Original investigation

# Changes in forward step velocity on step initiation from backward and forward leaning postures

Taro Ito [1)]　Takashi Azuma [2)]　Noriyoshi Yamashita [3)]

## Abstract

The integration of posture and movement are required for achieving the goal of motor task in biped stance. The aim of this investigation was to elucidate whether and how the differences of the postural requirement with changing the initial leaning postures affect the task performance (step velocity) in step initiation from a standing position. Ten healthy subjects performed the initiation of a single step forward as fast as possible from standing positions at three initial leaning postures (FI, forward inclination; US, upright stance; BD, backward declination of the body axis). The maximum step velocity at BD showed a higher value than at US or FI (ANOVA, $F_{2,259} = 3.60$, $P < 0.05$; Tukey post-hoc tests, $P < 0.05$, respectively). As the initial body declination to a backward direction increased, the duration of the backward shift in the center of pressure (CP) and excitatory activities in both the tibialis anteriors (TA) in the anticipation phase lengthened (CP, $F_{2,259} = 106.15$; TA of swing leg, $F_{2,258} = 131.21$; TA of stance, $F_{2,258} = 158.93$; $P < 0.001$, respectively), and the forward velocity acquired in the anticipation phase prior to the onset of the first heel-off became significantly higher ($F_{2,259} = 10.30$, $P < 0.001$). These results provide evidence that anticipatory activities prior to the first heel-off can contribute not only to creating the necessary conditions to initiate a step movement but also to increasing step velocity in step initiation.

**Key words**　Step initiation, Performance, Initial standing position, Anticipatory postural adjustments

## 1. Introduction

The differences in velocity when transferring the body mass on rapidly stepping forward from a quasi-static standing position have an important influence on performance in the field of sports, such as ball games, martial arts, and swordsmanship. On step or gait initiation, it is generally known that the anticipatory activities of the center of pressure (CP) and the bilateral tibialis anterior (TA) muscles emerge prior to the execution of the intended forward-oriented movement from a standing position (Crenna and Frigo, 1991; Ito et al., 2003). These phenomena are thought to play a role in transferring the

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position of the center of mass (CM) to the necessary state to initiate a stepping movement as anticipatory postural adjustments (APA) (Massion, 1992).

APA did not occur in cases lacking the postural requirement, such as voluntary movement with a very stable stance (Nardone and Schieppati, 1988) or on sitting (Yamashita and Moritani, 1989). Conversely, the larger postural requirement for initiating the intended forward-oriented movement, (for example, stepping forward from an initial standing position with a backward leaning posture), prolonged the duration of APA parameters (Crenna and Frigo, 1991; Lipshits et al., 1981). It is generally known, moreover, that APA parameters are enhanced with an increase in the motor performance of the forward-oriented movement from a standing position at rest, such as in arm raising (Lee et al., 1987), rising up on tiptoes (Ito et al., 2004), step initiation (Dietrich et al., 1994; Ito et al., 2003), or gait initiation (Brenière et al., 1987; Crenna and Frigo, 1991).

It has been revealed that the magnitude of medio-lateral APA (e.g., displacement of the CP towards the swing leg and of the CM towards the stance leg) influences the step time (Patchay and Gahéry, 2003; Azuma et al., 2007, 2008). Azuma et al. (2007) showed that the step time on step initiation from an initial CM position projected onto a plantar surface of the swing leg was significantly shorter than that from the CM position close to the stance leg, and suggested that the medio-lateral APA may be directly involved not only in increasing the propulsive force towards the stance leg, but also increasing the forward propulsive force at first heel-off (Azuma et al., 2007). Additionally, Azuma et al. (2008) observed that the step time with an initial CM position on the swing leg side were significantly shorter than in the standing position on the stance leg and for an upright stance. However, it is not yet clear whether the changes in APA parameters with degrees of postural requirement in sagittal directions affect future movement performance. If postural muscle activities involved in the APA markedly contribute to an increase in motor performance, this finding may provide additional insight into the target muscle sites for training, i.e., necessity of resistance training of postural synergists as well as the primary mover.

