Analysis of Postural Adjustment Responses to Perturbation

Stimulus by Surface Tilts in the Feet-together Position

Yusuke Maeda¹,* Toshiaki Tanaka¹ Yasuhiro Nakajima²
Koichi Shimizu³

¹Research Center for Advanced Science and Technology, Tokyo 153-8904, Japan
²Hokkaido Research Organization, Industrial Research Institute, Sapporo 060-0819, Japan
³Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan

Received 3 Mar 2010; Accepted 17 Jan 2011; doi: 10.5405/jmbe.867

Abstract

Base of support (BOS) influences the postural control of upright standing in humans. Since a narrowed BOS in the upright position makes postural control difficult, it is important to evaluate and practice balance with a narrowed BOS. We performed an experimental study to clarify the postural control mechanism in a feet-together position in response to dynamic perturbations. Subjects were 10 healthy young adults. Using an electrically operated platform, tilting perturbation was applied to subjects standing in feet-together position. Perturbation was in four directions: backward, forward, right, and left. Using a motion analysis system and electromyography (EMG), we simultaneously measured the three-dimensional postural change and EMG of seven muscles of the trunk and legs. We obtained joint angular change from the motion analysis and the integrated values of muscle activity and latency of the lower extremities from the EMG. In terms of pitch tilt, the ankle strategy was observed: this involved simultaneous contraction of the ankle muscles as usual in the upright position. In contrast, in terms of roll tilt, “counterweighting” was observed. We also observed a change in postural control to respond to the narrowed BOS. We found that, unlike the feet-apart position, the feet-together position, narrowing the BOS in the left-right direction causes a prominent change and makes postural control strategy difficult only in response to roll tilt perturbations. In the future, we need to investigate the effectiveness of balance training including roll tilting in the feet-together position in improving balance ability in the left-right direction.

Keywords: Postural control, Tilting perturbation, Response latency, Feet-together position

1. Introduction

Postural stability, also referred to as balance, is the ability to control the center of mass in relationship to the base of support (BOS) [1]. Balance requirements change according to the task and the environment. The task of maintaining balance while stationary (i.e., “static” balance during standing and sitting) differs from that of maintaining balance when the person or support surface is moving (i.e., “dynamic balance” during walking and responding to a perturbation) [2]. Therefore, it is necessary to evaluate not only static balance but also dynamic balance. For static balance evaluation, body sway in the upright standing position is measured by posturography [3,4]. Similarly, muscle activity, motion strategy, and moment are calculated to investigate the dynamic balance, using EMG, three-dimensional motion analysis systems, and force-plates, respectively [5,6].

Based on these evaluations, effective balance training methods have been developed. Granacher et al. reported that resistance training of the legs improved maximal muscle strength and performances in the functional reach test and tandem walk test [7]. Previous study showed that balance training with feedback information about BOS for hemiparesis patients resulted in improvement of gait with longer step length [8]. Many studies have focused on the BOS or the support surface. The BOS size is viewed as one factor that affects upright postural control, and a narrowed BOS in the upright position makes postural control difficult. According to [9], the smaller the BOS in the upright position, the greater the body sway. Hence, the feet-together position, with feet together in the upright position, is often used for clinical balance evaluation or training. Nnodim et al. reported that balance training with narrowed BOS (unipedal stance and tandem stance) produced modestly greater improvement than other training [10].
In terms of feet-apart (normal) stance position, experiments using linear motion or pitch and roll tilting of a support surface have obtained various findings about dynamic postural control. Carpenter et al. showed that postural control is achieved by leg movement during pitch tilting and by hip or trunk movement during pitch-roll tilting [11]. In addition, in terms of the complex tilting in both pitch and roll tilting directions, the perturbation direction in which each activity of each muscle is greatest has been identified using EMG [11]. Other study showed that forward tilt is mostly absorbed and corrected by flexing movements of the lower extremities [12]. Other study reported that postural control against pitch and roll motion of the support surface are programmed separately by the central nervous system [13]. Furthermore, the characteristics of each postural reflex or response have been described according to EMG latency after surface tilt. Studies reported that after perturbation, a short-latency reflex called a stretch reflex occurs, and then a long-latency reflex is observed at 40-120 msec [14,15]. Carpenter et al. demonstrated that postural response constitutes voluntary stabilizing reactions that are initiated with latencies of 350-750 msec [11].

