Dynamic Postural Adjustments in Stance in Response to Translational Perturbation in Presence of Visual and Somatosensory Disturbance

Yusuke Maeda1,* Toshiaki Tanaka1 Yasuhiro Nakajima2 Tomoya Miyasaka3
Takashi Izumi4 Norio Kato5

1Research Center for Advanced Science and Technology, University of Tokyo, Tokyo 153-8904, Japan
2Industrial Research Institute, Hokkaido Research Organization, Kitaku, Sapporo 060-0819, Japan
3Department of Prosthetics and Orthotics, College of Medicine, University of Tokyo, Minami-ku, Sapporo 060-8601, Japan
4Department of Community Development, School of International Cultural Relations, Tokai University, Minami-ku, Kita-ku, Sapporo 006-0814, Japan
5Graduate School of Information Science and Technology, Hokkaido University, Kitaku, Sapporo 060-0814, Japan

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Abstract

Despite many reports on the role of the sensory system in postural control, only a few studies have reported the relationship between sensory disturbance and dynamic postural control. To investigate capabilities for dynamic postural adjustment, this study quantitatively evaluated the response to translational perturbation. Perturbation was experimentally induced in eight subjects (all male, 21.3 ± 1.4 years old) using a platform movable in four directions (forward, backward, right, and left). The response was measured in terms of the center of pressure (COP) using posturography, and electromyography of the trunk and lower extremities, and joint angle using video analysis. The effect of sensory disturbance was examined when wearing translucent goggles and when standing on a soft mat. A significant difference was found in the displacement of COP between the cases with and without sensory disturbance. With disturbance, the medio-lateral and anterior-posterior components of the displacement increased in the posterior and lateral translations, respectively. In addition, postural response against forward translation was not affected by sensory disturbance compared with backward and medio-lateral translation. The results of these analyses provide information useful for the development of balance rehabilitation using translational perturbation.

Keywords: Postural control, Sensory disturbance, Translation, Center of pressure displacement

1. Introduction

The center of pressure (COP) must be placed at the base of a support to maintain a standing posture, which is referred to as postural control. Such control is achieved by the interaction of many components and includes the integration of visual, somatosensory, and vestibular system information as well as the execution of appropriate motor commands. However, visual and somatosensory inputs are not always accurate sources of orientation information [1]. When standing on a surface which is moving, or on a soft mat, somatosensory input is inappropriate for controlling the vertical position of the body. Dokka et al. reported that even in the absence of direct physical perturbations, subjects actively produce compensatory body movements in response to movement of the visual scene [2]. Vestibular signals alone cannot provide the central nervous system with accurate information on how the body is moving in space [1] and therefore another available sensory source must be selected [3].

Nashner et al. introduced the concept of “sensory-reweighting” for postural control [4]. Here, the “weight” of a sensory input depends on its accuracy as a reference for body motion [1]; in other words, as one mode of sensory input becomes less reliable, another mode is weighted more heavily. Other study observed this in normal subjects, who could maintain a standing posture in spite of visual and somatosensory disturbance [5]. It has been reported that the dependence on visual information for the control of balance is greater when standing in a leaning position than in a normal or neutral position [6], as the change in pressure distribution caused by leaning diminishes the usefulness of the pressure distribution information [7]. Buchanan and Horak reported that some subjects with bilateral vestibular loss were better than
2. Materials and methods

2.1 Subjects

Subjects were 8 healthy adults (all male, 21.3 ± 1.4 years old, height: 171.2 ± 3.3 cm, weight: 63.4 ± 5.2 kg). None of the subjects had any neurological disorder or orthopedic history associated with their lower limbs. Subjects were given a carefully written explanation of the experimental purpose, method, and privacy protection in advance of the experiment. They provided written informed consent to participate in this study.

2.2 Procedure

Using an electrically operated platform, dynamic translation perturbation was applied in four directions: forward, backward, right, and left. Each perturbation stimulus had a 1.28-s duration and a 0.25-m displacement (acceleration and deceleration lasted for 0.64 s at 0.6 m/s²). The subjects were asked to stand on the platform with their arms crossed to maintain an upright posture in the feet-apart position (approximately shoulder width). After letting the subjects practice the procedure several times, perturbation was applied at random intervals between 5-10 s after starting the measurement session in order to prevent anticipatory control. Data were excluded when the perturbation caused a step or steps of the lower limbs. In such cases, the trial was started over. A physical therapist stood laterally near the subject and was prepared to support him if necessary to ensure safety 3.

