Postural Control during Downward Head Movements in Young Subjects

JUNKO FUKUSHIMA¹⁾, TADAYOSHI ASAKA¹⁾, NATSUMI IKEDA¹⁾, YUMI ITO¹⁾

¹⁾*Division of Physical Therapy, Department of Health Sciences, Hokkaido University School of Medicine: West 5 North 12, Kitaku, Sapporo 060-0812, Japan.
TEL & FAX +81 11-706-3329, E-mail: jf002@cme.hokudai.ac.jp*

Abstract. We investigated postural sway in young subjects who were asked to rotate the head in the direction of visual targets. Thirteen subjects wore a helmet and stood on a force plate. They were asked to look at the targets quickly by directing the laser spot attached to the helmet on the target. Every subject showed consistent changes in the ground reaction force (Fx, Fy, Fz) and in the center of pressure (COP) associated with head movements. In 31% of all trials, force changes in Fx, Fy and Fz preceded head movements. During downward head movements, the anterior-posterior component of COP (COPx) exhibited the largest changes and the shortest latency. Ground reaction force in the anterior-posterior direction (Fx) also showed changes before the onset of downward head movements in 85% of the subjects (mean latency = -20 ms). However, the mean latency in other movements lagged behind the head movement onset. Electromyographic activities (EMGs) of the biceps femoris preceded the initiation of downward head movements by 22–54 ms in 2 subjects. These results indicate that goal-directed rotational head movements elicit COP changes. In addition, the COP changes preceding downward head movement suggest preparatory reactions related to anticipatory postural adjustments (APAs).

Key words: Head movement, Center of pressure (COP), Postural control

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INTRODUCTION

When we begin a voluntary movement, a change in the body geometry leads to a change in the projection of the center of mass (COM), which may move outside the area of support, needing to be corrected. Therefore, voluntary movements, particularly fast ones, are virtually always associated with changes that occur prior to the movement itself which can be addressed as anticipatory postural adjustments (APAs)¹⁾. Their assumed role is to minimize perturbations of the vertical posture that would be induced by the movement. Mechanical consequences of APAs can actually be observed as displacements of the center of pressure (COP) of the body on a support surface. The central nervous system apparently prepares

these adjustments before the actual perturbation occurs. Although the maintenance of postural balance is important to insure clear vision, there have been only a few studies that have examined postural sway in response to eye or head movement^{2–4)}.

It is counter-intuitive that eye or head movements elicit the perturbation of the posture, because of mechanical factors or simultaneously acting tonic neck and tonic labyrinthine reflexes. However, there have been several reports that head movements elicit changes in COP. Vuillerme and Rougier reported that head extension increased velocity and trajectory of COP⁵⁾ in young subjects. Buckley et al.⁶⁾ showed that changes of COP in the anterior-posterior direction (COPx) during head flexion were larger than those during head

extension in elderly subjects. These studies indicate the importance of investigating the effects of vertical head movements on posture. Although both studies confirmed COP changes during voluntary head movements, they did not compare the onsets of postural changes with those of the head movements. If head movement works to perturb posture, there is a possibility that APAs may be observed preceding the head movement. We, therefore, examined whether the onset of the ground reaction force or COP change precedes head movement.

In daily life, when we quickly look at an object located at more than 17 degrees away, we usually move not only the eyes but also the head⁷⁾. This is called gaze shift⁸⁾. Holland et al.⁹⁾ examined the movements of various segments of the body during gaze shift and found that the kinematics of the body parts were synchronized with gaze shift.

It is well known that the ratio of the involvement of head and eye movements is very variable among subjects in trials with gaze shift task⁸⁾, therefore, in this study, we instructed the subjects to rotate their heads, adjusting their laser spot on the helmet to the target. The purpose of this study is to examine whether change of COP precedes voluntary goal-directed fast head movements. The preliminary results were presented in abstract form¹⁰⁾.

