Numerical Analysis of Body Sway While Viewing a 3D Video Clip Without Perspective Clues

Yuki Mori, Yoshiki Maeda, and Hiroki Takada(✉)

Department of Human and Artificial Intelligent Systems, Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan
takada@u-fukui.ac.jp

Abstract. Recently, with the rapid progress in image processing and three-dimensional (3D) technology, stereoscopic images are not only seen on television but also in theaters, on game machines, etc. However, symptoms such as eye fatigue and 3D sickness are experienced when viewing 3D films on displays and visual environments. The influence of stereoscopic vision on human body has been also insufficiently understood; therefore, it is important to consider the safety of viewing virtual 3D contents. The aim of this study is to examine the effects of exposure to 2D/3D video clips on human equilibrium systems. Stereoscopic video clips with complexly ambulated spheres and their monocular (2D) vision were shown to subjects using binocular parallax smart glasses. We compared stabilograms recorded during exposure to video clips with/without depth cues on 3D images. The time-average potential function was obtained from stabilograms using stochastic differential equations as a mathematical model for body sway to conduct a numerical analysis.

Keywords: 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 [1]. 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 [2, 3].

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, vestibulocerebellum, cerebral cortex, and brainstem autonomic center, through the vestibular nuclei [4]. 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

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related anatomically and electrophysiologically [5], 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 [6] 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 [7]. 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 distance of body sway and distance of body sway per unit area [7].

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 [8]. In [9], the total distance of body sway 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. In addition, 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 was constructed.

2 Materials and Methods

2.1 Experimental Method

The subjects were 19 healthy young persons (21.4 ± 4.1 years old (mean ± standard), 19 middle-aged persons (49.5 ± 6.3 years old), and 19 elderly persons (69.3 ± 5.6 years old) with no past medical history of diseases of the ear or nervous system. The experiment was sufficiently explained to the subjects and written consent was obtained before the experiment.

Stabilometry was performed while watching 2D and 3D videos. For the stabilometer, the gravicorder GS3000 (Anima Corp., Tokyo) was used. The sampling frequency was set at 20 Hz. The subjects watched 3D videos using Smart glass BT-200 (EPSON, Tokyo). Four videos (2D and 3D) were prepared by reconstituting Sky Crystal (Olympus Memory Works Corp., Tokyo) after approval by the company (Fig. 1). In the experiment, the video was presented during the test with open eyes. The

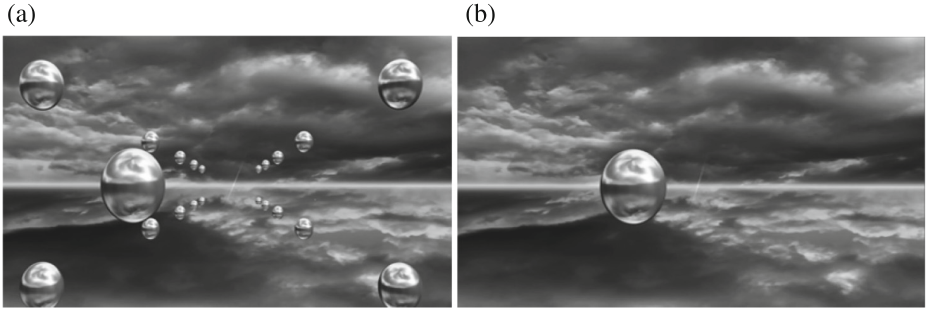

Fig. 1. Spheres are fixed at the 4 corners, giving perspective clues, and another sphere moves on the screen in a complex way (a). Video without spheres at the 4 corners, giving no perspective clue (b).

body sway was continuously measured during a 1-min test with open eyes and then a 1-min test with closed eyes, and the 4 videos were presented to all subjects. Measurement was performed in Romberg's posture, and the order of videos was randomized in consideration of the influence of the order effect. To exclude external stimulation other than the video, a blackout curtain was set in front of the subject to remove the influence of light penetrating the Smart glass.

