Effect of a Stereoscopic Movie on the Correlation between Head Acceleration and Body Sway

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Abstract. Visually induced motion sickness (VIMS) is caused by sensory conflict, the disagreement between vergence and visual accommodation while observing stereoscopic images. VIMS can be measured by psychological and physiological methods. We quantitatively measured the head acceleration and body sway before and during exposure to a conventional 3D movie. The subjects wore a head mount display and maintained the Romberg posture for the first 60 s and a wide stance (midlines of the heels 20 cm apart) for the next 60 s. Head acceleration was measured using an Active Tracer with 50 Hz sampling. The Simulator Sickness Questioner (SSQ) was completed immediately afterward. For the SSQ sub-scores and each index for stabilograms, we employed two-way ANOVA with leg postures and presence/absence of stereoscopic images as factors. Moreover, we assumed that the input signal was the head acceleration in the transfer system to control the body sway and estimate the transfer function.

Keywords: visually induced motion sickness, stabilometry, sparse density, head acceleration, transfer function analysis.

1 Introduction

The human standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism termed the righting reflex [1]. To maintain a standing posture when locomotion is absent, the righting reflex, centered in the nucleus ruber, is essential. Sensory signals such as visual inputs and auditory and vestibular inputs as well as proprioceptive inputs from the skin, muscles, and joints are involved in the body's balance function [2]. The evaluation of this function is indispensable for diagnosing equilibrium disturbances such as cerebellar degenerations, basal ganglia disorders, and Parkinson's disease in patients [3].

Stabilometry has been used to evaluate this equilibrium function qualitatively and quantitatively. A projection of a subject's center of gravity onto a detection stand is measured as an average of the center of pressure (COP) of both feet. The COP is

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traced for each time step, and the time series of the projections is traced on an x-y plane. By connecting the temporally vicinal points, a stabilogram is created. 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, and such parameters are widely used in clinical studies. The last parameter, in particular, depends on the fine variations involved in posture control [1]. This index is then regarded as a gauge for evaluating the function of the proprioceptive control of standing in human beings. However, it is difficult to clinically diagnose disorders of the balance function and to identify the decline in equilibrium function by utilizing the abovementioned indices and measuring patterns in the stabilogram. Large interindividual differences might make it difficult to understand the results of such a comparison.

The analysis of stabilograms is useful not only for medical diagnosis but also for achieving control of upright standing by two-legged robots and for preventing elderly people from falling [4]. Recent studies suggest that maintaining postural stability is a major goal of animals [5] and that they experience sickness symptoms in circumstances where they have not acquired strategies for maintaining their balance [6]. 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 [6]–[8]. Stoffregen and Smart (1999) reported that the onset of motion sickness may be preceded by significant increases in postural sway [9].

The equilibrium function in humans deteriorates when viewing three-dimensional (3D) movies [10]. This visually induced motion sickness (VIMS) has been considered to be caused by a disagreement between vergence and visual accommodation while viewing 3D images [11]. Thus, stereoscopic images have been devised to reduce this disagreement [12]–[13].

VIMS can be measured by psychological and physiological methods, and the simulator sickness questionnaire (SSQ) is a well-known psychological method for measuring the extent of motion sickness [14]. The SSQ is used herein for verifying the occurrence of VIMS. The following parameters of autonomic nervous activity are appropriate for the physiological method: heart rate variability, blood pressure, electrogastrography, and galvanic skin reaction [15]–[17]. A wide stance (with midlines of the heels 17–30 cm apart) reportedly results in a significant increase in the total locus length in the stabilograms for individuals with high SSQ scores, while the length in those of individuals with low scores is less affected by such a stance [18].

By using the SSQ and stabilometry, in this study, we examined whether the VIMS was induced by a stereoscopic movie. We also investigated the relationship between the body sway and head acceleration by using transfer function analysis.

