Effects of Galvanic Vestibular Stimulation on Statokinesigrams of the Elderly

Hiroki Takada, Masumi Takada, Masaru Miyao, Masashi Furuta, Kunihiko Tanaka, Tomoki Shiozawa, *Member, ISG*

***Abstract*— Special suits have been designed to simulate the physical functions of the elderly. However, it has been suggested that these suits do not simulate the postural instability that is actually observed in elderly subjects. We consider that postural instability in the elderly is caused by anomalous signals in the vestibules. In this study, we have verified this hypothesis by using galvanic vestibular stimulation (GVS) that can mask regular signals until they reach the vestibular nuclei. In conclusion, we could simulate the deterioration in equilibrium function with advancing age to a certain extent. We have also revealed that postural instability in the elderly may be improved by the presence of visual information.**

I. Introduction

In humans, the standing posture is maintained by the body's balance function, which is an involuntary physiological adjustment mechanism [1]. Aging causes deterioration in visual, auditory, and vestibular functions and in proprioceptive inputs from the skin, muscles, and joints [2], [3]. The information received by these sensory receptors reduces with advancing age. There is ample evidence of deterioration in many sensorimotor systems underlying postural control, even in elderly people without obvious signs of disease [4]. The postural sway in static and dynamic posturography correlates with age and functional parameters of balance [5], [6], and there is an increased heterogeneity of postural control abilities in healthy adults [7].

The risk of falling increases with increasing age, and falls in the elderly constitute an important health problem. The frequency of dizziness and balance problems increase with advancing age to become the most common complaints in patients older than 75 yr. [8]. The dizziness and postural imbalance in the elderly are frequently caused by vestibular, other sensory, or central nervous system disorders. In a retrospective study of more than 1000 cases of patients aged 70 yr. or older, who visited a dizziness clinic, 40% had benign paroxysmal positioning vertigo, followed by other vestibular or neurological disorders such as Menière's disease, vestibular neuritis, cerebral vascular episodes, and tumors [9]. Sensory vestibular hair cells and central vestibular neurons are differentiated cells that undergo continuing attrition from birth to old age, a senescence that varies anatomically by region [10]. Quantitative vestibular testing in humans has shown alterations with age as well; however, a decline with aging is not a prominent feature of all parameters [8].

Special suits have been designed to simulate the physical functions of the elderly (Fig.1). They comprise glasses with narrow visual fields to simulate poor eyesight, earplugs that reduce hearing ability, and weight loads that reduce movement ability. However, it has been suggested that these suits do not simulate the postural instability that is actually observed in elderly subjects (Fig.2). We consider that postural instability in the elderly is caused by anomalous signals in the vestibules. As we have mentioned above, this hypothesis appears consistent with the published data on the ocular and postural responses in the elderly. In this study, we have verified this hypothesis by using galvanic vestibular stimulation (GVS) that can mask regular signals until they reach the vestibular nuclei.

The term "galvanic" refers to electric current. An Italian physiologist, Luigi Galvani (1737–1798) observed that the leg muscles of a frog contracted when stimulated with an electric current produced by dissimilar metals [11]. Although Allessandro Volta (1745–1827), an Italian physicist disputed Galvani's experimental results and hypothesis concerning the origin of "animal electricity," Volta became the first person to report dizziness when he

Fig. 1. Special suit for simulating the physical functions of the elderly.

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H. Takada is with the University of the Air and Gifu University of Medical Science, 795-1 Ichihiraga Nagamine, Seki, Gifu 501-3892, Japan (phone: +81-575-22-9401; fax: +81-575-23-0884; e-mail: takada@ u-gifu-ms.ac.jp).

M. Takada was with Nagoya University Graduate School of Medicine and is with the 2nd Department of Physiology, Aichi Medical University School of Medicine, Nagakute, Aichi, 480-1195, Japan (e-mail: masumasu@ aichi-med-u.ac.jp)

M. Miyao is with Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan (e-mail: miyao@itc.nagoya-u.ac.jp).

M. Furuta is with Aichi University of Education, 1 Hirosawa, Igaya-cho, Kariya, Aichi 448-8542, Japan (e-mail: mfuruta@auecc.aichi -edu.ac.jp).

K. Tanaka is with Gifu University Graduate School of Medicine, 1-1 Yanagito, Gifu 501-1194, Japan (e-mail: kutanaka@cc.gifu-u.ac.jp).