In terms of postural control in the feet-together position, to the best of our knowledge, no studies have described quantitative analyses such as muscle latency time and muscle activity integration values and average angular change. In this position, because the BOS is narrowed in the left-right direction, the possibility exists that the postural control response described above might change to respond to tilting. Therefore, this study aimed to clarify part of the mechanism of postural control during dynamic tilting in the feet-together position through quantification of muscle activity and qualitative movement analyses. We discuss the results with regard to the clinical possibility of balance training in the feet-together position.

2. Materials and methods

2.1 Subject

The subjects were 10 healthy adults (age 23.4 ± 2.2 years; height 170.3 ± 8.6 cm; weight 61.2 ± 7.6 kg; 6 male and 4 female). No subject had a neurological disorder or orthopedic history in their lower limbs. Subjects were given a carefully written explanation of the experimental purpose, method, and privacy protection in advance of the experiment. They submitted their written informed consent to participate in this study. This research was part of a study that obtained approval from the ethics committee of Sapporo Medical University.

2.2 Stimulus parameters

Using an electrically operated platform with six degrees of freedom on axes (Mitsubishi Precision Company Ltd., Japan), we applied dynamic tilting perturbation in four directions, i.e., toe-up and toe-down stimuli around the frontal-horizontal axis of rotation; right-up and left-up stimuli around the sagittal-horizontal axis of rotation. The direction within the horizontal plane was defined as follows. The front side of a subject in the upright posture was defined as 0°; clockwise, right side, 90°; the back side, 180°; and the left side, 270°. In addition, the perturbation by which the floor pitched downward in the direction of 0° (toe-down) was defined as pitch forward. Similarly, the other directions were defined: motion in the direction of 90° (right-down), roll right; in the direction of 180° (toe-up), pitch backward; and in the direction of 270° (left-down), roll left. Furthermore, pitch tilt was defined as pitch forward and backward, and roll tilt was defined as roll right and left. A perturbation or a single dynamic stimulus was defined as having 300 ms duration and 15° movement (50°/s) from the horizontal direction.

2.3 Procedure

The subjects were asked to stand on the platform with their arms crossed to maintain their upright posture while staring at an object set 3 m ahead at eye level. At this time, the lower limbs were in the feet-together position to align the ankles with the pitch and roll axes of rotation. After letting the subjects practice the procedure several times, their motion and EMG were measured for a perturbation direction that was determined randomly. The perturbation was applied at random interval between 5–10 s after starting the measurement session to prevent anticipatory control. The data were excluded when the perturbation caused a step or steps of the lower limbs. The subjects completed one trial. If such case happened, the trial was started over. A physical therapist stood laterally near the subject and was prepared to support the subject if necessary to ensure each subject’s safety. Data recording started 1 sec prior to the perturbation, and finished 500 msec after the platform stopped.

2.4 Data collection

For three-dimensional motion analysis, a motion measurement system (VICON512; Oxford Metrics Ltd., UK) was used. In the system, five cameras were 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 frontal and occipital regions of the head, acromion, the spinous process of the seventh cervical vertebra, the spinous process of the tenth thoracic vertebra, upper and 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.

A utility telemeter (NEC Corp., Japan) was used to measure the EMG at a sampling frequency of 1.08 kHz to evaluate muscle activity in an unstrained condition. Three-dimensional motion measurements were performed simultaneously in synchronization with the EMG measurement (Fig. 1). Target muscles were the bilateral tibialis anterior muscle, medial head of gastrocnemius muscle, rectus femoris muscle, biceps femoris muscle, gluteus medius muscle, rectus abdominis muscle, and erector spinae muscle. For EMG measurements, surface electrodes (Ag/AgCL disks, 10 mm-diameter) were used. The electrodes were attached to the largest bulging area of the cutaneous surface of each muscle.
with a 30-mm interelectrode distance parallel to muscle fiber’s direction. The EMG signals were normalized by the EMG magnitude in the isometric contraction at the maximum muscle power. This value was determined in advance by the resistance given by the examiner with a bare hand [16]. We devoted particular attention to the fixation, except for the target areas, using Bohannon’s method, so that the greatest muscle power was elicited [17].