2.2 Investigation Items

The x-y coordinates were recorded at each sampling time-point in the tests with open or closed eyes, and the parameters were calculated. The obtained data were converted to time series of the center of gravity position in the x- (right direction was regarded as positive) and y- (forward direction was regarded as positive) directions in each test, and the circumferential area, total distance of body sway, distance of body sway per unit area, and density were evaluated. The circumferential area, total distance of body sway, and distance of body sway per unit area are analytical parameters of stabilograms used in previous studies, and we used these based on the equations established by the Japan Society for Equilibrium Research. The density is a parameter of that of multiple points scattered on a plane proposed by Takada et al., and it is considered to be involved in the stability of a standing position [10]. The parameters are defined as follows:

Circumferential area: The area of the region surrounded by the circumference (envelop) of body sway on the x-y coordinate system. An increase in the value indicates the instability of sway.

Total distance of body sway: The total distance of movement of the center of gravity within the measurement time. An increase in the value indicates the instability of sway.

Distance of body sway per unit area: A value calculated by dividing the total distance of body sway by the circumferential area. A decrease in the value indicates the instability of sway.

Density: The stabilogram is divided into squares, and the frequency of passing over the center of foot pressure is determined in each square. As the sway narrows, i.e., the local density increases, the value becomes closer to 1. Inversely, the value decreases as the sway widens.

These 4 parameters were calculated in each stabilogram of the tests with both open and closed eyes, and 2-way layout analysis of variance with 2 factors out of 3-dimensionality of the video, the presence or absence of perspective clues, age, and persistence of the influence of watching the video was performed for each parameter, followed by multiple comparison, setting the significance level at 0.05.

2.3 Numerical Analysis

The equations below have been proposed as mathematical models describing the body sway [11]:

$$\dot{z} = -gradU(z) + \mu\omega(t) \tag{1}$$

$$U(z) = -\frac{1}{2} lnG(z) \tag{2}$$

μ represents the noise amplitude coefficient, and ω represents a pseudorandom number. The time-average potential functions in the x- and y-directions were calculated from the frequency distribution determined in the experiment using Eq. (2). The calculated time-average potential functions were approximated using the quadratic equation below:

$$\widehat{U}(z) = az^2 + b \qquad z = (x, y) \tag{3}$$

The mathematical model of the body sway shown below was established using Eq. (1):

$$\dot{z} = -grad\ \widehat{U}(z) + \mu\omega(t) \quad z = (x, y) \tag{4}$$

Numerical analysis was performed using this model. In Eq. (4), setting the initial values of (x,y) at (0,0), the pseudorandom number ω was prepared using white Gaussian noise (mean ± standard deviation: 1 ± 1). Setting the noise amplification coefficient μ at $1 \leq \mu \leq 20$ (1 step) and time step Δt at $0.001 \leq \Delta t \leq 0.01$ (0.001 step), 22,000 steps of a numerical solution were set using the Runge-Kutta 4th order method. Of the numerical solutions, the first 10,000 steps were discarded, and the remaining 12,000 steps were divided into 1,200-step increments. The total distance of body sway (Xs) and circumferential area (Ys) were calculated in these time series. Designating the measured total distance of body sway and circumferential area as (Xr) and (Yr), errors (E) between the numerical solutions of the mathematical model and measured values were calculated using the equation below:

$$E = \sqrt{\frac{\sqrt{Yr}}{Xr}(Xr - Xs)^2 + (\sqrt{Yr} - \sqrt{Ys})^2} \quad (5)$$

.

3 Results

The 2D and 3D videos in which spheres giving perspective clues were fixed at the 4 corners and those in which spheres at the 4 corners were absent were presented in a random order, and the analytical parameters of stabilograms were compared. Typical stabilograms are shown in Fig. 2. No consistent tendency was noted among these stabilograms. The analytical parameters were calculated from the stabilograms. In the elderly subjects, the total distance of body sway, circumferential area, and density in the test with open eyes while watching the 3D video without spheres at the 4 corners significantly increased compared to those while watching the 2D video ($p < 0.05$) (Fig. 3). The distance of body sway per unit area while watching the 3D video without spheres at the 4 corners significantly increased in the test with open eyes compared to that with closed eyes ($p < 0.05$). No significant difference was noted in the other analytical parameters in the elderly subjects.