METHODS

Participants

Thirteen healthy young subjects (5 male and 8 female, mean $\pm$ SD ages: 22.5 ± 1.3 years old) were recruited for the study and an informed consent was obtained from each subject. Mean $\pm$ SD of their heights and weights were 161.6 ± 5.6 cm, 51.7 ± 6.8 kg, respectively. None of the subjects had neurological, musculoskeletal or visual impairment. Their visual acuity was normal or corrected to normal with contact lenses. The subjects were allowed to perform several practice trials before recording. Because the total time required for recording was 20 min at most, none of the subjects complained of fatigue.

Apparatus and procedures

Subjects were asked to stand bare foot on a force plate (Kistler, Switzerland) with their legs aligned to their shoulder width. The force plate was connected to an 8-channel amplifier. The subjects

wore a helmet on the front of which a laser spot was attached. A search coil was also put on the helmet to record head movements. The subjects' heads were placed inside a one cubic meter magnetic field for detecting head movements¹¹⁾. According to the Range of Motion (ROM) of the neck joints, five visual targets were presented: one straight-ahead, two at 50° upward and downward of the straight-ahead position in the vertical plane (Fig. 1A), and two at 60° to the right and left at eye level in the horizontal plane (Fig. 1B). Subjects were first instructed to fixate the central target at straight-ahead. Then, they were asked to look at one of the four targets with an auditory cue by adjusting the laser spot on the helmet to the target as fast as possible. The subjects performed 10 trials for each direction (e.g. Down, Up, Left and Right) in a block design.

The subjects were instructed not to move other parts of the body, and one of the authors observed the subjects closely. To detect minute movements of the upper trunk, an accelerometer (TA512G, Nihonkoden) was firmly positioned over the acromion. Muscle activities of 4 subjects were recorded with surface electrodes. Disposable self-adhesive electrodes were used to record the surface EMG of the following muscles on the right side of the body: trapezius, sternocleidomastoideus (SCM), biceps femoris (BF), rectus femoris (RF), long head of the hamstrings (HAM), tibialis anterior (TA), and lateral head of gastrocnemius (GAS) muscles. The electrodes were placed on the muscle bellies, with their centers 3 cm apart. In addition, a reference electrode was attached to the lateral aspect of the fibula. EMG signals were rectified and filtered with a band-pass of 50–500 Hz.

To examine whether the change in COP occurs when the subjects moved only the eyes, the subjects were asked to look at targets located at 10° right or left, and 50 up and down from the central fixation point, without head movements. Infrared oculography (DC to 50 Hz, –30 dB/octave; Eye Monitor TTK 2930, Takei Co., Tokyo, Japan) was used to record eye movements. Head position was recorded to confirm that they did not show any head movements in this task. We also examined COP changes during head movements with closed eyes. In this case, eye movements were monitored with electrooculography (EOG), because infrared oculography was not available for closed eyes. Head movements and ground reaction force were

Fig. 1. A: Experimental set up. Subjects stood on a force plate, wearing a helmet. A search coil was attached to the helmet to detect head movements in a magnetic field. The subjects were instructed to look at targets 50 degrees upward and downward, by adjusting the light on the helmet to the targets. B: Horizontal targets were located 60 degrees to the right or left of the subject. C: X, Y and Z represent the directions of ground reaction force. Fx: anterior to posterior component of ground reaction force. Fy: medial to lateral component of ground reaction force, Fz vertical component of ground reaction force.

recorded by the same procedure as described above.

Data analysis

The vertical and horizontal components of head position, three components of ground reaction forces (Fx, Fy, Fz in Fig. 1C), and muscle activities were stored on a data recorder for off-line analysis. All data were digitized at 1 kHz using a 16-bit analog/digital board (NB-MIO-16x; National Instrument), and analyzed. The trajectory of COPx

(anterior-posterior component of COP) was calculated with our interactive computer program¹²⁾ on a Macintosh computer. Head position traces were differentiated to obtain head velocity. All data that consisted of head position, head velocity, reaction force (Fx, Fy, Fz, COPx), acceleration of the trunk and EMG were aligned at the onset of head movements. Head position, eye position, the reaction forces and COPx were superimposed to confirm that they showed a consistent direction. To find out the onset of head movements, we drew a straight line along the initial slope of the head position traces. The onset was determined as the time at which the straight line along the head position traces intersected the base line. To evaluate the mean value of reaction forces in an individual subject, we drew a straight line along SD and the onset was determined as the intersection of the red line and the mean trace. The onsets of the muscle activities were determined as the point beyond the mean $\pm$ 2SD of the baseline. Statistical significance was evaluated by factorial ANOVA, Fisher's PLSD and the paired *t*-test with a significance level of $p < 0.05$.