![Diagram of experiment equipment](image)

Figure 1. Set-up of experiment equipment.

2.5 Data analysis

Using software for body part angles (Body Builder; Oxford Metrics Ltd., UK), three-dimensional changes of joint angles in the sagittal and coronal planes were computed for the trunk, hip joints, knees, and ankles. By quantifying the angle change amount as the difference between the angle in the upright position before a perturbation and the angle in the upright position in a steady state after the perturbation had ceased, we calculated the mean value of all subjects. For EMG data analysis, biological information analysis software (Bimutas II; Kissei Comtec Co. Ltd., Japan) was used. After high-pass filtering (20 Hz) and full-wave rectification smoothing (simple moving average of 201 points to 1.08-kHz sampling), signals were normalized by the peak amplitude in the isometric contraction of maximum power. The response latency time and the amount of muscle activity were computed from the normalized EMG. We defined the response latency time as the period between two time points: T1 and T2. In fact, T1 was the time when the perturbation was applied, and T2 was the time when muscle activity starts. Both T1 and T2 were identified as the times when the marker on the platform started to move, and when the EMG amplitude exceeded 2 SD (standard deviation) of its baseline [18]. The amount of muscle activity was evaluated using the time-integrated value of muscle discharge in the tilting perturbation (0–300 ms).

2.6 Statistical analysis

Group differences in latency time and differences in muscle activity between the muscles were compared using one-way ANOVA with Tukey post-hoc tests. The level at which we inferred significance was 5%. All statistical analysis were calculated using SPSS13.0 software (SPSS, Japan).

3. Results

The results of joint angle change, muscle activity and latency over all subjects in pitch forward, pitch backward, and roll right are shown on the left sides, middle, and right sides of Tables 1, 2, and 3, respectively.

3.1 Pitch forward

The average change in the ankle joint was larger than in any other joint. The latent times of the anterior tibialis, rectus femoris, and biceps femoris muscles on both sides were significantly shorter than those of other muscle groups (p < 0.05). No statistically significant differences in the amount of muscle activity were observed.

3.2 Pitch backward

The average change in the ankle joint was again larger than in any other joint. The latent times of the gastrocnemius, biceps femoris, and erector muscles of the spine on both sides were significantly shorter than those of other muscle groups (p < 0.05). No statistically significant differences in the amount of muscle activity were observed.

3.3 Roll right

For the roll right and the roll left perturbation, the same tendency was observed in a symmetrical manner. Therefore, in this report, we describe the results only for roll right perturbation. We observed angle changes in the ankle joint, trunk, knee and hip joints. The latent times of the gastrocnemius, tibialis anterior, and gluteus medius on the left side were significantly shorter than those of other muscle groups (p < 0.05). No statistically significant differences in the amount of muscle activity were observed.

4. Discussion

In agreement with previous results, we found that the ankle joint played a critical role against pitch forward and backward in the feet-together position [11,13]. In response to 15° perturbation stimulation, the ankle joint changed 10° against pitch backward and 6° against pitch forward, indicating that an ankle strategy had been chosen. The activities of the tibialis anterior in pitch forward and of the gastrocnemius in pitch backward were higher than those of other muscles. Furthermore, these activities had long latency, indicating that they were voluntary and related to the central nervous system. The long-latency responses were preceded by short-latency responses of the gastrocnemius in pitch forward and the tibialis anterior in pitch backward. This is attributed to the synaptic stretch reflex derived from G1a fibers. During pitch forward and backward, the stretch reflex appears in the ankle muscles; the continuing activity of these muscles engenders their simultaneous contraction, thereby achieving postural control. Carpenter et al. conducted an experiment using a tilting perturbation foot-apart position [11]. They reported that the activities of ankle muscle were high and the latency of the soleus, erector spineae muscle with pitch backward, tibialis
Consequently, the hip strategy switches to the hip strategy when the BOS is narrowed. In the previous study, because gluteus medius activity was low and there was no stretch reflex, it might have little influence on response to perturbation in the forward-backward direction.

