Indices to Detect Visually Induced Motion Sickness Using Stabilometry

Hiroki Takada[1], Kazuhiro Fujikake[2], Masaru Miyao[2] and Yasuyuki Matsuura[3]

[1] Gifu University of Medical Science, 795-1 Ichihiraga Nagamine, Seki, Gifu 501-3892, Japan

[2] Graduate School of Information Science, Nagoya University, Chikusa, Nagoya 464-8601, Japan

[3] Graduate School of Natural Sciences, Nagoya City University, Mizuho, Nagoya 467-8501, Japan

[1] takada@u-gifu-ms.ac.jp, [2] miyao@itc.nagoya-u.ac.jp, [3] y.matsuura@nsc.nagoya-cu.ac.jp

Keywords: Stabilometry. Statokinesigram (SKG). Sparse density (SPD). Chain 2 (CH2).

Abstract. We measured the sway in the body's centre of gravity (stabilometry) in 49 healthy men and women aged between 19 and 74 years while they stood in Romberg's posture and watched a three-dimensional (3-D) movie of a roller coaster ride. Measurements were made under several conditions such as the presence or absence of sound. We propose a method for evaluating the reality of 3-D images and sound using stabilometry. Increased peculiar patterns were observed in the statokinesigrams (SKGs) of subjects who perceived 3-D images as sensory information. Since these patterns comprised a partial trajectory with a cusp, they could be extracted by composing partial sequences in which the acceleration vectors were larger than a certain threshold value. Using these patterns, we attempted to evaluate the effect of a 3-D movie with stereo sound on the equilibrial function.

Introduction

In humans, the standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism called the 'righting reflex' (Okawa *et al.*, 1995). In order to maintain the standing posture in the absence of locomotion, the righting reflex that is centered 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 required for the body's balance function (Kaga 1992). Evaluating this function is indispensable for diagnosing equilibrium disturbances such as cerebellar degenerations, basal ganglia disorders, or Parkinson's disease in patients (Okawa *et al.*, 1996).

Stabilometry has been employed to evaluate the equilibrial function both qualitatively and quantitatively. A projection of a subject's centre of gravity onto a detection stand is measured as the 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 statokinesigram (SKG) is obtained, as shown in Figure 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 quantify the instability involved in the standing posture; these parameters are widely used in clinical studies. It has been revealed that the last parameter, in particular, depends on the fine variations involved in posture control (Okawa *et al.*, 1995).

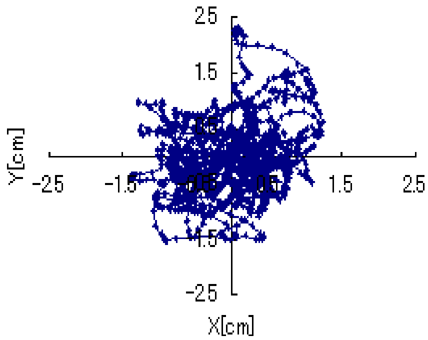

Figure 1. An SKG of a subject who watched the 3-D movies with stereo sound.

Therefore, this index is regarded as a gauge to evaluate the function of proprioceptive control of standing in human beings. However, it is difficult to diagnose disorders of the sense of the balance function and to identify declines in the equilibrial function clinically by using the abovementioned indices to measure SKG patterns. Large inter-individual differences might make understanding the results relatively difficult.

Mathematically, the sway in the COP is described by a stochastic process (Collins *et al.*, 1993; Emmerik *et al.*, 1993, Newell *et al.*, 1997). We examined the adequacy of using a stochastic differential equation and investigated the most suitable 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) used as a mathematical model of the sway:

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

The non-linear property of SDEs is important (Takada *et al.*, 2001). The potential curved surface has multiple minimal points. In the neighbourhood of these points, the SDE shows stable local movement with a high-frequency component, and therefore, we can expect a high density of observed points in the neighbourhood on the SKG.

Figure 2. A scene from a high place on a jet coaster.

The analysis of SKGs is useful not only for medical diagnosis but also for explaining the control of upright standing of two-legged robots and for preventing falls in the elderly (Fujiwara *et al.*, 1993). Recent studies (Stoffregen *et al.*, 2000) suggested that maintaining postural stability is one of the major goals of animals and that they experience sickness symptoms in circumstances where they have not acquired strategies to maintain their balance (Riccio & Stoffregen, 1993). They argued that motion sickness is caused not by sensory conflict but by postural instability, although the most widely known theory of motion sickness is based on the concept of sensory conflict (Oman, 1982; Reason, 1978; Stoffregen & Riccio, 1993). Stoffregen and Smart (1999) reported that the onset of motion sickness may be preceded by significant increases in postural sway.

We consider that the equilibrial function in humans deteriorates with visual inputs such as three-dimensional (3-D) movies. A disagreement between the visual inputs and proprioceptive inputs can also be induced by 3-D movies. If the movies are accompanied by a sense of reality, we can expect a physiological reaction (PR) that does not appear usually. In this study, we attempt to observe if this PR is reflected in the sway of COP. We assumed that the locally dense points mentioned above might decrease. In this study, we propose a method to measure the effect of 3-D images and stereo sound on the equilibrial function.