The aim of this investigation was to elucidate the functional role of APA based on changes in the EMG activities of postural synergists and in the forward step velocity associated with shifts of the initial forward-backward leaning posture on step initiation.

## 2. Methods

### 2.1 Subjects and task conditions

Ten healthy subjects (mean age: 23.8 ± 6.0 years, height: 171.3 ± 4.4 cm, body weight: 65.6 ± 10.1 kg, and foot length: 26.7 ± 0.5 cm) performed the initiation of a single step forward with the right swing foot as fast as possible from the initial standing position while adopting three leaning postures (FI, forward inclination; US, upright stance; BD, backward declination of the body axis). When the subject is static, the ground projections of the CM and CP are superimposed. The three different standing positions on step initiation were strictly regulated by the CP as follows: FI, step initiation from a 50% position of the forward CP shift on maximum forward inclination of the body axis without bending the trunk; US, step initiation from an upright position at rest (the CP position was 45% of the foot length from the heel point; cf. Ito et al., 2003); BD, step initiation from a 50% position of the backward CP shift on maximum backward declination of the body axis without bending the trunk.

### 2.2 Experimental procedure

Each subject was instructed to stand with the feet parallel and 5 cm apart on a force platform (AMTI OR6-5); to maintain their CP in each reference CP position by monitoring the X-Y plotter placed 2 m in front of the eyes at eye level; to initiate stepping forward with a right foot departure at their own pace; to step in a straight line with a consistent step length (40% of the body height); to land on the target (a horizontal strip of aluminum tape, 10 cm wide × 100 cm long, able to detect the first foot-contact signal) with the heel of the swing leg; to walk through the heel-off (HO), toe-off (TO1), and foot-contact (FC1) of the swing leg, toe-off (TO2) and foot-contact (FC2) of the stance leg (cf. Fig.1). Each subject was well trained for this motor task, and performed 10 trials adopting three standing positions respectively, separated by a 5-min rest period. The electromyographic (EMG) activities of the lower extremity muscles, a goniogram (Penny & Giles, M110) of the hip joint, foot on-off signals, and ground reaction forces and moments were simultaneously recorded during the experiment.

### 2.3 Data processing and analysis

The CP and CM in the sagittal plane were computed from the force and moment data sampled at 1 kHz. EMG signals were amplified, filtered with a bandwidth of 10-500 Hz, rectified, sampled at 1 kHz, and normalized to the isometric maximal voluntary muscle contraction (MVC) for each subject.

Data in which the initial CP position exceeded the reference CP by ± 10 mm or in which the step length was inappropriate according to the lack of a first foot-contact signal were excluded.

The data could be divided into two phases: anticipation and execution phases. The boundary line of these phases was the onset of the HO. The variables measured from the digitized EMG and mechanical data were as follows (cf. Table 1): Step Time, duration required for stepping from the HO to FC1; Vmax, maximum forward velocity which was generated approximately at the FC1; Vant, forward velocity of the CM at the HO (forward velocity achieved in the anticipation phase); Vexe, forward velocity of the CM, which subtracts the Vant from the Vmax (forward velocity achieved in the execution phase); CPdur and CPmax, duration and maximum backward displacement of the CP in the anticipation phase, respectively; TAWdur and TATdur, durations of anticipatory EMG activities of the TAs in the swing and stance legs, respectively; TAWamp and TATamp, the mean amplitudes of the anticipatory EMG activities of the TAs for the TAWdur and TATdur, respectively; SRamp and SOamp, the mean amplitudes of the EMG activities in the sartorius of the swing leg from the HO to maximal deflection of the hip flexion and in the soleus of the stance leg from the TO1 to FC1, respectively; the angular velocity of swing hip flexion was from the onset to maximal deflection.