RESULTS

Mean peak head velocity of all subjects was 379.3 deg/s (515.1 ± 132.8 deg/s for up, 253.2 ± 41.9 for down, 386.6 ± 69.0 for left and 362.8 ± 102.3 for right movement). Peak head velocity in the upward direction was significantly higher than those of the other directions ($F [3,108] = 42.1$, $p < 0.0001$), without interaction.

Each subject in all the trials showed a consistent change in Fx, Fy, Fz and COPx associated with head movement. Figure 2 shows a typical example of a subject whose head moved upward to the target. Figure 2A indicates 8 superimposed trace of head movement and Fx of one subject, and Fig. 2B shows the average $\pm$ SD of the same subject. The onsets of Fx preceded movement of the head position by 37.7 ms.

Table 1 shows the average and standard error (SE) of the latencies of the onset of ground reaction force. Fx and Fz are shown for up and down head movements, Fy and Fz for horizontal head movements. The mean latency of all directions was 41.7 ms after the onset of head movement. Fx for downward head movement preceded the head movement onset by 20 ms on average, while

Fig. 2. A: Superimposed traces of head position and Fx component of ground reaction force in a typical example. The zero point is the onset of head movement. An arrow indicates the onset of Fx. B: Averaged traces (thick line) and standard deviation (thin line) of Fig. 2A.

upward head movements showed mean latencies of 66.2 ms in Fx and 42.3 ms in Fz, which lagged behind the head movement onset. The mean latency of Fz in downward movements was 32.9 ms. In the course of downward head movements, Fx (Table 1) exhibited the shortest latency (mean = -20 ms), which was significantly shorter than the latencies in the other tasks ($F [7,104] = 3.38, p < 0.01$), without significant interaction. Fx preceded downward head movements in 11 of the 13 subjects. Although force changes preceded the head movements in several subjects, the mean latency in movements other than Fx in the downward head movement, lagged behind the onset of movement (Table 1). In left horizontal movements, the mean latencies were 64.1 ms and 43.9 ms, for Fy and Fz, respectively, while in right movements the mean latencies were

50.3 ms and 4.5 ms in Fy and Fz, respectively. To summarize the results, in downward head movements, about 85% of the subjects showed changes in Fx preceding the onset of head movements.

COPx was calculated during up and down head movements for all subjects. A typical example of an averaged trace for downward movement of the head in one subject is shown in Fig. 3A. The mean $\pm$ SDs of all subjects were 4.0 ± 0.9 (range 2.0~7.6) cm for downward and 1.6 ± 0.7 (range 0.8~2.8) cm for upward head movements. The COPx for downward movement was significantly larger than that of upward movement ($t = 5.08, p = 0.003$). The averaged latencies of COPx for down and upward head movements were -17.2 ms and 55.4 ms, respectively, which was also significantly different ($t = 4.04, p = 0.001$). To summarize, the COPx in downward movement showed larger changes and earlier onsets than those of upward head movements. Also, the changes of COPx preceded the onset of head movements.

To examine the contribution of eye movements in the goal-directed head movements, we examined force changes and COP in the subjects when they were asked to move only their eyes, without head movements. We did not detect consistent changes in reaction forces or COP during horizontal or vertical eye movements without head movements, as shown in Fig. 3B. Head movements with eyes closed were examined for 3 subjects. They showed changes in reaction forces or COPx similar to those during head movements.

For 4 subjects, an accelerometer was placed on the acromion to measure the onset of trunk movements. In 19 of the 40 trials, the shoulder movements lagged behind the head movement onset. However, in 21 trials, force changes preceded the head movement onsets. In these cases, the force changes preceded the onset of both head and trunk movements.