T. Shiozawa is with Aoyama Gakuin University, Shibuya, Shibuya-ku, Tokyo 150-8366, Japan (e-mail: shiozawa@busi.aoyama.ac. jp).

applied the current across his own head with his voltaic pile. The technique remains unchanged, but GVS has become increasingly popular in recent decades as a research and sometimes clinical tool. With respect to understanding the aetiology of the human GVS response, the origin of GVS-evoked reflex has not been explicated thus far.

According to previous researches related to the brain, the entire labyrinth with the semicircular canals and otoliths is affected by the GVS [12], [13]. Functional magnetic resonance imaging (f-MRI) during the GVS shows three different sensory systems that are activated in the insula-thalamic region: the vestibular, auditory, and nociceptive systems [14].

GVS at a small stimulus current (0.25–2 mA) can evoke a prolonged galvanic body sway [15] and transient electromyographic response in the leg muscles of a standing human [16], [17]. The onset of the GVS-evoked body sway is rapid and appears to be almost complete within 1 or 2 s of stimulus onset. The sway is in the direction of the anode and affects all body segments [18]. This mechanism has been explained as follows: GVS suppresses the firing rate in the output of the afferent nerves from the vestibular apparatus in the anode side [19], and the subject has an illusion that the human body devotes itself

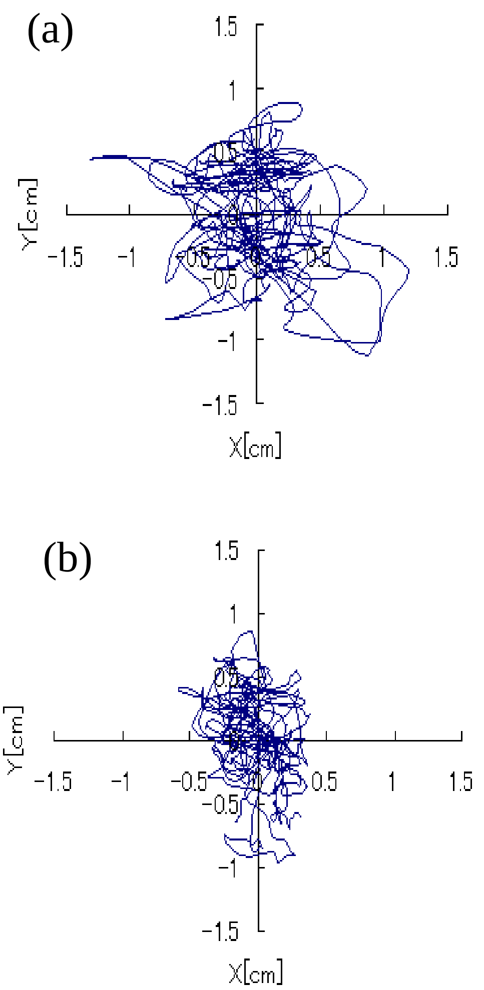


Fig. 2. Typical statokinesigrams [5] recorded when a subject's eyes were closed (a) and when this subject wore the special suit (b).

to the direction of the cathode [20]. Stabilometry has been employed to evaluate the abovementioned equilibrium 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 points in the temporal vicinity, a statokinesigram (SKG) is composed, as shown in Fig.2. Several parameters such as the area of sway (S), total locus length (L), and so forth have been proposed to quantify the instability involved in the standing posture, and these parameters are widely used in clinical studies. However, it is difficult to diagnose the balance function disorders and to identify the declines in the equilibrium function clinically with the abovementioned indices by measuring the SKG patterns. 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 [21]–[23]. We have examined the adequacy of using a stochastic differential equation (SDE) and investigated the most adequate SDE for our research. In the SDE as a mathematical model of the sway, $G(\mathbf{x})$, the distribution of the observed points $\mathbf{x}$, has the following correspondence with $V(\mathbf{x})$, the temporal averaged potential function.

$$V(\mathbf{x}) = -\ln G(\mathbf{x})/2 + \text{const.}$$

The value of $V(\mathbf{x})$ can be obtained from an SKG and must be approximated to a polynomial of the fourth degree [24]. The potential curved surface has multiple minimal points. In the neighborhood of these points, the SDE shows a local stable movement with a high-frequency component (the fine variations involved in posture control) and therefore we can expect a high density of observed points (COPs) in this neighborhood on the SKG. The sparse density (SPD) depends upon the dispersion of the COPs as well as L/S which is regarded as a gauge to evaluate the function of proprioceptive control of standing in human beings. The SPD (See Appendix) is known as an index to evaluate the postural instability in stabilometry [25].