### 2.4 Statistical analysis

One-way ANOVA (conditions on adopting a standing position) and Tukey post-hoc tests were used to assess outcome variables. A significance level of $P < 0.05$ was chosen.

Table 1 Differences in means (±SD) of measured parameters in the anticipation and execution phases among three initial standing positions on step initiation

| Parameters | Forward inclination | Upright stance | Backward declination | ANOVA *F* values (*df*) | Probability |
|---|---|---|---|---|---|
| Step Time (ms) | 292 ± 46 | 291 ± 54 | 293 ± 52 | 0.97 (2,258) | $P$=0.971 *NS* |
| Vmax (m/s) | 1.28 ± 0.15 | 1.27 ± 0.18 | 1.33 ± 0.18 | 3.60 (2,259) | $P$<0.05 |
| Vant (m/s) | 0.42 ± 0.10 | 0.45 ± 0.10 | 0.49 ± 0.11 | 10.30 (2,259) | $P$<0.001 |
| Vexe (m/s) | 0.86 ± 0.13 | 0.82 ± 0.14 | 0.84 ± 0.13 | 1.99 (2,259) | $P$=0.139 *NS* |
| CPdur (ms) | 499 ± 105 | 594 ± 128 | 759 ± 126 | 106.15 (2,259) | $P$<0.001 |
| CPmax (cm) | 10.3 ± 1.9 | 7.7 ± 1.0 | 4.9 ± 1.4 | 277.91 (2,254) | $P$<0.001 |
| TAWdur (ms) | 446 ± 116 | 553 ± 131 | 758 ± 142 | 131.21 (2,258) | $P$<0.001 |
| TAWamp (%) | 56.5 ± 23.8 | 60.9 ± 22.0 | 55.2 ± 18.1 | 0.20 (2,258) | $P$=0.197 *NS* |
| TATdur (ms) | 442 ± 111 | 546 ± 122 | 763 ± 133 | 158.93 (2,258) | $P$<0.001 |
| TATamp (%) | 74.6 ± 41.7 | 78.9 ± 46.9 | 65.6 ± 38.7 | 2.21 (2,258) | $P$=0.112 *NS* |
| SRamp (%) | 60.7 ± 28.8 | 57.9 ± 21.9 | 52.6 ± 17.8 | 2.64 (2,255) | $P$=0.074 *NS* |
| SOamp (%) | 102.6 ± 39.6 | 99.6 ± 38.0 | 95.0 ± 39.5 | 0.86 (2,258) | $P$=0.426 *NS* |

Abbreviations: Step Time, duration required for stepping from the first heel-off to foot-contact; Vmax, maximum forward velocity; Vant, forward velocity acquired in the anticipation phase; Vexe, forward step velocity acquired in the execution phase; CPdur and CPmax, duration and maximum backward displacement of the center of pressure in the anticipation phase, respectively; TAWdur and TATdur, durations of the anticipatory electromyographic (EMG) activities of the tibialis anterior (TA) in the swing and stance legs, respectively; TAWamp and TATamp, average amplitudes of the anticipatory EMG activities of the TA for the TAWdur and TATdur, respectively; SRamp and SOamp, the mean amplitude of the EMG activity in the sartorius of the swing leg and in the soleus of the stance leg in the execution phase, respectively. NS, "not significant".

### 3. Results

A total of 300 trials involving the ten subjects were considered appropriate for the main analysis. Of these, 12 trials with FI, 15 trials with US, and 11 trials with BD conditions were excluded due to excessive deviation from the reference CP position, or an inappropriate step length. There was a significant difference among the initial standing positions, which were shown by the deviations from the CP position at rest (3.30 cm ± 0.95 back on BD, 0.09 ± 0.43 cm back on US, and 3.69 ± 1.14 cm front on FI, respectively; $F_{2,259} = 1352.46$, $P < 0.001$; cf. lower illustrations in Fig.1).

