ANALYSIS OF ROLE OF VISION IN HUMAN UPRIGHT POSTURE CONTROL

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Abstract-**In this study, we investigated the role of the visual feedback in human upright posture control. To make the role of vision clear, we compared the visual, vestibular and somatosensory feedback systems in their ability to perceive movement and suppress short- and long-term sway. First, we measured thresholds for the perception of movement. Then effects of each feedback system to suppress short- and long-term sway were analyzed through posture control experiments, in which the available sensory input was limited. The visual and somatosensory thresholds were small (< 0.1 degree) while the vestibular threshold was relatively large (> 0.5 degree). The results of the posture control experiments suggested that the visual system contributed to suppression of sway in the frequency range below 0.4 Hz and the system had a minor effect in frequencies above 0.5 Hz. These results support our previous finding that the visual system does not allow a normal subject to maintain an upright posture by itself. The somatosensory system, on the other hand, suppressed body sway around 0.2 and 0.9 Hz. The higher frequency range might enable the system to maintain an upright posture by itself.**

Keywords – **Upright posture, sensory feedback, role of vision, threshold for sway perception, sway suppression**

I. INTRODUCTION

Human upright posture is stabilized by sensory feedback from the vestibular and visual sensors and the somatosensory system. In order to understand the basic mechanisms of sensory feedback, it is important to investigate the characteristics of all three sensory feedback systems. The characteristics of the somatosensory and vestibular feedback have been extensively studied [1]-[9]. The results of [6]-[9] suggest that the somatosensory and vestibular systems can maintain an upright posture alone. On the other hand, the experimental results in [10] suggest that the visual feedback system contains a large time delay and, consequently, the system does not by itself allow a subject to maintain an upright posture. Numerous analyses of the relationship between visual stimuli and postural responses have been carried out [11]-[13]. These analyses have revealed that the visual feedback system primarily utilizes information in a relatively low frequency range (up to 0.4 Hz). However, the role of the visual system in postural control is less understood.

In the present study, we investigated the role of the visual feedback system in the following three aspects: i) perception of sway, ii) suppression of short-term sway around the equilibrium point, where the body sway angle with respect to vertical is nearly zero, and iii) suppression of long term-sway induced by slow drift of the equilibrium point. We compared the feedback systems in the three aspects to make the role of the visual feedback system clear. In order to investigate a visual contribution to the perception of body sway, we measured thresholds for the perception of movement. Effects of each feedback system to suppress short- and long-term sway were analyzed through posture control experiments, in which the available sensory input was limited to only one, or a pair, of the vestibular, visual, and somatosensory feedback systems.

II. METHOD

In the present study, for the sake of simplicity, an upright posture control system in the sagittal plane was analyzed, i.e., only the anteroposterior (AP) body sway was considered. Automatic postural reactions to correct AP body sway can be classified on the basis of the joint about which most rotation appears to occur: ankle and hip strategies [14]. The former is most effective for small and slow body sway around the equilibrium point. In contrast, the latter is used when responding to larger and faster displacement. In the present study, we focused on slow and small sway and therefore considered only the ankle strategy. In this strategy, the body moves as a rigid mass in relation to the ankle joints.

A. Threshold for Perception of Sway

To measure vestibular, visual, and somatosensory thresholds for the perception of sway, we employed a method proposed by Fitzpatrick et al. [15]. In their definition, "perception of sway" is being able to give a subjective, correct report about the sway direction. The thresholds for the perception of sway were determined when the following sensory feedback was available: A1) only somatosensory input, A2) only vestibular information, A3) only vision, and A4) the combination of vestibular and visual inputs. Ten healthy male subjects, aged between 21 and 75 years, took part in experiments A1, A2, and A4, while one more subject, 34 years old, participated in experiment A2. None of them had any history of neurological disorders.

We produced movements of either the subject's body (experiments A2 and A4), the subject's visual field (experiment for visual threshold), or the platform, on which the subject stood (somatosensory threshold). The movements were either forward or backward rotations about the ankle joints with various magnitudes. The subjects were asked to identify the directions of the imposed movements. In each experiment, one subject performed several tens of trials, each of which began from the identical angle, where the body sway angle with respect to vertical was zero. The direction of the movements was randomly chosen. After a movement was imposed, the subject was asked to nominate the direction of the perceived body sway or equivalent movement during the

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trial. If the subject reported the correct direction, we regarded the imposed movement as perceived. Otherwise, the movement was regarded as unperceived. If the subject perceived the movement, the magnitude of the movement was reduced by 0.1 degree in the next trial, and conversely, if the subject could not perceive the movement, the magnitude was increased by 0.1 degree. Every subject carried out four or five trials with a magnitude close to his threshold for the perception of the movement. The threshold was defined as the smallest magnitude that the subject could perceive in more than 75 % of the trials of the same magnitude. The thresholds for the forward and backward movement were determined in each experiment.

