Numerical Simulation of Equilibrium Systems while Viewing 2D/3D Video Clips without Perspective Clues

Yuki Mori[1], Yoshiki Maeda[1], Fumiya Kinoshita[1,2] and Hiroki Takada[1*]

[1]*Department of Human and Artificial Intelligent Systems, Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan*
[2]*Institute of Innovation for Future Society, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan*
**E-mail address: takada@u-fukui.ac.jp*

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The influence of 3-D images on body sway was investigated using videos of complex sphere movement in space and Smart glass. In addition, perspective clues were added to the videos and the influence on body sway was compared. Significant changes in analytical parameters were noted when the videos without spheres at the 4 corners giving no perspective clue were presented, showing that the standing position control system became unstable while viewing the video without perspective clues, compared to that while viewing them with such clues. On comparison between the 2D and 3D videos, significant changes were noted in the elderly group in the test with open eyes while viewing the video without perspective clues, but no significant change was noted in the young or middle-aged subjects.

Key words: Body Sway, Stabilograms, Three-Dimensional (3D), Depth Cues, Time-Average Potential

1. Introduction

With the improvements in 3D image display technology, 3D images utilizing TV and game devices have become commonplace. On the other hand, 3D images have adverse effects, such as discomfort, dizziness, and eye strain, depending on the viewing condition (International standard organization 1993). However, knowledge of the influence of 3D images on the body is insufficient, and experimental studies should be conducted to investigate how to safely view such images (Yano *et al.*, 2001, 2003). Biological signals from the vestibular system, which may be the most frequently referred to among the body balance systems, are also projected to the vestibular nuclei present in the brainstem. Balance sense signals are transmitted to the higher centers, such as the spinal motoneurons, oculomotor neurons, vestibule-cerebellum, cerebral cortex, and brainstem autonomic center, through the vestibular nuclei (Barmack, 2003). Vestibular stimulation is transmitted to the vomiting center present in the medulla oblongata through the vestibulo-autonomic nerve system, and motion sickness is induced through the vestibulo-vegetative reflex. The vestibular and autonomic nerve systems are closely related anatomically and electrophysiologically (Balaban and Poster, 1998) suggesting their close relationship with symptoms of motion sickness, and quantitative evaluation of motion sickness based on body sway, which is an output of the body balance system, is considered possible. The input into the vestibular system described above is controlled by the visual and somatosensory systems and parietal lobe. Regarding the developmental mechanism of visually induced motion sickness, the sensory conflict theory (Reason and Brand, 1975) is generally accepted, similarly to that of typical motion sickness.

Stabilometry performed as a balance test is useful to comprehensively evaluate the balance functions, such as the evaluation of the stability of a standing position and diagnosis of central disease-associated equilibration disturbance (Suzuki *et al.*, 1996). Stabilometry is a simple test in which a 60-s recording starts when a standing position is stabilized. To increase the diagnostic value of body sway, analytical parameters of stabilograms have been proposed, including the total locus length and total locus length per unit area (Suzuki *et al.*, 1996).

In this study, the influence of a 3D video of complex sphere movements in space on body sway was investigated, and changes in a mathematical model describing the body balance system were examined. In addition, whether or not perspective clues stabilize the standing position control system was investigated.

The Simulator Sickness Questionnaire (SSQ) is the best-known psychometric method to evaluate visually induced motion sickness. This questionnaire is comprised of 16 subjective items considered useful to evaluate simulator sickness (Kennedy *et al.*, 1993). In Scibora *et al.* (2007), the total locus length significantly increased corresponding to the load in a high compared to low score group.

In this study, the influence of a 3D video of complex sphere movement in space on body sway was investigated using Smart glass. Also, perspective clues were added to the 3D video, and their influence was compared with the above, including the subjective evaluation using SSQ. Furthermore, time-average potential functions were calculated from stabilograms, and a mathematical model of body sway

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Table 1. Age in subjects' group (mean ± standard deviation).

Group	Age (yr. old)
Young	21.4 ± 4.1
Middle-aged	49.5 ± 6.3
Elderly	69.3 ± 5.6

was constructed.

2. Model and Evaluation

The subjects with no past medical history of diseases of the ear or nervous system were voluntarily participated in this study. A subject belongs to one of three groups (young, middle-aged, and elderly) that consist nineteen healthy persons (Table 1). The experiment was sufficiently explained to the subjects and written consent was obtained before the experiment.

Stabilometry was performed while viewing 2D/3D video clips. Gravicorder GS3000 (Anima Corp., Tokyo) was used as a stabilometer. The sampling frequency was set to be 20 Hz. Using Smart-Glass BT-200 (EPSON, Tokyo), the subjects watched four kinds of 2D/3D video clips that were reconstructed from Sky Crystal (Olympus Memory Works Corp., Tokyo) with approval by the company (Fig. 1). In this experiment, one of video clips was presented to the subjects during the test with their eyes open. The body sway was continuously measured for one minute with eyes open and for the next one 1 minute with eyes closed. The measurement was performed in Romberg's posture, and the order of video clips was randomized in consideration of the influence of the order effect. In order to exclude external stimulation other than the video clip, a blackout curtain was set in front of the subject so that we can remove visual influence through the Smart-Glass.