The nonlinear property of SDEs is important. SDEs are affected by electric current during periodic GVS. It is considered that a periodic function s(t) is added to the SDE as a forcing term, and the form of the potential function V(x) changes [26]. An effective potential is estimated as

$$V_{eff}(x) = U(x) + s(t)x,$$

where x expresses a space variable in the lateral direction, that is, the direction of the GVS-evoked body sway. Using the SPD in the analysis of SKGs, we have investigated the metamorphosis in the potential function V(x) in this study. By comparing the SKGs, we herein study the effects of aging and GVS on the sway of COP.

II. Material and Method

Thirty two healthy subjects volunteered for the study, and they were divided into two groups: the group of young people aged <22 yr. (20 ± 1 yr.) and the group of elderly people aged ≥65 yr. (70 ± 4 yr.). Each group had the same number of subjects. In the subsequent stabilometric analysis, we recorded the COP at rest and during GVS.

A. Stabilometry

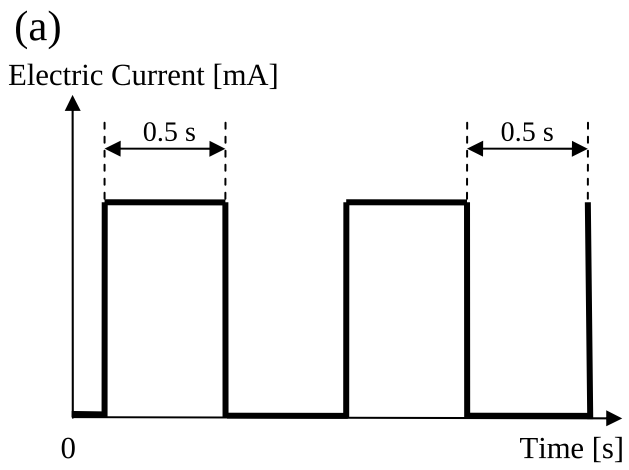
For 1 min before the sway was recorded, the subjects stood still in the Romberg posture with their feet together on the detection stand of a stabilometer (G5500, Anima Co., Ltd.). The COP sway was then recorded (sampling frequency, 20 Hz) at 25 °C when the subjects stood with their eyes open (1 min) and looked at a visual target placed at a distance of 3 m or when their eyes were closed (the following 1 min). The SKGs were simultaneously recorded using the stabilometer.

B. GVS

Every 1 s, rectangular current impulses were output from an electronic stimulator (SEN-3301, Nihon Kohden Co., Ltd.). The duration of the current was set to be 0.5 s (Fig.3a). A small electric current (0.6–2.0 mA) was percutaneously applied on both sides of the mastoid processes through the Ag/AgCl electrodes of an isolator (SS-104J, Nihon Kohden Co., Ltd.) (Fig.3b). We set the amplitude of the electric current to the maximum value obtained in the following anti-GVS test; this value varied among subjects.

C. Anti-GVS test

The initial current was set to be 0.6 mA. An addition of 0.2 mA was made to the last current every 20 s. Conversely, 0.2 mA were subtracted from the last current after the stimulus current reached 2.0 mA. We employed the anti-GVS test with the proviso that the test was be ended whenever the subject wanted or the systolic blood pressure (SBP) decreased to 90 mm of Hg or less, or we observed a sudden drop; the difference between the sudden drop and the stationary blood pressure was larger than 40 mm of Hg [27].



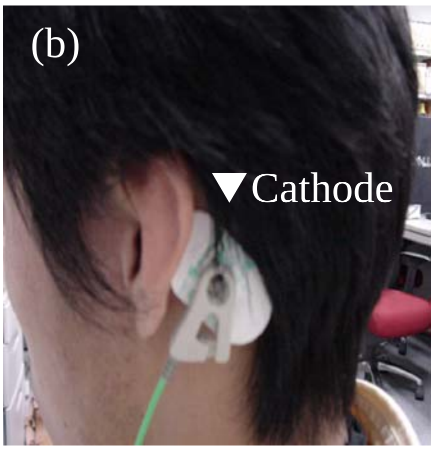


Fig.3. Bilateral monopolar GVS. (a) Rectangular current impulses. (b) Two electrodes to two mastoid processes (cathode-left and anode-right).