In contrast, we observed changes in postural control involving achieving balance using the weight of the trunk is likely. Klein-Vogelbach designated postural control by which the same tendency was observed on the left and right of each muscle. Therefore, in this table, we show only the results for the left side muscle of each.

Significant activity was not distinguished in LGM for pitch forward and backward. The same tendency was observed on the same tendencies as those found in our study.

Table 1. Joint angle change (degrees).

<table>
<thead>
<tr>
<th></th>
<th>Pitch forward</th>
<th>Pitch backward</th>
<th>Roll right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexion</td>
<td>Extension</td>
<td>Flexion</td>
</tr>
<tr>
<td>Ankle</td>
<td>6.3 ± 5.8</td>
<td>Ankle</td>
<td>9.8 ± 3.7</td>
</tr>
<tr>
<td>Knee</td>
<td>3.2 ± 2.8</td>
<td>Knee</td>
<td>1.2 ± 1.4</td>
</tr>
<tr>
<td>Hip</td>
<td>1.1 ± 5.5</td>
<td>Hip</td>
<td>4.8 ± 2.9</td>
</tr>
<tr>
<td>Trunk</td>
<td>#</td>
<td>Trunk</td>
<td>#</td>
</tr>
</tbody>
</table>

Table 2. Muscle activity (%MVC*ms).

<table>
<thead>
<tr>
<th></th>
<th>Pitch forward</th>
<th>Pitch backward</th>
<th>Roll right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean±SD</td>
<td>Mean±SD</td>
<td>Mean±SD</td>
</tr>
<tr>
<td>LGA</td>
<td>3781.7 ± 3428.3</td>
<td>6473.9 ± 5436.8</td>
<td>LGA 6601.7 ± 5868.0</td>
</tr>
<tr>
<td>LT</td>
<td>2827.8 ± 2183.6</td>
<td>6443.1 ± 5387.1</td>
<td>LT 2095.7 ± 555.4</td>
</tr>
<tr>
<td>LR</td>
<td>1963.4 ± 953.0</td>
<td>2810.3 ± 1648.0</td>
<td>LR 1044.1 ± 303.0</td>
</tr>
<tr>
<td>LB</td>
<td>808.7 ± 396.1</td>
<td>1387.8 ± 797.8</td>
<td>LB 1177.3 ± 411.2</td>
</tr>
<tr>
<td>LA</td>
<td>1057.9 ± 964.2</td>
<td>766.0 ± 580.0</td>
<td>LA 1046.7 ± 272.3</td>
</tr>
<tr>
<td>LS</td>
<td>1128.4 ± 464.2</td>
<td>1991.3 ± 530.0</td>
<td>LS 1546.1 ± 1808.3</td>
</tr>
</tbody>
</table>

Table 3. Latency (ms).

<table>
<thead>
<tr>
<th></th>
<th>Pitch forward</th>
<th>Pitch backward</th>
<th>Roll right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean±SD</td>
<td>Mean±SD</td>
<td>Mean±SD</td>
</tr>
<tr>
<td>LGA</td>
<td>17.2 ± 60.3</td>
<td>23.3 ± 12.6 *</td>
<td>LGA 74.8 ± 67.1 *</td>
</tr>
<tr>
<td>LT</td>
<td>29.0 ± 12.9</td>
<td>130.6 ± 67.7</td>
<td>LT 78.6 ± 22.1 *</td>
</tr>
<tr>
<td>LR</td>
<td>34.2 ± 37.2</td>
<td>143.8 ± 79.5</td>
<td>LR 135.6 ± 35.7</td>
</tr>
<tr>
<td>LB</td>
<td>53.3 ± 19.6</td>
<td>64.3 ± 23.6 *</td>
<td>LB 157.4 ± 46.0</td>
</tr>
<tr>
<td>LS</td>
<td>110.0 ± 26.3</td>
<td>52.7 ± 24.3 *</td>
<td>LS 152.6 ± 32.8</td>
</tr>
</tbody>
</table>

Clear latency was not distinguished besides the five muscles for pitch forward and backward shown above, and in both rectus abdominis for roll right. *: significantly shorter than those of other muscle groups (p < 0.05).