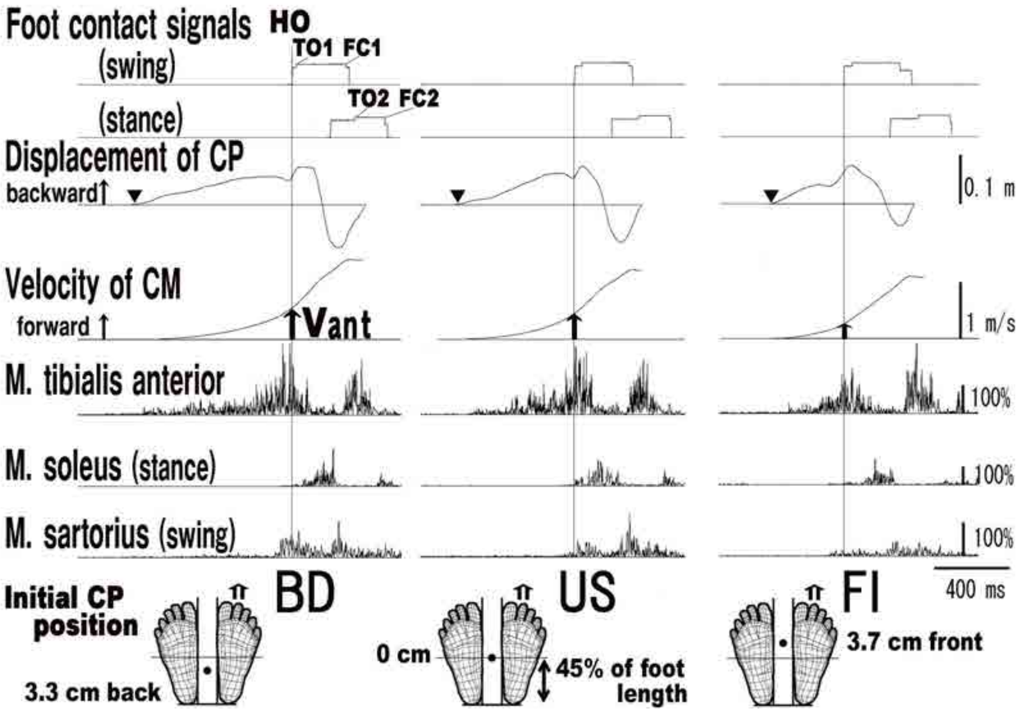


Fig.1. Typical traces of kinetic and EMG data during the initiation of a single step forward on adopting three initial standing positions (left, backward body declination, BD; center, upright stance, US; right, forward body inclination, FI). Lower illustrations show antero-posterior body leaning, which was strictly regulated by the position of the center of pressure (CP; filled-circle (●) between the feet) during bipedal stance prior to the onset of step movement with right foot departure. The inverted, filled triangle (▼) indicates the onset of the anticipatory phase. Vant (🠉) shows the forward velocity of the center of mass (CM) acquired in the anticipation phase. HO (vertical line), TO1, FC1, TO2, and FC2 indicate the heel-off, toe-off, foot-contact of the swing leg, and the toe-off and foot-contact of the stance leg, respectively.

As shown in representative samples obtained from one subject in Fig.1, the backward shift of the CP, the forward velocity of the CM, and the excitatory EMG activities of both TA muscles (Fig.1 shows the TA on the stance leg side) emerged prior to the HO on step initiation adopting the three standing positions. As shown in Table 1, the Step Time from the HO to FC1 was the same length across the tested standing positions. Vmax showed significant differences among experimental conditions (Table 1); moreover, Vmax under the BD condition showed a higher step velocity than for US or FI (Tukey post-hoc tests; $P < 0.05$, respectively). Vant values were significantly different according to the experimental conditions, whereas no difference was confirmed in Vexe data among the three standing positions (Table 1). The initial CP position significantly affected the CPdur, TAWdur, and TATdur, as shown in Table 1. The CPmax decreased inversely as initial body leaning in a backward direction intensified (Table 1); therefore, no evidence that the CP amplitude was related to an increasing step velocity was obtained. There was no significant difference in the TAamp, SRamp, and SOamp regarding the changing initial CP positions, as shown in Table 1. With respect to the angular velocity of swing hip flexion, no difference was confirmed among the experimental conditions (91.9°/s ± 26.3 on BD, 99.0°/s ± 33.1 on US, and 99.4°/s ± 35.9 on FI, respectively; $F_{2,259} = 1.46$; not significant, *NS*).