D. Statistics

We analyzed the following indices on the SKGs: the area of sway (S), total locus length (L), total magnitude of acceleration (A), A/L, SPD S_k (k = 2, 3), and total locus length involved in the chain (LC) [28] in order to measure the postural instability caused by the effects of aging and the GVS. With regard to these factors, we tested with two arrangements having two levels. Six kinds of values were calculated on an SKG observed when the subjects' eyes were open or closed. We then employed a two-way analysis of variance (ANOVA) with repeated measures for each index and the visual conditions (presence or absence of visual information). The number of repetitions was set to 16 (the number of subjects). We examined the null hypothesis such that there was no interaction between the two factors and no difference between the population means at various levels. Moreover, multiple comparisons were employed along with Tukey's method. In both these statistical tests, a value of $p < 0.05$ was considered to be significant.

III. Results

In Figs.4 and 5, we have shown the typical SKGs that were recorded when each subject's eyes were closed. Figures 4b and 5b show the results during the GVS. In these figures, the vertical axis shows the anterior and posterior movements of the COP, and the horizontal axis shows the right and left movement of the COP. The amplitudes of the sway that was observed in the elderly subjects (Fig.5) tended to be larger than those of the sway that was observed in the young people (Fig.4). Furthermore, the lateral movement of the COP was often observed during the GVS shown in Figs.4b and 5b.

In this study, we employed a two-way ANOVA with repeated measures to analyze the indices for the SKGs recorded when the subjects stood with their eyes closed. No interaction between the factors (aging/presence or absence of GVS) could be detected in the statistical analyses. All indices except S and SPD were affected by the age factor. Further, postural instability was found to increase significantly with age irrespective of the visual conditions. The parameters L, A, SPD, and LC also increased during GVS regardless of the visual conditions ($p < 0.05$). The GVS tended to cause an increase in the A/L observed when the subjects' eyes were opened. Furthermore, we employed the following multiple comparisons among all groups: a) young group at rest, b) elderly group at rest, c) young group with a GVS load, and d) elderly group with a GVS load. There was no difference between the results for groups b) and c).

IV. Discussion

It has been pointed out that posture tends to be maintained for the duration of the stimulus and there is often a reversed sway when the stimulus is stopped [18].

Lateral oscillations in Figs.4b and 5b were thus observed during the GVS. According to the two-way ANOVA with repeated measures for SPD, a main effect was obtained for the GVS factor. We considered that metamorphosis in the potential function V(x) was caused by GVS, and the mathematical model was appropriate to the stochastic resonance in the SDEs. It was reported that the stochastic resonance in the heart rate variability was caused by the GVS [29].

SPD is also known to be an indicator of deterioration in the vestibular cerebellum [28]. With respect to SPD, a significant effect was not found for the aging factor. Postural instability might be caused by the deterioration of the pathways involved in some vestibular nuclei except those of the vestibular cerebellum.

According to the two-way ANOVA with repeated measures for all indices except S and SPD, significant effects were obtained for both factors. No effect on S could be detected in this study. Further, there was no difference in SPD among all the abovementioned groups. There was also no difference between the results for groups b) and c) in accordance with the multiple comparison employed along with Tukey’s method. Using the GVS, we could simulate the deterioration in the equilibrium function with advancing age to a certain extent. Therefore, it can be concluded that postural instability in the elderly is caused by the anomalous signals in the vestibules.

In order to compare the SKGs recorded when the subjects stood with their eyes open and those recorded when the subjects had their eyes closed, we calculated the Romberg ratio for the indices under the above-mentioned conditions a)-d). According to the results of the Friedman tests, the Romberg ratio was not affected by the GVS load. However, L, A, and LC were found to increase significantly with advancing age. Postural instability in the elderly can be improved by the presence of visual information.