A1) Somatosensory Threshold: The subject stood with both feet on a platform, whose rotational axis was collinear with that of the ankle joints. The subject was strapped at the head and waist to a rigid back support to suppress vestibular and visual inputs. Accordingly movement of the platform could only be perceived with the somatosensory system. The rotational speed of the platform was 0.35 degree/sec.

A2) Visual Threshold: The subject stood with both feet on a stable platform. The subject's body was strapped with a rigid back support to suppress the vestibular feedback. Because the angle of the ankles was fixed during the experiment, the somatosensory feedback provided no relevant information about sway. A visual enclosure (800 mm in width, 900 mm in depth, and 2,000 mm in height) was employed to provide the movement of visual field [10]. The rotational speed of the visual enclosure was 0.27 degree/s.

A3) Vestibular Threshold: The subject, who was blindfolded, stood on an L-shaped platform. During the experiment, the angle of the ankle was kept constant, and thus the vestibular feedback was the only information source about the sway. The rotational speed of the L-shaped platform was 0.35 degree/s.

A4) Combination of Visual and Vestibular Inputs: The subject stood on the L-shaped platform used in experiment 3 with eyes open. Consequently, in addition to the vestibular input, visual information was available to perceive the sway. The other conditions were same as those in experiment A3.

B. Posture Control Experiments

Measurements: We conducted posture control experiments to investigate the effects of each sensory system to suppress short- and long-term sway. The subjects were asked to stand as still as possible under the following conditions: B1) natural standing (all feedback systems), B2) standing with eyes closed (the somatosensory and vestibular inputs), B3) standing on a sway-referenced support (the vestibular and visual inputs), B4) standing on a sway-referenced support with eyes closed (only vestibular information), and B5) standing on a rotational platform with fixed back support (only the somatosensory input). In all experiments, we assumed that the ankle strategy was used. Ten healthy male subjects, aged between 22 and 47 years, took part in experiments B1, B2, B3, and B4, while eight healthy male volunteers, ranging in age from 22 to 57 years, participated in experiment B5. None of the subjects had any history of neurological disorders.

B1 and B2: The only difference between B1 and B2 was that eyes were open in B1, but closed in B2. The subject stood on a platform. A position sensor system (Hamamatsu Photonics Co., Japan) was used to measure the sway angle by detecting the position of a light-emitting diode attached to the subject's waist. In each experiment, one subject performed four trials, each of which lasted 50 s. The sway angle was measured at every 0.05 s.

B3 and B4: The only difference between B3 and B4 was that eyes were open in B3, but closed in B4. A sway-referenced support was employed to maintain the ankle joints at a constant angle and, thus reduce a somatosensory (mainly proprioceptive) contribution. To measure the angles of the leg, body, and support, the position sensor system used in B1 and B2 was employed. The other conditions were same as those in B1 and B2.

B5: A platform, whose rotational axis was collinear with that of the ankle joints, was employed. The subject stood in the same way as experiment A1. Because the subject's body was immovable under the experimental conditions, the subject controlled a computer model that simulated his body dynamics using the ankle strategy. A servomechanism controlled the angle of the platform (the ankle angle) according to the sway angle of the computer model. Information about the sway angle of the model was fed through the somatosensory feedback. In other words, forward leaning of the model caused the same amount of toe-up rotation and conversely, ankle plantarflexion occurred when the model leaned backward.

Data Analysis: Measured sway angle data were analyzed in the following way. First, we calculated a linear trend of the time series obtained in a trial. The slant parameter of the linear trend was reckoned to indicate the amount of long term-sway induced by slow drift of the equilibrium point. After the linear trend was removed from the measured time series, the standard deviation of the resultant signal was calculated. We regarded that the standard deviation indicated the amount of short-term sway around the equilibrium point. The overall average of the slant parameter of the linear trend and the standard deviation of the short-term sway were calculated in each experimental condition. By a pairwise comparison of the averages, the effect of each sensory system to suppress the long- and short-term sway was analyzed. For example, the effect of vision was investigated by comparing B1 with B2 and B3 with B4.

