stereoscopic movie (c)–(d), and the conventional 3D movie (e)–(f)

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 ($p < 0.01$).

4 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

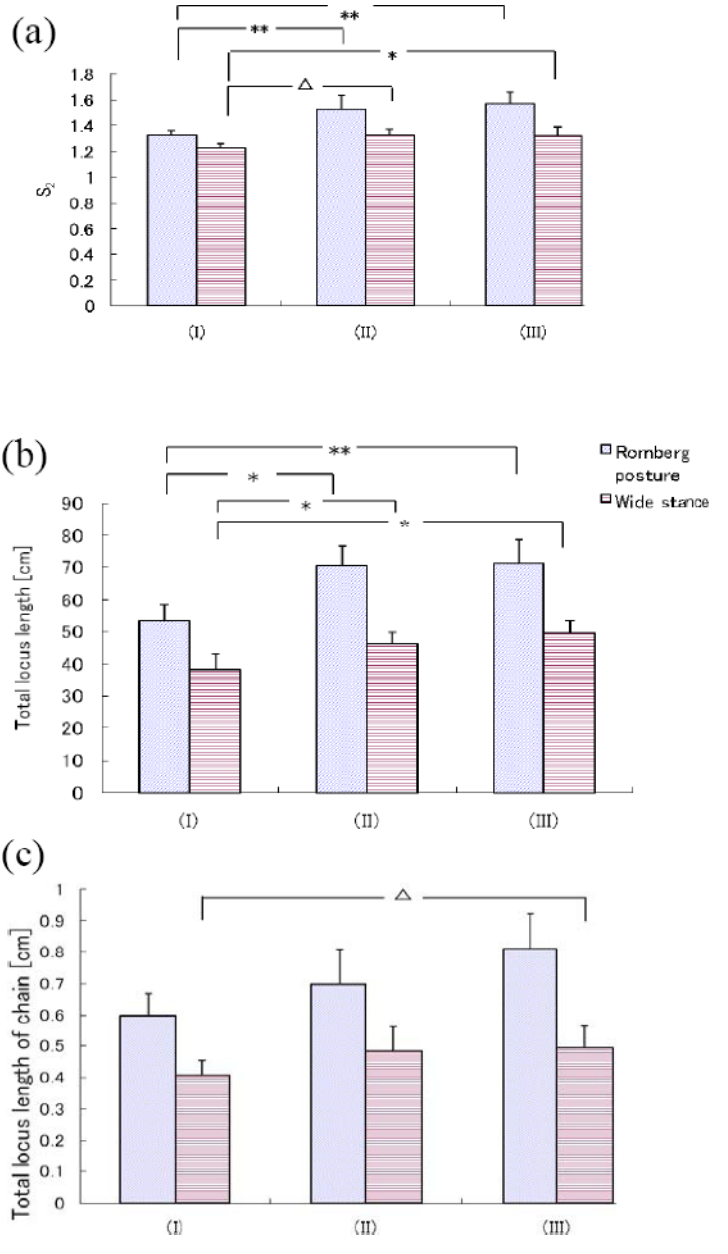

Fig. 4. Typical results of the two-way ANOVA with repeated measures for indicators [27]; the total locus length (a), the SPD (b), and the total locus length of chain (c) (**$p < 0.01$,*$p < 0.05$)

minimal points of the time-averaged potential function in the SDEs (Fig. 3). 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 ($p<0.05$).

Multiple comparison 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 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 when the subjects stood with their feet wide apart (Fig.3b, 3d, 3f) than when they stood with their feet close together (Fig.3a, 3c, 3e). As shown in Fig. 3d and 3f, 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.

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Appendix

Here, we describe the new quantification indices—SPD and total locus length of chain [25].

A Sparse density

SPD was defined by an average of the ratio $G_j(1)/G_j(k)$ for j = 3, 4, ..., 20, where $G_j(k)$ is the number of divisions having more than k measured points; a stabilogram was divided into quadrants whose latus was j times longer than the resolution. If the center of gravity is stationary, the SPD value becomes 1. If there are variations in the stabilograms, the SPD value becomes greater than 1. Thus, SPD depends on the characteristics of the stabilogram and the shift in the COP.

B Chain

The force acting on the center of gravity of the body was defined in terms of the difference in the displacement vectors. In particular, we focussed on singular points at which statistically large forces were exerted. On the basis of these forces, chains were eliminated from the stabilogram in the form of a consecutive time series. If the times measured at these points were in the temporal vicinity, these points were connected by segments (sequences). Figures formed by these sequences were called “chains” because of the shape of the connections. The figures of the sequences of points at which large forces were exerted show that the chain had a cusp pattern.