V. Conclusion

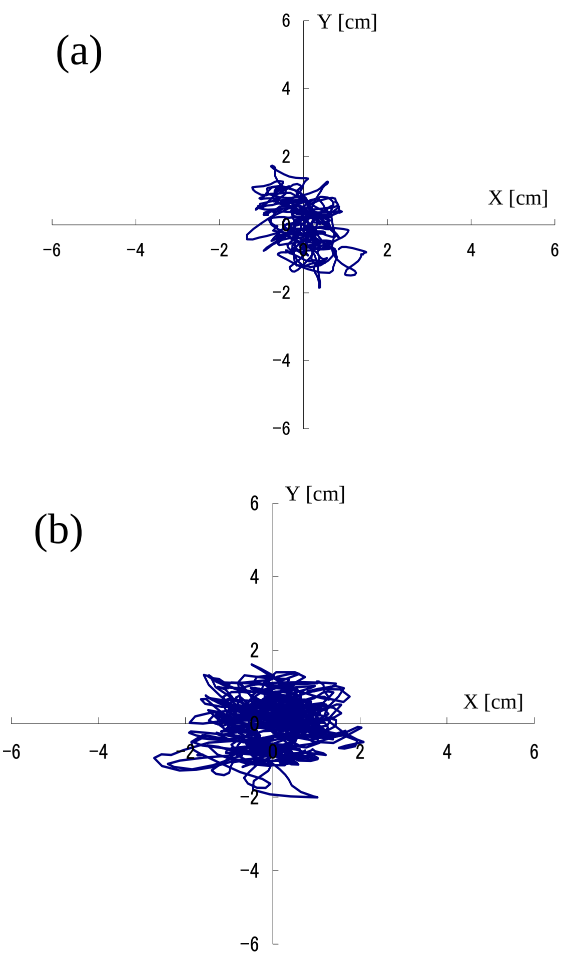
In this study, we have confirmed the following:

1) Metamorphongsis in the temporally averaged potential function in the SDEs was caused by GVS.

2) Postural instability in the elderly could be improved by the presence of visual information.

3) Using the GVS, we could simulate the deterioration in equilibrium function with advancing age to a certain extent.

In Japan, GVS has been integrated into a machine in order to enhance virtual reality [30]. Furthermore, this technique can be applied to special suits (Fig.1). This technique will also be useful in nursing education because



Figs.4. Typical SKGs recorded for a young subject (20 yr. & Male) whose eyes were closed. The SKG was observed at rest (a) and during the GVS (b).

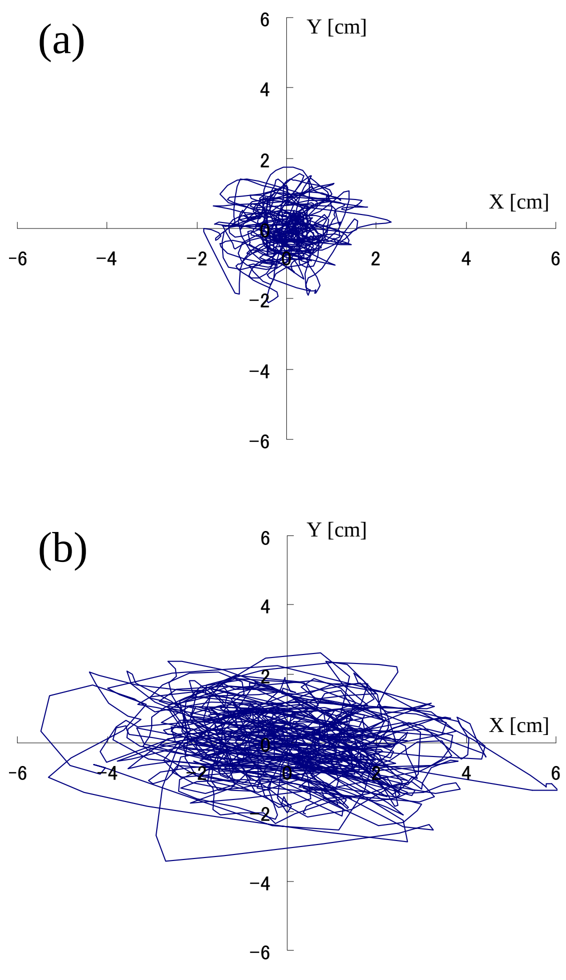


Fig.5. Typical SKGs recorded for an elderly subject (68 yr. & Male) whose eyes were closed. The SKG was observed at rest (a) and during the GVS (b).

the methods for caring for an elderly person would be improved by understanding the physical characteristics of the elderly. We can also utilize the abovementioned technique in order to educate that the risk of falls increases with increasing age. As the next step, we would examine a curative effect of GVS on the deterioration in the equilibrium function with advancing age because effective balance training studies have employed the principle of overload to elicit improvements in stability in young adults [31].