To elicit sensory disturbance, translucent goggles (goggles condition) and a soft mat (mat condition) were used. Perturbation was applied under the following four conditions: normal condition (open eyes, no mat); mat condition (open eyes, standing on the mat); goggles condition (wearing goggles, no mat); mat + goggles condition (wearing goggles and standing on the mat) (Fig. 1). Normal ski goggles whose lenses were covered by translucent film were used. The hardness of the mat corresponded to rubber C7 in Japanese Industrial Standard 7312.

2.3 Data collection

Fig. 2 shows the experimental set up of this study. To analyze the movement of the COP, a force plate (Custom-built device, Kyowa Electronic Instruments Ltd., Tokyo, Japan) on the platform. The sampling rate was 1000 Hz (converted to 100 Hz for analysis). A utility telemeter (MT11, NEC Corp., Tokyo, Japan) was used to measure electromyography (EMG) at a sampling frequency of 1000 Hz to evaluate muscle activity under an unstrained condition in the following target muscles: right tibialis anterior, right medial head of the gastrocnemius, right rectus femoris, right biceps femoris, bilateral gluteus medius, bilateral rectus abdominis, and bilateral spinal erectors. The EMG signals were normalized by the EMG magnitude during isometric contraction at the maximum muscle power. This value was determined in advance by resistance given by the examiner. Particular attention was paid to the fixation, except for the target areas, using Bohannon’s method to ensure that the greatest muscle power was elicited [11]. For three-
dimensional (3D) motion analysis, a motion measurement system (Frame-DIAS, DKH Ltd., JPN) was used. The sampling frequency of each camera was set at 120 Hz. At the measurement points, 14-mm-diameter infrared reflective markers were placed. The measurement points were the acromion, lower ends of the sternum, anterior and posterior superior iliac spine, the greater trochanter, knee joint center, lateral malleolus, heel, and the fifth metatarsal head. The platform, utility telemeter, and motion measurement system were synchronized and operated simultaneously.

2.4 Data analysis

Fig. 3 illustrates the method of data analysis. COP parameters under perturbation were calculated, and the total COP distance and COP latency (time from perturbation to start of COP motion) were analyzed. In addition, COP displacement was qualitatively analyzed, Fig. 3(a). For EMG data analysis, biological information analysis software (Bimutas II, Kissei Comtec Co. Ltd., Tokyo, Japan) was used. After high-pass filtering (20 Hz) and full-wave rectification smoothing (simple moving average of 201 points), signals were normalized by the peak amplitude during isometric contraction at maximum power. Two kinds of muscle latency times were calculated from the normalized EMG. The muscle latency time against the platform (p-latency) was defined as the period between two time points, T1 and T2, where T1 is the time when perturbation was applied and T2 is the time when muscle activity started. T1 and T2 were identified as the times when the marker on the platform started to move, and when the EMG amplitude exceeded 3 standard deviations of its baseline respectively [12]. The muscle activity latency against COP (c-latency) was defined as the period from the beginning of COP movement and the start of muscle activity. The amount of muscle activity was evaluated using the time-integrated value of muscle discharge in the perturbation (Fig. 3(b)). For 3D angle change calculation, Frame-DIAS was used. Then, the angle changes of the trunk, hip, knee, and ankle joint in the sagittal and frontal planes were analyzed. Fig. 4 and the appendix give definitions of each joint angle. The angle produced by the first and second vector was calculated for each part. The mean value of all subjects was calculated by quantifying the angle change as the difference between the angle in the upright position before perturbation and the angle in the upright position under a steady state after perturbation had ceased.

![Figure 4. Definition of angle change.](image)

2.5 Statistical analysis

The differences in each COP parameter, angle change, and muscle activity between the four conditions were compared using repeated measures analysis of variance (ANOVA) with Bonferroni post-hoc tests and the Friedman test. Significance was inferred at $P < 0.05$. Statistical analysis was conducted using SPSS13.0 software (SPSS, Tokyo, Japan).