The correlation between head movement and the movement of the center of gravity has been investigated in general, and a corporative effect was seen in their relationship [19]. By showing a stereoscopic movie to the subjects, Takeda et al. verified that there is a corporative correlation between the head movement and the sway [20]. We herein assume that the input signal, x(t), is the head acceleration in the transfer system to control the body sway as shown in Fig. 1. In this figure, we denote the Fourier transform by a capital letter corresponding to the letter of function being transformed (such as y(t) and Y(f)). The transfer function H(f) is defined as a Fourier transform of the impulse response h(f). In our experiments, we cannot observe the output signal of the transfer system but only the signal added to the noise n(t). Based on a theorem (Winner-Khinchine):

$$W_{xx} = |X(f)|^2 = \sigma_x{}^2 \mathscr{F}(R_{xx}), \tag{1}$$

we can easily estimate a power spectrum W_{xx}. On the right-hand side of Eq.(1), σ_x expresses the standard deviation and $\mathscr{F}(R_{xx})$ means the Fourier transform of the auto-correlation function with respect to the signal x(t) [21]. In this study, we estimate the transfer function that controls the sway as follows.

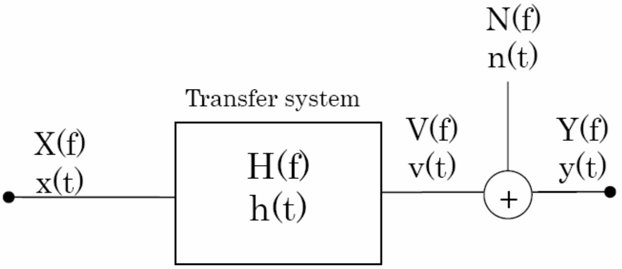

Fig. 1. A transfer system and its output, y(t)

2 Materials and Methods

Ten healthy subjects (age, 23.6 ± 2.2 years) voluntarily participated in this study. All of them were Japanese and lived in Nagoya and its surrounding areas. 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 h 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. By using an air conditioner, we adjusted the room temperature to 25 °C and kept the room dark. All subjects were tested from 10 a.m. to 5 p.m. in the room. The subjects wore an HMD (iWear AV920; Vuzix Co. Ltd.) on which 2 kinds of images were presented in a random order (Fig. 2): (I) a visual target (circle) whose diameter was 3 cm; (II) a conventional 3D movie that shows a sphere approaching and moving away from subjects irregularly (Fig. 3).

Fig. 2. The setup of the experiment [22]

Fig. 3. A scene in the movie [22]

2.1 Experimental Procedure

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 at a sampling frequency of 20 Hz during the measurement, while the head acceleration was simultaneously recorded by the active tracer (AC-301A; GMS Co. Ltd.) at 50 Hz; subjects were instructed to maintain the Romberg posture for the first 60 s and a wide stance (with the midlines of heels 20 cm apart) for the next 60 s. The subjects viewed one of the images, i.e., (I) or (II), on the HMD from the beginning until the end. The SSQ was filled before and after stabilometry.

2.2 Calculation Procedure

We calculated “total locus length,” which is commonly used in the clinical field for stabilograms [23]. In addition, new quantification indices termed “SPD” were also estimated [24].

When subjects stood with their feet close together (Romberg posture), the coherence function between the head acceleration x(i) and the movement of the centre of gravity y(j) was estimated as

$$\mathrm{coh}_{x(i)y(j)}(f) = |W_{x(i)y(j)}|^2 / (W_{x(i)x(i)}\ W_{y(j)y(j)}), \tag{2}$$

where i and j expressed the component (1: lateral, 2: anterior/posterior). By using the Fast Fourier transform algorithm, power spectrums $W_{x(i)x(i)}$, $W_{y(j)y(j)}$ were estimated. On the basis of Eq.(1), we calculated cross spectrums $W_{x(i)y(j)}$. The coherence means an index for the degree of the linear correlation between input and output signals

(0 ≤coh ≤1). There exists a completely linear correlation between these signals when coh =1. In this study, we assumed that a linear system intervenes between the head and the body sway only if coh ≥ 0.12 (significant correlation coefficient for N = 512, $p < 0.01$). Moreover, we estimated the transfer function as follows:

$$H(f)= W_{x(i)y(j)} / W_{x(i)x(i)},$$

and the transfer function gain (TFG) |H(f)|.