We also calculated the frequency spectrum (the range between 0.02 and 1.5 Hz) of the short-term sway to investigate the working range of each sensory system. After the power spectrum was normalized by the total power, it was divided into 15 bins, each of which had a width of 0.1 Hz. Then the obtained spectra were averaged over all trials in each experimental condition. We calculated the spectral ratios, B2/B1 and B4/B3, to investigate the working range of the visual system and the ratios, B3/B1 and B4/B2, for the somatosensory system.

III. Results and discussion

A. Threshold for Perception of Sway

Table 1 summarizes the measured sensory thresholds for the perception of sway. The average of the each experimental condition is given. For all sensory conditions, there was no significant difference between the ability to perceive forward or backward movement. The somatosensory and visual thresholds were 0.1 degree (the smallest value tested) whereas the vestibular thresholds were relatively large. These results, which agree with what Fitzpatrick et al. [15] observed, suggest that the somatosensory and visual feedback systems are predominant in the perception of body sway.

TABLE I
SENSORY THRESHOLDS FOR THE PERCEPTION OF SWAY. AVERAGE OF EACH CONDITION IS SHOWN. A1: SOMATOSENSORY, A2: VISUAL, A3: VESTIBULAR, A4: VESTIBULAR + VISUAL (UNIT: DEGREE)

	Number of subjects	Anterior threshold	Posterior threshold
A1	10	0.10	0.10
A2	10	0.10	0.10
A3	11	0.54	0.64
A4	10	0.11	0.12

B. Posture Control Experiments

Fig. 1 shows examples of body sway obtained in each experimental condition. Body sway was very small during natural standing whereas the largest sway was observed in B4. The overall average of the standard deviation of the short-term sway increased in the order of B1 (natural standing), B2 (standing with eyes closed), B5 (standing with only the somatosensory input), B3 (the vestibular and visual systems) and B4 (only the vestibular information). These results are reasonable, indicating that the standard deviation became larger as the number of the available information sources was decreased. Table II summarizes the effects of each sensory system to suppress short- and long-term sway. Marks '++' and '+' denote that the system suppressed the short- or long-term sway. Here, '++' represents statistical significance ($p < 0.01$). A mark '-' shows a minor contribution of the system to suppression of body sway. As shown in the table, the visual system contributes to suppression of both short- and long-term sway. These effects of vision might be relevant to so-called visual stabilization of posture. The somatosensory system can suppress the short-term sway, but it cannot prevent the equilibrium point from drifting. The vestibular system can suppress neither short- nor long-term sway.

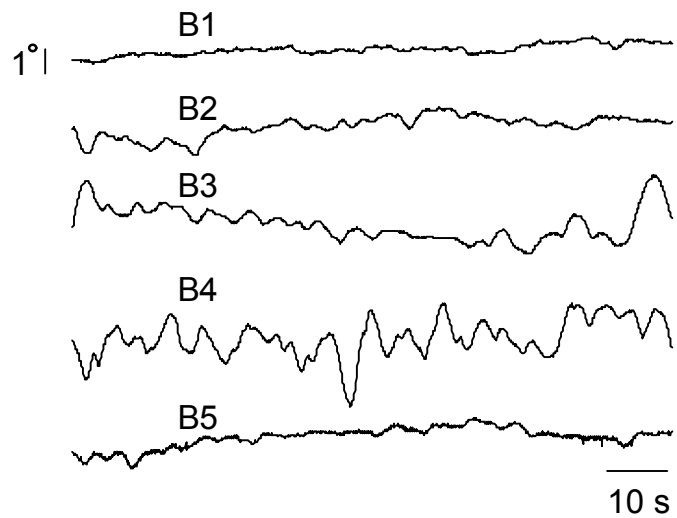

Fig. 1. Examples of body sway obtained in each experiment. (a) B1 (natural standing), (b) B2 (standing with eyes closed), (c) B3 (standing with the vestibular and visual systems), (d) B4 (only the vestibular input) and (e) B5 (only the somatosensory input).

TABLE II
THE EFFECT OF EACH SENSORY SYSTEM IN SUPPRESSION OF SWAY. MARKS '++' AND '+' DENOTE THAT BODY SWAY WAS SUPPRESSED. '++' REPRESENTS STATISTICAL SIGNIFICANCE ($p < 0.01$). '-' SHOWS THAT THE SYSTEM HAD A MINOR EFFECT IN SWAY SUPPRESSION.