3. Results

3.1 COP

Fig. 5 presents typical time series of COP trajectories under the normal and mat + goggles conditions. COP position in the upright stance before perturbation was at the origin. The COP trajectory was recorded during the perturbation. The COP trajectory is largely in an orthogonal direction for backward, right, and left translations under the mat + goggles condition compared to that under the normal condition. In particular, an
increase in displacement under the mat + goggles condition was observed after COP was reversed. Table 1 shows the COP parameter results. No significant differences in sensory conditions of total COP length were observed in any of the four directions. COP latency under the mat and mat + goggles conditions was longer than that under the normal condition for backward, right, and left translations. For maximum COP displacement, the medio-lateral (M-L) component of backward translation and the anterior-posterior (A-P) component of right and left translations under the mat and mat + goggles conditions were longer than those under the normal condition.

### 3.2 Muscle activity

Fig. 6 shows the p-latency times. No differences in sensory conditions were observed in any of the four directions. Fig. 7 shows the results of the c-latency, where “(+)” means that the muscle activity started after the COP had started to move. In terms of forward translation, all muscles except the gastrocnemius were negative. This means that muscle activity started before the COP movement. For backward, right, and left translations, the anterior tibialis and left gluteus medius muscles began to act almost at the same time as COP started to move, followed by the other muscles. No differences in sensory conditions were observed in any translation direction. Fig. 8 shows the results of muscle activity. No statistical differences in sensory conditions were observed in forward translation. The activity of the gastrocnemius, rectus femoris, biceps femoris, and right erector of the spine under the mat + goggles condition against backward translation was larger than that under the normal condition according to Friedman’s test. Similarly, the activity of the anterior tibialis, gastrocnemius, and left gluteus medius against right translation, and the gastrocnemius, rectus femoris, left and right gluteus medius, and left and right spinal erectors against left translation was larger than that under the normal condition. The muscle activity under the mat + goggles condition tended to increase against backward, right, and left translations.

**Table 1. COP parameters.**

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Mat</th>
<th>Goggles</th>
<th>Mat + Goggles</th>
<th>Repeated ANOVA</th>
<th>Post hoc</th>
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<tr>
<td><strong>Total COP length (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Anterior</td>
<td>237.4</td>
<td>47.6</td>
<td>319.6</td>
<td>176.8</td>
<td>301.5 96.5</td>
<td>294.7 209.1</td>
</tr>
<tr>
<td>Posterior</td>
<td>216.1</td>
<td>30.2</td>
<td>215.7</td>
<td>34.7</td>
<td>252.3 62.1</td>
<td>291.4 108.8</td>
</tr>
<tr>
<td>Right</td>
<td>255.3</td>
<td>40.3</td>
<td>269.6</td>
<td>56.5</td>
<td>261.8 50.6</td>
<td>312.6 53.4</td>
</tr>
<tr>
<td>Left</td>
<td>242.6</td>
<td>51.1</td>
<td>277.2</td>
<td>48.3</td>
<td>255.1 47.9</td>
<td>271.9 35.5</td>
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<tr>
<td><strong>COP latency (msec)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Forward</td>
<td>144.3</td>
<td>74.1</td>
<td>198.6</td>
<td>88.2</td>
<td>195.7 43.5</td>
<td>182.9 84.2</td>
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<tr>
<td>Backward</td>
<td>141.4</td>
<td>67.2</td>
<td>244.3</td>
<td>85.8</td>
<td>202.9 23.6</td>
<td>211.4 110.7</td>
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<tr>
<td>Right</td>
<td>147.1</td>
<td>29.8</td>
<td>218.6</td>
<td>68.2</td>
<td>150.0 40.8</td>
<td>204.3 41.6</td>
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<td>191.4</td>
<td>37.2</td>
<td>110.0 52.6</td>
<td>171.4 44.9</td>
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<tr>
<td><strong>Maximum COP displacement (mm)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Forward</td>
<td>82.8</td>
<td>12.7</td>
<td>89.3</td>
<td>16.9</td>
<td>91.0 15.5</td>
<td>95.5 21.8</td>
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<tr>
<td>Backward</td>
<td>48.0</td>
<td>24.0</td>
<td>52.9</td>
<td>27.0</td>
<td>48.7 20.5</td>
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<tr>
<td>Right</td>
<td>78.5</td>
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<td>83.6</td>
<td>12.9</td>
<td>89.2 13.8</td>
<td>85.7 11.1</td>
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<td>16.4</td>
<td>116.8</td>
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<td>108.2 21.2</td>
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<tr>
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<td>79.3</td>
<td>37.6</td>
<td>53.5 21.8</td>
<td>76.2 17.3</td>
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<tr>
<td></td>
<td>99.9</td>
<td>9.6</td>
<td>110.2</td>
<td>18.3</td>
<td>109.4 13.4</td>
<td>105.3 17.6</td>
</tr>
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</table>
3.3 Angle change

Table 2 shows average angle change. No differences in sensory conditions were observed for average angle change in forward, right, or left translation. The average change in the ankle joints under the mat condition was larger than that under the normal condition with back translation.