The x-y coordinates of center-of-pressure (COP) were recorded at each sampling time in both tests with eyes open/closed. Based on the equations established by the Japan Society for Equilibrium Research, analytical indices for stabilograms: the area of sway, total locus length, and total locus length per unit area, were calculated from time series of the COP in the x- (right direction was regarded as positive) and y- (forward direction was regarded as positive) directions for each test as well as previous studies. We also calculated the sparse density (SPD), which is a parameter proposed by Takada *et al.* (2003), and it is said that the SPD can evaluate stability of the posture. The parameters are defined as follows:

2.1 Total locus length per unit area

A value obtained from the calculation, dividing the total locus length Xr by the area of sway Yr. A decrease in the value indicates the instability of the posture.

2.2 Sparse density (SPD)

The SPD is defined by an average of the ratio $G_j(1)/G_j(k)$ for $j = 3, 4, \ldots, 20$, where $G_j(k)$ is the number of divisions having more than k measured points. A stabilogram is divided into quadrants whose latus is j times longer than the resolution. If the center of gravity is stationary, the SPD value is 1. If there are variations in the stabilograms, the SPD value is greater than 1. Thus, the SPD depends on the characteristics of the stabilogram and the minimal structure of the time-average potential function.

(a)

(b)

Fig. 1. Spheres are fixed at the 4 corners, giving perspective clues, and another sphere moves on the screen in a complex way (a). An image extracted from a video clip without spheres at the 4 corners, giving no perspective clue (b).

Spheres were fixed at the 4 corners in the 2D/3D video clips with perspective clues. 2D/3D video clips with/without perspective clues were presented in a random order, and the above-mentioned sway values were calculated from the stabilograms. Age, solidity of the subjects' vision (2D/3D) and the presence of perspective clues were assumed to be important factors, on which a two-way analysis of variance (ANOVA) was conducted for the number of repetitions 19. In addition, the two-way ANOVA for each sway value was followed by multiple comparison (Nemenyi test). In this paper, the significance level was set at $p = 0.05$.

Stabilograms were measured while viewing video clips; 2D A, 2D B, 3D A, and 3D B that were corresponding to a 2D video clip with perspective clues, a 2D without perspective clues, a 3D with perspective clues, and a 3D without the clues, respectively (Fig. 2). There was no significant interaction between any couple of factors and no significant main effect for each-aged group with eyes open/closed.

In the elderly subjects (Fig. 2), total locus length, area of sway, and the SPD while viewing the 3D video clip without the perspective clues were significantly greater than those while viewing the 2D ($p < 0.05$). The area of sway while/after viewing the 3D without the perspective clues was significantly greater that those while/after viewing the

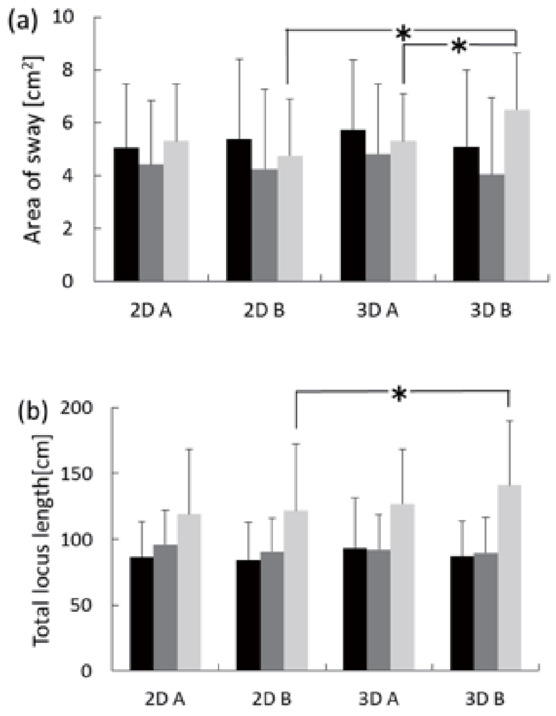

Fig. 2. Sway values in the elderly subjects with their eyes open; Area of sway (a), Total locus length (b). Black square: Young subjects; gray square: middle-aged subjects; white square: elderly subjects.

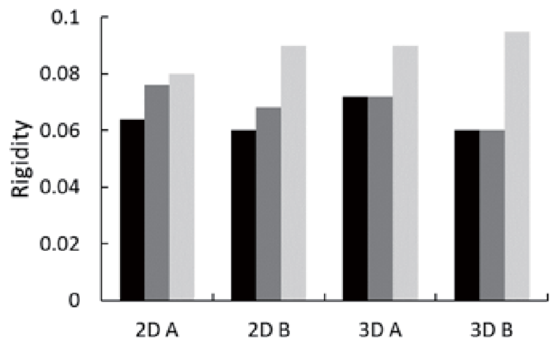

Fig. 3. Rigidity $\mu\Delta t$ under each condition (with their eyes open). Black square: Young subjects; gray square: middle-aged subjects; white square: elderly subjects.