Stabilograms were measured while viewing video clips, 2D A, 2D B, 3D A, and 3D B that were corresponding to a 2D video with perspective clues by spheres at the 4

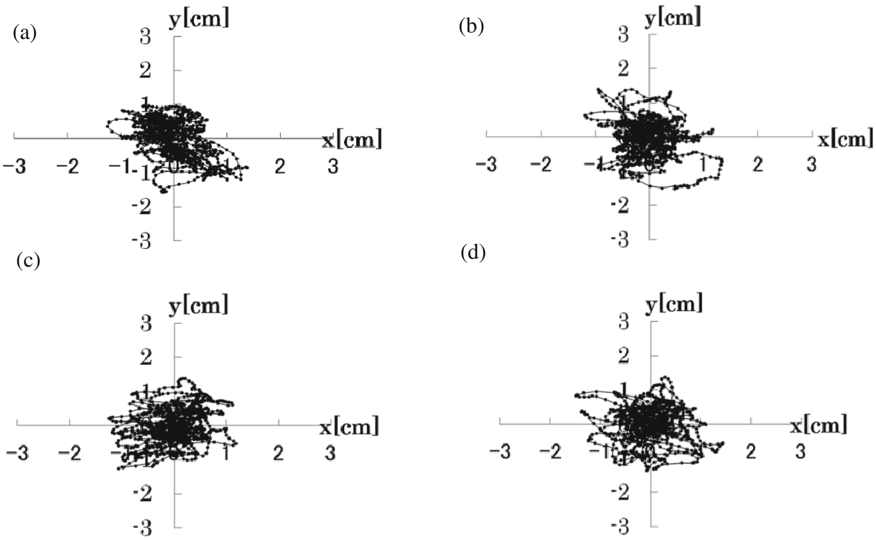

Fig. 2. Typical stabilograms (in the same subject): stabilograms while watching the 2D video showing the perspective clues (a), 3D video showing the perspective clues (b), 2D video showing no perspective clue (c), 3D video showing no perspective clue (d).