4. Discussion

The results of this study demonstrate that two factors are associated with postural control against translational perturbations in the presence of sensory disturbance. In particular, the results of the COP parameter analysis show that sensory disturbance exaggerated displacement in the direction orthogonal to the direction of perturbation. In the time series analysis, COP reversed to follow the direction of perturbation after it had moved in the direction opposite to that of perturbation once. The increase in the orthogonal component
of COP was observed in the later period. While the initial component of the response in the early period is based on the stiffness of the muscles and tissues [13], the continuous modulation in the later period is due to the feedback system using peripheral sensory inputs [14]. The central nervous system must estimate the characteristics of the perturbation, but the magnitude is not clearly known until the perturbation has finished [13]. Ting et al. reported that the direction of the floor reaction force plays an important role in controlling the direction of automatic postural response [15]. In the present study, the floor reaction force exerted on the plantar surface continued to change because of the soft mat, which made directional control difficult and resulted in increased movement. At the time of posterior translation, Henry et al. reported that the horizontal force vectors are directed outward and the authors assumed that this reflected the biomechanical constraints of a toe-out position [16]. At the time of left or right translation, displacement in the left and right direction is controlled mainly by the hip joints [17]. At the same time, postural movements to the front and back are also controlled through the forward-pushing function of the lower leg on the non-load side and the backward-pushing function of the lower leg on the load side [16]. This suggests that the sensory disturbances triggered by the mat made it difficult to control forward and backward movements. This study thus clearly shows that the increase in COP displacement in the direction orthogonal to disturbance was the characteristic postural response in the presence of visual and somatosensory disturbance.

The results of this study also show that although sensory disturbance hardly affects forward translation, it affects backward translation and causes changes in postural strategy. Even during sensory disturbance, forward translation resulted in COP latency and displacement and muscle activity similar to those observed under the normal condition. A previous study found a correlation between COP latency after forward translation and the activity of the agonist muscle, the tibialis anterior [18]. It was also reported that COP displacement is sensitive to backward translation because of the involvement of unnecessary steps [19]. This is apparently because sensitivity of the muscle spindles intensifies in the presence of fear related to posture [20]. Similarly, the present study showed that p-latency was negative at the time of backward COP displacement and that muscle activity started before COP displacement. These results indicate that muscle activity in response to forward translation starts prior to COP displacement, even during sensory disturbance, and that the extent of displacement in adjusting posture is similar to that seen under the normal condition.

On the other hand, backward translation increases the angle of the hip joint, although not significantly, presumably through an ankle + hip strategy. The factors associated with the transition from an ankle strategy to a hip strategy for controlling stance posture are mainly an aging-related functional decline of the ankle joint [5] and a decrease in afferent sensory input due to an ischemic foot [21]. As in the decline of sensory input, somatosensory disturbance induced by the mat clearly influences postural control. It has been reported that the function of the somatosensory system declines when the body is tilted and that this functional decline is compensated for by the visual and vestibular sense systems [7]. In the present study, the functional decline in the somatosensory system due to the mat was amplified by the disturbance of the visual and vestibular sense systems from wearing the goggles. This appears to have greatly affected postural control during backward translation and increased postural instability, thus forcing a transition to an ankle + hip strategy.
The results of this study will be extremely important for the development and application of rehabilitation therapy that uses postural disturbance. For example, COP displacement in the orthogonal direction of a translational perturbation may be a useful parameter by which an individual’s adjustment to a sensory disturbance in the dynamic postural response can be evaluated. We believe that further study is needed to elucidate how dynamic postural control during sensory disturbance enhances other sensory mechanisms.

5. Conclusion

This study clarified the characteristics of postural responses to translational perturbation under conditions of sensory disturbance by using EMG force plates, and 3D motion analysis. The characteristic response to translational floor perturbation during sensory disturbance was an increase in orthogonal COP components. This result may be used for evaluation of the dynamic postural response against sensory disturbance. In addition, postural control during forward translation was rarely affected by sensory disturbance, suggesting that it would be useful for evaluating balance capabilities and formulate a balance training program.

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References