... and quadriceps femoris with pitch forward were 44 ms, 68 ms, 73 ms, and 85 ms, respectively, revealing the same tendencies as those found in our study. Because the feet-together position narrows the BOS only in the left-right direction, it might have little influence on response to perturbation in the forward-backward direction.

In contrast, we observed changes in postural control against roll right and left due to the feet-together position. The narrowed BOS in the left-right direction changed from muscle contraction of the gluteus medius to the movement of the trunk and hip. This suggests that it is difficult to maintain upright standing against roll tilt with the gluteus medius in the feet-together position. Bloem conducted an experiment using a tilting perturbation with foot-apart position [19]. They showed that latency for the left gluteus medius during roll right was 25-30 ms, and that muscle contraction amplitude was relatively high for this muscle. The present study, however, found no conspicuous increase in activity of the left gluteus medius and no stretch reflex. Because gluteus medius activity was low and left flexion of the trunk was considerable, postural control involving achieving balance using the weight of the trunk is likely. Klein-Vogelbach designated postural control by which balance is controlled not by muscle activity but by the weight of the trunk as “counterweight” [20]. With right rolling and left perturbation in the feet-together position, postural control strategy using a counterweight should be chosen. In addition, previous study observed that, in terms of the postural control strategy in the forward-backward direction, the ankle strategy switches to the hip strategy when the BOS is narrowed [6]. Consequently, the feet-together position, which renders the
BOS narrow in the left-right direction, appears to trigger a change in postural control only during roll right and left.

The present results indicate that dynamic lateral balance ability should be improved by training involving roll tilting perturbation in the feet-together stance. The postural control mechanism may depend on the direction of external perturbation within the BOS. Therefore, balance training in multiple planes should be used. For example, muscle activities of the trunk and lower extremities in the pitch, roll, and yaw planes may be important in dynamic balance ability. In particular, because elderly people tend to use the hip strategy [21], the left-right perturbation in the feet-together position would be useful to induce this strategy. Commissaris et al. introduced a movable platform that could induce rotational perturbations in either the pitch or roll direction [22]. Moreover, home-based balance training using a “wobble board” improved balance ability for young adults [23]. In the future, it will be necessary to develop balance training methods including multi-directional perturbation and various BOS conditions using a movable platform or a wobble board.

The present study focused on analysis of joint moments and muscle activities during rotational perturbations in the pitch and roll plane. In the near future, assessment and training of dynamic balance ability in multiple planes may be required. In this study, we did not estimate moment of each joint or center of gravity. However, these parameters will need to be clarified using a floor-reaction force platform in a future study.

5. Conclusions

Traditionally, analyses of dynamic postural adjustment have typically been performed in the natural upright position, with feet in a shoulder-width stance. In contrast, we conducted experimental analyses of upright postural control response in the feet-together position, which is suggested to elicit different responses from those obtained in the conventional upright position. While giving tilting stimulation to subjects in the feet-together position using an electrically operated platform, we measured the postural responses using EMG and a three-dimensional operating analysis system. Examination of the relationship between muscle activity and joint angle change revealed that, in terms of forward and backward pitch, the ankle strategy is performed by the simultaneous contraction of ankle joint muscles, the same tendency as that for the conventional upright position. On the other hand, counterweight was observed in terms of right-left roll, indicating a change of postural control in response to the narrowed BOS. In the future, we need to investigate the effects of balance, training including multi-directional tilting in the feet-together position, and to develop an efficient program.

6. Acknowledgements

We thank Dr. Takeshi Tsuruga for his help in the preparation and collection of experimental data, and Dr. Satoshi Shirogane and Mr. Yohei Ohyama for their assistance with the experiments.

References