APPENDIX

We herein describe the new quantification indices—"SPD" and "Chain"—that we proposed in [28].

A. Sparse density (SPD)

SPD was defined by a scaling average of the ratio as $G_j(1)/G_j(k)$. An SKG was divided into quadrates whose latus is j times longer than the resolution, and $G_j(k)$ expresses the number of divisions including more than k measured points. If the centre of gravity does not move, the SPD value becomes 1. If there are variations in the SKGs, it becomes greater than 1. In this manner, SPD depends on the characteristic of the SKG and the motion process of the COP.

B. Chain

The force acting on the centre of gravity of the body was defined in terms of the difference in the displacement vectors. In particular, we focused on the singular points where statistically large forces were exerted. Based on these forces, chains were eliminated from the SKG in the form of a consecutive time series [28]. If the times measured at these points were in the temporal vicinity, these points were connected by segments (sequences). The figures formed by these sequences were called "Chain" because of the shape of the connections. The chain was defined to have a cusp pattern by the figures of the sequences of the points where large forces were exerted.

REFERENCES

[1] T. Okawa, T. Tokita, Y. Shibata, T. Ogawa, H. Miyata. (1995) Stabilometry: significance of locus length per unit area (L/A) in patients with equilibrium disturbances. *Equi. Res. 55*. pp. 283-293.

[2] A. Goto. (1992) Effects of eye tracking stimulation on movement of body's center of gravity and head in elderly subjects. *Journal of Otolaryngology of Japan*. *95*. pp. 164–171.

[3] H. C. Diener, J. Dichgan, "On the role of vestibular, visual and somato sensory information for dynamic postural control in humans," in *Prog. Brain Research*, vol.76, O. Pompeoano, J. H. J. Allum. Ed. Amsterdam: Elsevier, 1988, pp. 253-262.

[4] F. B. Hoak, C. L. Shupert, A. Mirka. (1989) Components of postural dyscontrol in elderly: a review. *Neurobiol. Aging*. *10*. pp. 727-738.

[5] H. Takada, Y. Kitaoka, S. Iwase, Y. Shimizu, T. Watanabe, M. Nakayama, M. Miyao, K. Mihashi. (2003) Characteristic changes of sway of center of gravity with advancing age. *Env. Med*. *47*. pp. 85-89.

[6] L. Wolfson, R. Whipple, C. A. Derby, P. Amerman, T. Murphy, J. N. Tobin, L. Nashner. (1992) A dynamic posturography study of balance in healthy elderly. *Neurology*. *42*. pp. 2069-2075.

[7] J. J. Collins, C. J. De Luca, A. Burrows, L. A. Lipsitz. (1995) Age related changes in open-loop and closed-loop postural control mechanisms. *Exp. Brain Res. 104*. pp. 480-492.

[8] P. D. Sloane, R. W. Baloh, V. Honrubia. (1989) The vestibular system in the elderly: clinical imprecations. *Am. J. Otolaryngol*. *10*. pp. 422-429

[9] A. Katasarkas. (1994) Dizziness in aging: a retrospective study of 1194 cases. *Otolaryngol. Head Neck Surg*. *110*. pp. 296-301.

[10] A. Vernadakis. (1985) The aging brain. *Clin. Geriatr. Med*. *1*. pp. 61-94.

[11] D. L. Waldman, R. C. Fitzpatrick. (2002) What does galvanic vestibular stimulation stimulate? *Advances in Experimental Medicine and Biol*. *508*. pp. 119-128.

[12] R. Zink, S. Steddin, A. Weiss, Th. Brandt, M. Dieterich. (1997) Galvanic stimulation in humans: effect on otolith function in roll. *Neurosci. Lett*. *232*. pp. 171－174.

[13] R. Zink, S. F. Buchuer, A. Weiss, A. Th. Brandt, M. Dieterich. (1998) Effects of galvanic vestibular stimulation on otolithic and semicircular canal eye movements and perceived vertical. *Electroenceph. Clin. Neurophysiol*. *107*. pp. 200－205.

[14] S. E. Bucher, M. Dieterich, M. Wiesmann, A. Weiss, R. Zink, T. A. Yousry, T. Brandt. (1998) Cerebral functional MRI of vestibular, auditory and nociceptive areas during galvanic stimulation. *Ann. Neurol*. *44*. pp. 120-125.