3 Results and Discussion

Scores for SSQ-N (nausea), SSQ-OD (eyestrain), SSQ-D (disorientation), and SSQ-TS (total score) were 11.4 ± 3.7, 18.2 ± 4.1, 23.7 ± 8.8, and 19.8 ± 5.3, respectively. Sickness symptoms seemed to appear with the exposure to the stereoscopic images although there were large individual differences.

Typical stabilograms are shown in Fig. 4. 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. 4c–4d) tended to be larger than those of the control sway (Fig. 4a–4b). Although a high density of COP was observed in the stabilograms (Fig. 4a–4b), the density decreased in stabilograms during exposure to the conventional stereoscopic movie (Fig. 4c–4d).

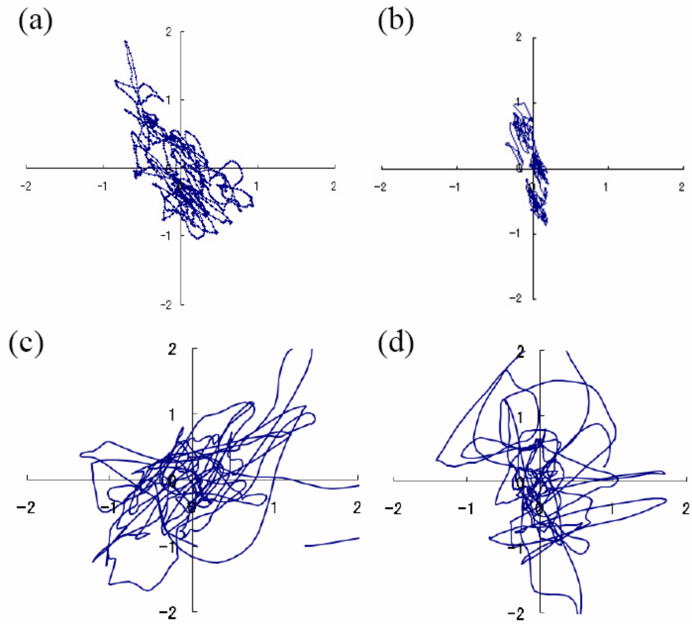

Fig. 4. Typical stabilograms observed when subjects viewed a static circle (a)–(b) and the conventional 3D movie (c)–(d) [22]

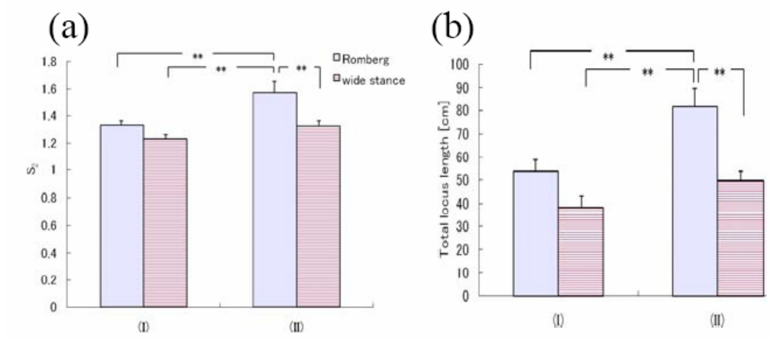

Fig. 5. Typical results of two-way ANOVA with repeated measures for indicators; the total locus length (a) and the SPD (b)