Muscle activities of the trapezius, SCM, RF, BF (long head), TA and GAS (lateral head) were measured in 4 subjects. As shown in Fig. 4, EMG responses of BF preceded the initiation of downward head movements. In 2 subjects, BF activities preceded the onset of downward head movements by 22 ms and 54 ms, respectively. These values of BF onsets preceded the onset of Fx and Fz by 20~43 ms. However, responses in other muscles including GAS were not consistently

Table 1. Average and SE (Standard Error) latencies of the forces onset

Direction	Up		Down		Left		Right	
	Fx	Fz	Fx	Fz	Fy	Fz	Fy	Fz
Mean (msec)	66.2	42.3	-20	32.9	64.1	43.9	50.3	4.5
SE	4.6	2.5	2.7	3	4.9	4.6	5.5	1.1

Fx: anterior-posterior component of reaction force, Fy: medial-lateral component of reaction force, Fz: vertical component of reaction force.

Up: the subject looked at a target located 50 degrees upward; Down: 50 degrees downward; Left: 60 degrees to the left; Right: 60 degrees to the right.

Fig. 3. A: Averaged traces of head position and COPx of one subject during head movements downward. COPx preceded head onset by 60 ms. The zero point is the onset of head movement. B: Averaged traces of eye movements without head movement. No change in COPx was observed.

observed before and after the initiation of head movements.

No significant difference was found in the latencies of force changes between male and female subjects ($F [1,110]=0.155$, $p=0.687$). No significant difference was found in the peak head velocities ($F [1,110]=1.886$, $p=0.172$) or onset of trunk movements ($F [1,58]=2.915$, $p=0.093$) between the subjects who showed early onset of the force

changes with latencies of less than 50 ms and those with longer latencies.

For downward head movements, we examined the correlation among head velocity, onset of COPx and trajectory of COPx in individual subjects. Head velocity showed positive correlation with latency ($r=0.62$, $p=0.02$), indicating that slow head velocity resulted in early onset of COPx. There was no significant correlation between COPx trajectory and COPx latency ($r=-0.26$, $p=0.39$), or between head velocity and COPx trajectory ($r=0.14$, $p=0.63$) during downward head movements.

DISCUSSION

In the present study, all of the subjects showed changes in ground reaction force and COP on the force plate during head movements. In about one third of the head movement trials in all directions, force changes preceded head movements. Above all, 85% of the subjects showed changes in Fx and COPx, which preceded downward head movements. In addition, muscle activities preceded the onset of downward head movements by 22 ms and 54 ms, respectively in 2 subjects.

In daily life, we move not only our eyes but also our heads to look at objects. This is called gaze shift. In the present experiment, we did not examine the gaze shift task, but we asked the subjects to perform a head movement task in which the subjects looked at the target by adjusting the laser spot on the head to the target. We, therefore, could obtain reproducible head movements with the amplitudes large and constant enough to evaluate the onset of ground reaction forces, as shown in Fig. 2AB.

It is said that we can move the head freely without disturbing posture, because the tonic neck reflex and tonic labyrinthine reflex cancel out each

Fig. 4. Electromyographies of the right sternocleidomastoideus (SCM), right quadriceps (QUAD), biceps femoris (BF) are shown. Right shoulder movement (shoulder) recorded by accelerometer, head position (angle of neck bending), Fx (anterior-posterior component of reaction force) and Fz (vertical component) are shown. The zero point is the onset of head movement.

other¹³⁾. However, previous studies have reported that changes in COP occur when subjects performed head flexion or extension^{5, 6)}. Our results were consistent with the findings of Buckley et al., because we observed larger COPx change in downward head movements than in upward head movements.

Why did only downward head movements cause larger and preceding COPx changes? In horizontal head movements, the COM position of the head remains near the mastoid bone. Therefore, it is not likely to show large changes in ground reaction force in the medial to lateral direction (Fy). On the other hand, vertical head movements change the COM position of the head, because the rotation axis (near C1) is distant from the head COM. The amplitude of actual vertical head movements was not 50°, because the rotational axis for the head movements was at the joint of the occipital bone and the atlas (C1). We measured the angles of neck bending with a goniometer, when the subjects looked at the targets at 50° upward or downward. Actual angles of neck bending in the up and down directions were about 10~20° and 25~45°

respectively. Downward head movements caused larger angle changes, so it is possible that they resulted in the largest perturbing effects on COM. These neck angle differences may be involved in the large trajectory of COPx in downward movements. Thus, it is possible that downward head movements could threaten postural controls. This would explain the result that downward head movement elicited COPx preceding head onset.