[15] A. C. Coats. (1973) Effect of varying stimulus parameters on the galvanic body-sway response. *Annals. of Otology, Rhinology and Laryngology*. *82*. pp. 96-102.

[16] L. M. Nashner, P. Wolfson. (1974) Influence of head position and proprioceptive cues on short latency postural refrex evoked by galvanic stimulation of human labyrinth. *Brain Res*. *67*. pp. 255-268.

[17] T. C. Britton, B. L. Day, P. Brown, J. C. Rothwell, P. D. Thompson, C. D. Marsden. (1993) Postural electromyographic responses in the arm and leg following galvanic vestibular stimulation in man. *Exp. Brain Res*. *94*. pp. 143-151.

[18] B. L. Day, A. Severac Cauquil, L. Bartolomei, M. A. Pastor, I. N. Lyon. (1997) Human body-segment tilts induced by galvanic vestibular stimulation: a vestibularly driven balance protection mechanism, *J. Physiol*. *500*. pp. 661-672.

[19] J. M. Goldberg, C. Fernández, C. E. Smith. (1982) Response of vestibular nerve afferents in the squirrel monkey to externally applied galvanic currents. *Brain Res*. *252*. pp. 156-160.

[20] R. Fitzpatrick, D. Burke, S. C. Gandevia. (1994) Task-dependent reflex responses and movement illusions evoked by galvanic vestibular stimulation in standing humans. *J. Physiol*. *478*, pp. 363-372.

[21] J. J. Collins, C. J. De Luca. (1993) Open-loop and closed-loop control of posture: A random-walk analysis of centre of pressure trajectories. *Exp. Brain Res*. *95*. pp. 308-318.

[22] R. E. A. Emmerik, R. L. van Sprague, K. M. Newell. (1993) Assessment of sway dynamics in tardive dyskinesia and developmental disability: sway profile orientation and stereotypy. *Moving Disorders*. *8*. pp. 305-314.

[23] K. M. Newell, S. M. Slobounov, E. S. Slobounova. (1997) Stochastic processes in postural centre-of-pressure profiles. *Exp. Brain Res*. *113*. pp. 158-164.

[24] H.Takada,, Y. Kitaoka, Y. Shimizu. (2001) Mathematical Index and Model in Stabirometly. *Forma*. *16 (1)*. pp. 17-46.

[25] K. Fujikake, M. Miyao, R. Honda, M. Omori, Y. Matsuura, H. Takada. (2007) Evaluation of high quality LCDs displaying moving pictures, on the basis of the form obtained from statokinesigrams. *Forma*. *22(2)*. pp. 199-206.

[26] H. Takada, K. Tanaka, Y. Matsuura, M. Takada, K. Yokoyama, M. Furuta, K. Fujikake, M. Miyao, T. Shiozawa. (2007) Effects of galvanic vestibular stimulation on form of the potential function. *Bulletin of the Society for Science on Form*. *22(1)*. pp. 69-70.

[27] M. Takada, T. Yamauchi, K. Tanaka, T. Shiozawa, M. Furuta, M. Miyao, Y. Kitaoka, H. Takada. (2007) An investigation into the Galvanic Vestibular Stimulation as a technique to simulate deterioration of the balance function. *Japanese Journal of Erg*. *43*. S230-S231 (In Japanese).

[28] H. Takada, Y. Kitaoka, S. Ichikawa, M. Miyao. (2003) Physical meaning on geometrical index for stabilometry. *Equi. Res. 62(3)*. pp. 168-180.

[29] R. Soma, D. Nozaki, S. Kwak, Y. Yamamoto. (2003) 1/f noise outperforms white noise in sensitizing baroreflex function in the human brain. *Physical Review Letters*. *91(7)*. pp. 078101-1-4.

[30] H. Ando, M. Sugimoto, T. Maeda, "Wearable Momoent Display Device for Nonverbal Communications," *IEICE Trans. Inf. & Syst*., vol.E87-D (6). pp. 1354-1360, 2004.

[31] Th. Brandt, S. Krafczyk, I. Malsbenden. (1981) Postural imbalance with head extension : improvement by training as a model for ataxia therapy. *Ann. N. Y. Acad. Sci*. *374*. 646-649