3D with the perspective clues ($p < 0.05$). The total locus length per unit area while viewing the 3D without the perspective clues was significantly greater than that with eyes closed afterward ($p < 0.05$). No significant difference was noted in the other analytical parameters in the elderly subjects.

In the young subjects, the total locus length while viewing the 2D without the perspective clues was significantly greater than that in the test with closed eyes ($p < 0.05$). No significant difference was noted in the other analytical indices for stabilogram. In the middle-aged subjects, no significant difference was also noted in any indices.

Based on the Markov property and the x-y independence in components of the body sway, the Brownian motion is system proposed as a mathematical model to express the equilibrium function (Goldie *et al.*, 1986; Collins and De Luca, 1993). In general, stochastic processes including the Brownian motion are expressed by stochastic differential equations (SDEs) that are expected to apply to diagnose the vertigo. In contrast, we focused on the individuality of this equilibrium system and showed that it is necessary to consider the nonlinearity in the following SDE (Takada and Miyao, 2012);

$$\dot{z} = -gradU_z(z) + \mu w_z(t) \tag{1}$$

where μ and $w_z(t)$ express the noise coefficient and the white noise, respectively ($z = x, y$). This second term $\mu w_z(t)$ expresses small perturbation for the time-average potential function $U_z(z)$, which drives the COP. Assuming that the motion process is stationary without the anomalous diffusion, we have succeeded in deriving the relationship between the potential function $U_z(z)$ in each SDE and the stationary distribution $G_z(z)$ for each component of the body sway as

$$U_z(z) = -\frac{1}{2}\ln G_z(z) \tag{2}$$

under the condition of $\mu = 1$. However, this condition requests to normalize the data in the analysis of the time series. In this study, we employed numerical analysis of the SDE (1) including the coefficient μ, and we estimated the optimal value to reproduce form of the stabilogram. In this study, we assumed Histograms obtained from the stabilometry is regarded as stationary distributions (Takada, 2004). Based on Eq. (2), the potential functions are regressed to the parabolic polynomial as

$$\hat{U}_z(z) = az^2 + bz \tag{3}$$

by using the mean square method. Substituting this polynomial (3) into the first term in the right hand side of Eq. (1) as $U = \hat{U}$, we employed numerical analysis of the SDEs (1). Setting the initial value (x, y) to be $(0, 0)$, $w_z(t)$ is substituted to pseudo random numbers whose distribution is regarded to be uniform (mean $\pm$ standard deviation: 1 ± 1). Numerical solutions of 11,200 steps are herein obtained from the Runge-Kutta formulae of 4th degree of the Eq. (1) at $\mu = 1, 2, \ldots, 20$ and $\Delta t = 0.001, 0.002, \ldots, 0.01$ step, respectively. The first 10,000 steps of these are dumped due to the initial dependency, and the left 1,200 steps are acceptable as a numerical solution. Ten numerical solutions are calculated for each video clip. The total locus length Xs and the area of sway Ys are also estimated from the numerical solutions as well as the analysis of stabilograms measured in this study. Stabilograms resulted from the numerical solutions are evaluated by the residual sum of squares as

$$E = \left[\frac{\sqrt{Y_r}}{X_r}(X_r - X_s)^2 + (\sqrt{Y_r} - \sqrt{Y_s})^2\right]^{1/2}, \tag{4}$$

where square roots are calculated to adjust the dimension and scale difference between the total locus length and the area of sway. We herein assume that the stabilograms resulted from the numerical solutions are well reproduced at the coefficient condition $\mu\Delta t$ to minimize E in Eq. (4).

3. Rigidity in System to Control Standing Posture

In the test with the elderly subjects' eyes closed, the total locus length and area of sway were significantly greater after viewing the 3D video clip without the perspective clues than those after viewing the 3D with the perspective clues. The area of sway while viewing the 3D without the perspective clues was significantly greater than that while viewing the 3D with the perspective clues, showing that the system to control standing posture became unstable due to the 3D viewing without perspective clues.

In the elderly subjects, the total locus length, the area of sway, and the SPD S_2 while viewing the 3D video clip without the perspective clues were significantly greater than those while viewing the 3D video with the perspective clues, but no significant change was noted in the young or middle-aged subjects, suggesting that the increases were due to aging-related reduction of the balance function, and elderly persons are more markedly influenced by 3D images.

The time-average potential function for each condition was estimated, and numerical analysis was performed using Eq. (4). The numerical solutions for total locus length and area of sway were calculated, and errors E from the measured values were also calculated. The product of the noise amplitude μ and time step Δt was estimated so that the minimum E as the optimum value was obtained in the numerical analysis. The product $\mu\Delta t$ is shown as Fig. 3, which means rigidity of system to control upright posture. In the middle-aged and elderly subjects, the rigidity after viewing the 3D video without perspective clues was greater than that after viewing the videos with the perspective clues. Irrespective to their ages and the perspective clues, the rigidity after viewing the 3D video was greater than that after viewing the 2D, suggesting that the characteristic of the measured body sway was reproduced by the mathematical model.

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