	Short-term sway	Long-term sway
Visual	++	+
Vestibular	-	-
Somatosensory	++	-

Fig. 2 illustrates the spectral ratios: (a) depicts the effect of vision in each frequency bin and (b) shows that of the somatosensory system. A large value in a bin shows that body sway in the frequency range increased by removing visual information (a) or somatosensory information (b) and suggests that the sensory information has the major effect in the range. As shown in the figure, the visual system mainly suppresses body sway in the frequency range between 0.2 and 0.4 Hz. These results agree with the fact that the system utilizes information up to 0.4 Hz [10]-[13]. However, it has a minor contribution to suppression of body sway above 0.5 Hz and accordingly it cannot allow a normal subject to maintain an upright posture by itself [10]. On the other hand, the results in Fig. 2(b) show two peaks: one in a low frequency range (around 0.2 Hz) and the other around 0.9 Hz. The higher-frequency working range agrees with the frequency range of the characteristic body sway caused by ischemic blockage at the thigh level [1]-[2]. The suppression in the high-frequency range may enable the somatosensory system to maintain an upright posture by itself. However, this point needs to be investigated more thoroughly because there was relatively little power in the sway angle at this higher frequency range under the experimental conditions.

IV. Summary

In the present study, we investigated the role of the visual feedback system in perception of body sway, and suppression of short- and long-term sway. To make the role of vision clear, we compared the sensory feedback systems in the three aspects. The visual and somatosensory thresholds for the perception of sway were small (< 0.1 degree) while that of the vestibular system was relatively large (> 0.5 degree). The

results of the posture control experiments suggest that the visual system contributes to suppression of both short- and long-term sway. However, its working range is mainly between 0.2 and 0.4 Hz and it has a minor effect in suppression of body sway above 0.5 Hz. Accordingly the visual system might be too slow to allow a normal subject to maintain an upright posture by itself. On the other hand, the somatosensory system has two working ranges around 0.2 and 0.9 Hz. The higher frequency range might enable the system to maintain an upright posture by itself. (This point, however, needs to be investigated further because there was little power in sway angle in the frequency range under the experimental conditions.) These findings agree with the results of our previous studies [9]-[10], in which we have shown that the somatosensory system allows a normal subject to maintain an upright posture by itself but the visual system does not.

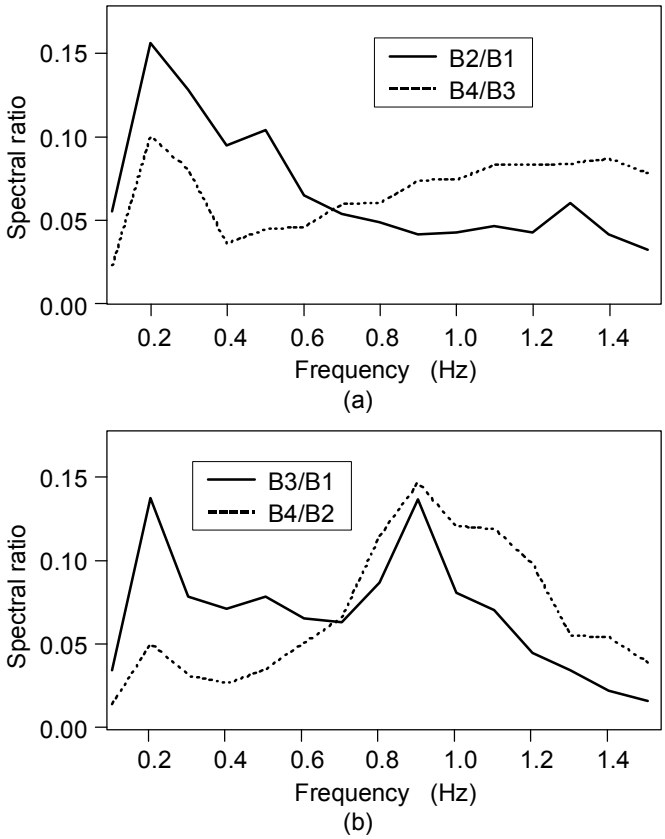

Fig. 2. Normalized spectral ratios: (a) shows the effect of the visual feedback system and (b) that of the somatosensory system. The visual effect was investigated by two pairwise comparisons (B2 with B1 and B4 with B3). The effect of the somatosensory system was analyzed in the same manner.

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