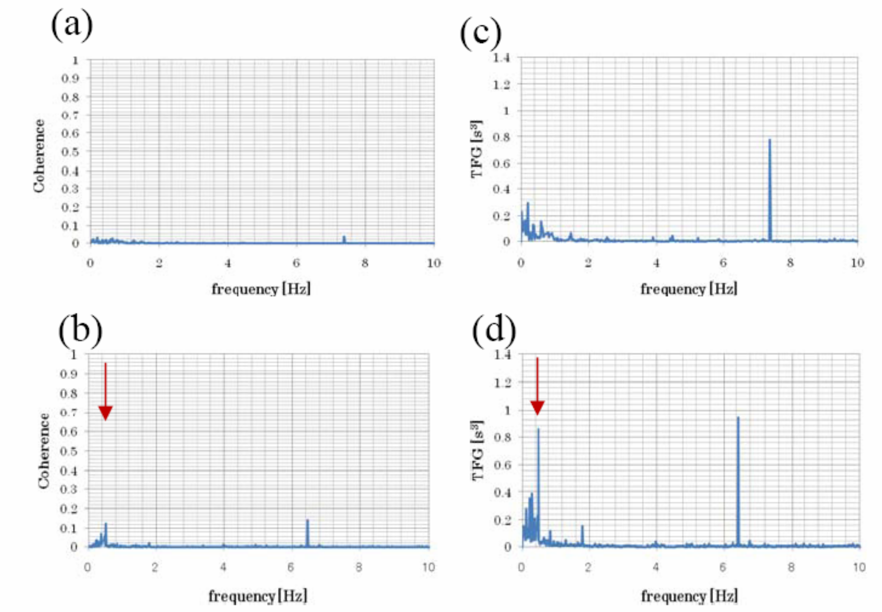

Fig. 6. Representative examples of the distributions of coherence function (a), (b) and transfer function gain (c), (d) between the head acceleration (anterior/ posterior) and the lateral sway

Furthermore, stabilograms measured in an open leg posture with the midlines of heels 20 cm apart (Fig. 4b, 4d) were compared with those measured in the Romberg posture (Fig. 4a, 4c). COP was not isotropically dispersed but was characterized by considerable movement in the anterior-posterior (y) direction (Fig. 4b, 4d). Although this trend is seen in Fig. 4d, the diffusion of COP was larger in the lateral (x) direction and had spread to the extent that it was equivalent to the control stabilograms (Fig. 4a)

According to the two-way analysis of variance (ANOVA) with repeated measures, there was no interaction between the factors of posture (Romberg posture or standing posture with their feet wide apart) and images (I or II). For the total locus length and the sparse density (Fig. 5a, 5b), there were main effects in response to both factors ($p < 0.01$). Multiple comparisons revealed that these indices significantly increased when the subjects viewed the 3D movie (II) with their feet close together (Romberg posture). The VIMS could be detected by these indices for stabilograms.

When the subjects stood with their feet close together (Romberg posture), transfer function analysis was implemented with the head acceleration (input) and the body sway (output). We estimated the coherence function (2), i.e., $coh_{x(1)y(1)}(f)$, $coh_{x(1)y(2)}(f)$, $coh_{x(2)y(1)}(f)$ and $coh_{x(2)y(2)}(f)$. For any frequency, $coh_{x(1)y(1)}(f)$ and $coh_{x(1)y(2)}(f)$ were less than 0.12 (significant correlation coefficient for $N = 512$, $p < 0.01$) (Fig. 6a). On the other hand, $coh_{x(2)y(2)}(0.51)$ was more than 0.12. $coh_{x(2)y(j)}(0.51)$ and $coh_{x(2)y(j)}(7)$ during the exposure to the 3D movie (II) remarkably increased for $j = 1, 2$ (Fig. 6b).

While watching the 3D movie, the lateral sway might become dependent on its transverse component of the head movement. Moreover, we estimated the transfer functions. Fig. 6c and 6d showed their TFG before and during the exposure to the stereoscopic movie, respectively. The TGF during the exposure to the 3D movie (II) simultaneously increased, which was obtained from the transfer function between the head acceleration (anterior/posterior) and the lateral sway. The transfer function is considered to be useful for the linear prediction of the response to the load, such as the Galvanic Vestibular Stimulation [25], which enhances the head acceleration (anterior/posterior).

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