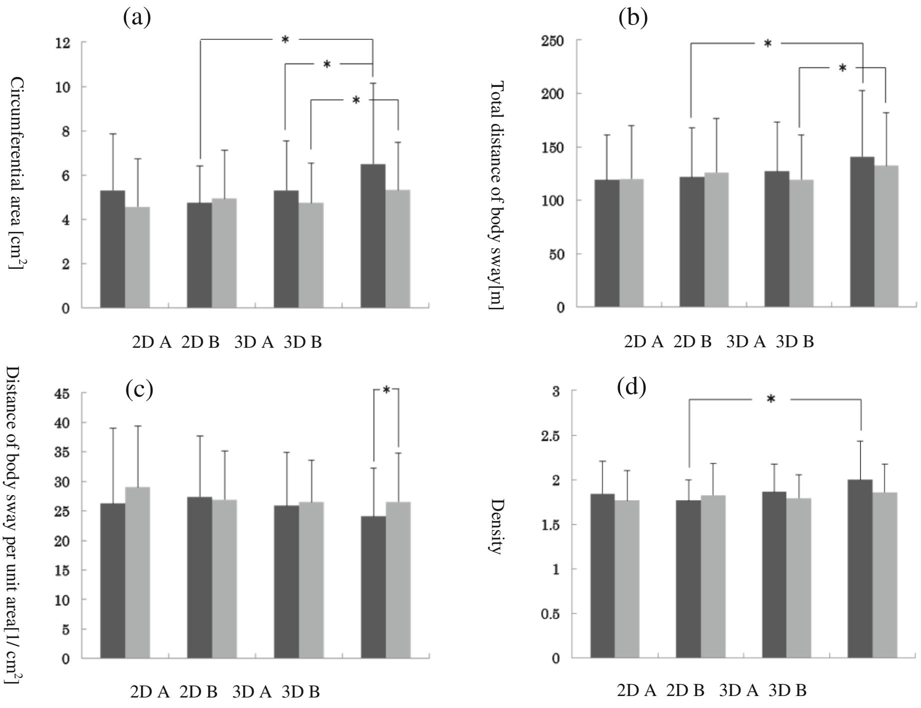

Fig. 3. Body sway in elderly subjects: circumferential area (a), Total distance of body sway (b), Distance of body sway per unit area (c), Density S_2 (d) (*$p < 0.05$).

corners, a 2D video without perspective clues, a 3D video with perspective clues, and a 3D video without the clues.

In the young subjects, the total distance of body sway while watching the 2D video without spheres at the 4 corners significantly increased in the test with closed eyes compared to that with open eyes ($p < 0.05$). No significant difference was noted in the other analytical parameters. In the middle-aged subjects, no significant difference was noted in any analytical parameter.

The time-average potential function of each measured data was calculated, and numerical analysis was performed using Eq. (4). The numerical solutions for the total distance of body sway and circumferential area were calculated, and errors (E) from the measured values were calculated. Regarding combination of the noise amplification coefficient μ and time step Δt of the numerical solution with the minimum E as the optimum value, scattering roughness of sway, $\mu * \Delta t$, was calculated (Table 1).

In the middle-aged and elderly subjects, the scattering roughness of sway was greater after viewing the 3D video without perspective clues by spheres at the 4 corners than that after viewing the videos with the perspective clues. Irrespective to their ages and the perspective clues, the scattering roughness was greater after viewing the 3D video than that after viewing the 2D video.

Table 1. Sparseness of sway ($\mu * \Delta t$) under each condition

	2D A	2D B	3D A	3D B
Young subjects with open eyes	0.064	0.06	0.072	0.06
Young subjects with closed eyes	0.068	0.072	0.076	0.072
Middle-aged subjects with open eyes	0.076	0.068	0.072	0.06
Middle-aged subjects with closed eyes	0.06	0.072	0.072	0.076
Elderly subjects with open eyes	0.08	0.09	0.09	0.095
Elderly subjects with closed eyes	0.095	0.09	0.08	0.095

4 Discussion

In the elderly subjects in the test with closed eyes, the total distance of body sway and circumferential area significantly increased when they watched the 3D videos with and without perspective clues. In the test with open eyes, the circumferential area significantly increased when they watched the videos without perspective clues, showing that the standing position control system became unstable when they watched the videos without perspective clues compared to watching them with such clues.

On comparison of the body sway between watching the 2D and 3D videos, in the elderly subjects in the test with open eyes while watching the videos without perspective clues, the total distance of body sway, circumferential area, and density S_2 significantly increased while watching the 3D video, 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.

In the numerical solutions of the mathematical model, the scattering roughness of sway increased while watching the 3D video without perspective clues compared to that while watching the 3D video with such clues in the elderly subjects. In the middle-aged and elderly subjects, the scattering roughness of sway was greater after viewing the 3D video without perspective clues by spheres at the 4 corners than that after viewing the 2D video with the perspective clues, suggesting that the characteristic of the measured body sway was reproduced by the mathematical model.

5 Conclusion

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 watching the video without perspective clues, compared to that while watching 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 watching the video without perspective clues, but no significant change was noted in the young or middle-aged subjects. The reason for the marked influence on the elderly subjects may have been an aging-related reduction of the body balance function, strongly reflected in the body sway while watching the 3D video.

We successfully developed a mathematical model describing the above findings. Values similar to the measured data were obtained using this model, suggesting that it is useful to clarify the influence of 3-D images on the body balance function.

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