Materials and Methods

Stabilometry. In order to evaluate the effect of 3-D movies and stereo sound on the equilibrial function, we prepared the following 4 types of movies: (a) 2-D movie (ordinal one), (b) 2-D movie with stereo sound, (c) 3-D movie, and (d) 3-D movie with stereo sound. These movies were 66 sec in length, and were repeat scenes of a roller caster ride in Six Flags, an amusement park in Los Angeles; the movie was produced by 3DTV Company (Figure 2)., We projected (a), (b), (c), and (d) in an irregular order on an 80-inch silver screen at a distance of 3 m from the video projectors (DLA-G10) offered by LET'S Corporation. The 3-D effect comprised linear polarized lights in the horizontal and vertical directions. The movies were displayed to healthy subjects standing in Romberg's posture, and we obtained electrocardiograms (ECG) and measured the sway in the body's COP (stabilometry) in 49 healthy men and women (30 M and 19 F) aged between 19 and 74 years. The COP was measured every 0.05 s with the force plate system (DKH Company) in which a Kistler force plate was employed. The subjects wore polarized 3-D glasses (90 degree linear polarization) when viewing the 3-D images.

Indices measuring patterns of the SKG. Sparse density (SPD), an analytical index in the SKG, was added to the previous indices such as A and L/A. The SKG was divided into quadrates, the latus of which was j times longer than the resolution. The SPD was defined by a scaling average of the ratio $F_j(1)/F_j(k)$ as follows:

Table 1. Factors in two-way ANOVA

Factors		The number of dimensions of the movie	
		2	3
The presence or absence of stereo sound	Absence	(A_1, B_1)	(A_1, B_2)
	Presence	(A_2, B_1)	(A_2, B_2)

$$SPD = \frac{1}{18}\sum_{j=3}^{20}\frac{F_j(1)}{F_j(k)}, \tag{2}$$

Where $F_j(k)$ denotes the number of divisions that include more than k measured points. If the pattern of the SKG was dispersed, the value of Eq.(1) was large; otherwise, this ratio converged to 1. The SPD (1) might increase to a value that is considerably larger than 1 if a disagreement between the visual inputs and proprioceptive inputs was induced by the effect of the 3-D images or stereo sound.

Statistics. We calculated the values of A, L/A, and the SPD S_k $(k = 2,3,4,5)$ from the time series obtained in the previous section in order to verify the effects of various factors (the presence or absence of stereo sound, the number of dimensions of the movie, etc.) on the sway of COP. With regard to these factors, we set 2 arrangements with 2 levels (Table 1). Six kinds of values were calculated on an SKG, and we employed two-way analysis of variance (ANOVA) with repeated measures for each index. The number of repetitions was set to 49 (the number of subjects). We examined the following null hypothesis: there is no interaction between the 2 factors and no difference between the population means at various levels. Moreover, the population mean for each level was estimated and one-way ANOVA was employed along with Tukey's method. In both these statistical tests, $p < 0.05$ was considered to be significant.

Results

The results of the two-way ANOVA with repeated measurements are shown in Table 2. No interaction between the factors could be detected in the analyses of the SKGs. The SPD could statistically distinguish between the SKGs recorded when the subjects watched the 3-D movie and the 2-D movie ($p < 0.05$). No significant differences were observed in the calculations of the other previous indices. In accordance with the one-way ANOVA for the SPD, the SKGs recorded when the subjects watched the 3-D movie were also statistically different from those recorded when the subjects watched the 2-D movie (Table 3).

Table 2. Two-way analysis of variance (ANOVA) table with repetitions

(a) On the area of sway

Source	Degrees of Freedom	Mean Square	F-value	$F_{(1,192)}$
A×B	1	0.02	0.01	3.89[a]
A_i	1	3.63	0.47	
B_i	1	25.69	3.30	
Total	192	7.79		

(b) On the total locus length per unit area

Source	Degrees of Freedom	Mean Square	F-value	$F_{(1,192)}$
A×B	1	584.51	0.16	3.89[a]
A_i	1	29.07	0.01	
B_i	1	11274.75	3.11	
Total	192	3620.88		

Discussion

According to this statistical analysis (Tables 2 and 3), the SPD could only distinguish between the SKGs recorded when the subjects watched the 3-D movie and those recorded when the subjects watched the 2-D movie. In particular, the SPD was considered suitable for the evaluation of virtual reality.

In the two-way ANOVA mentioned above, 2 arrangements with 2 levels were set (Table 1); therefore, there were 4 statistical levels in this experiment. Multiple comparisons were also employed

Table 3. The result of one-way ANOVA

Levels	A_1	A_2	B_1	B_2
Means[a]	4.58 31.5 17.15	4.31 34.35 19.10	4.08 33.02 15.31	4.81 32.85 20.94
Difference of means[a]	0.27 2.82 1.95		0.72 0.17 5.64[b]	
5% point[a]	0.78 3.61 5.57			

[a]The values in the upper, middle, and lower row represents area of sway (A), total locus length per unit area (L/A), and the SPD, respectively.