It was reported that the shortest spinal reflex requires about 50 ms after movement¹⁴⁾. If the muscle activities seen in this study were the results of the spinal reflex, they would have appeared with latencies of more than 50 ms after the onset of movements. Vestibulo-spinal reflex with head turn might have needed at least 70 ms after the onset of head movement¹⁵⁾. Therefore, spinal reflexes do not explain the early onset of our results (–54~–22 ms) in EMG, suggesting that the neuronal command for postural control was preprogrammed to prepare for the onset of head movements.

In the present study, muscle activities preceding head movements were observed only in the biceps femoris, while the other muscle activities were

observed after the onset of head movements. Horak et al.⁴⁾ reported that the muscle activities in the gastrocnemius showed very low amplitudes when the head was moved. Anson et al.¹⁶⁾ reported that voluntary head rotation revealed inhibition of the H-reflex during 20 ms before and 100 ms after head movement in the contralateral soleus muscles. These results suggest the possibility that activities in the lower leg muscles such as the gastrocnemius and soleus, were suppressed before and after the head movements invoked in the present study. In the present study, it is possible that muscle activities in the lower extremities were inhibited during head movements. However, we cannot exclude the possibility that we were technically unable to detect activities in these muscles. There is a limitation to the interpretation of the EMG findings in this study, because of the small sample size, and further studies are necessary regarding individual differences in muscle activities.

Head movements usually accompany upper trunk movements⁴⁾. Since head movements preceded upper trunk movements in about half of the cases in the present study, trunk movements alone cannot explain the preceding force change.

We could not detect force change during eye movement without head movements, as shown in Fig. 3B. Basically, in the goal-directed head movements invoked in the present study, the eye direction of the vestibuloocular reflex (VOR) is opposite to the head movement. Therefore, eye movements cannot explain the force change preceding the head. Similar changes in reaction forces and COPx were observed in head movements with eyes closed. This suggests that the involvement of eye movements was not likely to be the cause of APAs for downward head movements. The difference between the results of a previous study by Strupp et al.³⁾ and the present study may be due to the experimental conditions. Whereas Strupp et al. directed subjects to follow a target moving sinusoidally, our task required saccadic eye movements.

We examined what kind of characteristics were involved in the early onset of the force change. In the present study, downward movements in Fx showed significantly shorter latencies than those of the other directions. No factors, such as the onset of upper trunk movement, peak head velocities or sex were related to the short latencies.

Peak head velocity for the upward direction was significantly higher than those of the down or horizontal movements. The reason why the upward head movement showed a higher velocity may be due to the number of neck muscles involved. Most of the neck muscles are located in the dorsal part of the neck and the contraction of these muscles enables higher velocity. Despite the higher velocity in upward head movements, this did not produce perturbing effects compared to downward head movements as described above. Rather, in the subjects whose head velocity was not high, early onset of postural change occurred. This suggests the possibility that subjects used individual strategies to keep their postural stability.

We assigned the task to the subjects in a block design. One might argue that learning effects should be considered. Although we cannot exclude the possibility that repeated head movements in the same direction might encourage a constant change in COPs, the results did not change consistently from the beginning to the end of the trials.

It has been reported that the patients with Parkinson's disease fall more frequently among patients with neurological diseases¹⁷⁾. In the clinical field, we have had many instances of the patients with Parkinson's disease falling when they turned their heads due to auditory cues (e.g. being called by their name unexpectedly). Many studies have indicated that the instability of posture in Parkinsonian patients may be due to the involvement of the basal ganglia in the preparation and initiation of motor acts for changing postural demands^{18, 19)}. However, to clarify the reason, further studies are needed to examine the postural instability during head turning in these patients.

In conclusion, the onsets of COPx and Fx preceding head movements seen in this study may be preprogrammed movements that relate to anticipatory postural adjustments (APAs), despite the small sample size and diversity of the results between individuals.

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