[b] Two levels were statistically different at significant level 0.05.

Table 4. Averages of the SPDs in multiple comparisons

Factors	B_1	B_2
A_1[a]	14.81 46.36	19.49 42.42
A_2[a]	15.80 48.19	22.40 52.07

[a] The values in the upper and lower rows represent S_3 and S_5, respectively.

along with Tukey's method. The population means for any statistical level were statistically not different. However, the auditory reality might be evaluated if the value of k, the characteristic involved in the SPD S_k, was large (Table 4).

In order to include the physical meaning of the SPD, the force acting on the centre of gravity of the body was defined on the basis of the difference between the displacement vectors (Takada *et al.*, 2003). In particular, we focused on singular points where statistically tiny or large forces were exerted. If the times measured at these points were temporally vicinal, these points should be connected by segments (sequences). Chain 1 (CH1) is represented by the figures of the sequences of points where tiny forces were exerted, and chain 2 (CH2) is represented by the figures of the sequences of those points where large forces were exerted. These chains could not only be applied to indices to analyze the SKGs but also to measure temporal variations in postural instability.

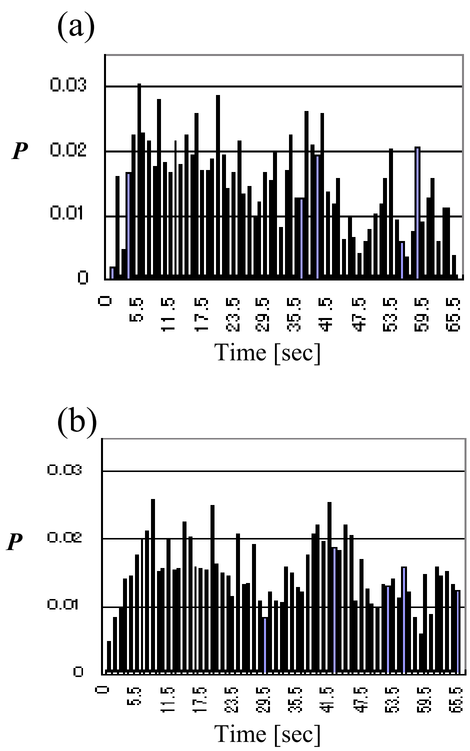

Figure 3. ***P***, proportion of the CH2 evaluated the reality of 3-D images.
(a) On the basis of the SKGs of 19 subjects that were 19– 50 years old. 0 sec indicates the time of commencement of the 3-D movie.
(b) On the basis of SKGs of 30 subjects that were 51 to 74 years old. The proportion was calculated from the frequency.

The total locus lengths of CH1 and CH2 are used to measure these chains. With regard to CH2, the force acting on the centre of gravity is considered to be strong, and we believe that it indicates the control that prevents falls (righting reflex). It was shown that the SPD was statistically effective and stable in the classification of SKGs both with and without alcohol intake. The SPD detected deterioration in the function of the vestibular cerebellum. Takada *et al.* (2003) also showed that the cross correlation between the SPD and the total locus length of the CH2 was high (>0.8).

Increased peculiar patterns were observed in the SKGs of subjects who perceived 3-D images as sensory information. Since the pattern comprised a partial trajectory with a cusp, it could be extracted as CH2. As mentioned above, the SPD detected the deterioration in the function of the vestibular cerebellum, and this deterioration was correlated with the total locus length of the CH2s (Takada, 2003). Hence, the CH2 was regarded as a detector of deterioration and could measure the effect that a 3-D movie with stereo sound had on the equilibrial function. The reality of 3-D movie with stereo sound might be evaluated by P, which is the proportion of the CH2s, that was derived from the arrival histogram of a peculiar pattern (Figure 3).

We herein compared the P of the elderly (Figure 3b) with that of the youth (Figure 3a). Peaks of the former in Figure 3b were delayed for 4 sec. The delay in this PR might be due to deterioration of the feedback system comprising sensory and motor nerves.

The peculiar patterns were observed when the crossties shown to subjects flowed down at an average speed of 43–69 degrees per second. Motion sickness was found in the sway which was affected by optokinetic stimulation, OKS (Lestienne et al., 1977). Recent studies have shown that OKS (40-60deg/s) enhances the amount of sway.

Conclusions

In this study, we proposed a method to measure the effect of 3-D images and stereo sound on equilibrial function. We considered that the peculiar pattern extracted as CH2s could be practically applied for the measurement of 'visually induced motion sickness' and its prevention. In the next step, we should measure the sickness severity level correlated with postural instability. The sickness severity would be evaluated by the skin potential, electrocardiography, electrogastrography and other subjective assessments.

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