### 4. Discussion

The main finding in our study was that the forward maximum step velocity under the BD condition, i.e., step initiation from a backward leaning posture, was higher than those under the other conditions. Comparison with motor performance on step initiation from forward-backward leaning postures identified significant differences in the maximum step velocity, but not in the step time. On step initiation from left-right leaning postures (Azuma et al., 2007), however, the step time was significantly shortened on step initiation from a standing position while loading the body weight on the swing leg side, whereas no differences in the left-right leaning postures was observed in the maximum step velocity. The higher forward step velocity (the present study) and the shorter step time (Azuma et al., 2007) were due to prolongation of the anticipatory duration of EMG activities in the postural synergists, and not due to EMG activities in the primary mover. Therefore, the antero-posterior and medio-lateral APA may be involved in the gain of the forward CM velocity and shortening of the duration (step time) required from the first heel-off to foot-contact of the swing leg, respectively. It is generally known that the amplitude of the antero-posterior APA, i.e., the TA burst, is directly correlated with the velocity of the CM (Crenna and Frigo, 1991; Ito et al., 2003), while it has been reported that the medio-lateral APA can increase the maximum angular velocity of swing hip flexion when performing rapid leg flexion from a standing position (Nouillot et al., 1992). Azuma et al. (2008) found that the movement of step initiation from a standing position with the body leaning diagonally backward on the swing leg side was accompanied by the highest forward step velocity and the shortest step time among the various initial standing positions. Azuma's findings may indicate functional interaction between the antero-posterior and medio-lateral APA.

According to the present results, the maximum step velocity on BD was significantly higher than in the other two conditions. Conversely, Dietrich et al. (1994) reported that the CP in the initial standing position shifted forward in conjunction with the increase in the peak velocity of the subsequent movement on step initiation. A consideration of the difference of the goals between the self-paced and reaction-time movements might help explain this discrepancy. It is conceivable that subjects tried to reduce the time required for postural control by shifting their bodies forward in preparation for the reaction motor task in Dietrich's experiment (1994). However, the present result regarding the self-paced movement was unexpected.

In the present results, the forward velocity achieved in the anticipation phase rose significantly with increased backward leaning in the initial standing position, notwithstanding the invariable forward step velocity acquired in the execution phase. The larger backward declination of the body axis increased the duration of the CP and both the TAs in the anticipation phase, whereas no difference across the tested standing positions was noted in EMG amplitudes of the primary synergies for stepping forward. These suggested that prolonging of the anticipatory EMG activities of the postural muscles (i.e., TA) increases the force-time area of the forward propulsive force until the onset of the HO, i.e., the forward velocity acquired in the anticipation phase. The cutaneous messages from the vibration-stimulated sole area on adopting an upright stance allow the central nervous system to displace the CM in the opposite direction to the stimulated area (Kavounoudias et al., 1998). This indicates that the information from the plantar cutaneous afferents along with the proprioceptive inputs from the ankle muscles and joint take part in postural control to reduce the gap between the body and equilibrium position. The high step velocity on BD may be caused by the coincidence of the directional goal between postural control in the anticipation phase and intended movement in the execution phase.

The lack of appropriate support for the movement induced an error in the goal of directional movement or a reduction of motor performance (Hess, 1943). Our present results confirmed this supporting theory. The forward velocity acquired in the anticipation phase amounted to approximately 35% of the maximum step velocity across the tested standing positions. This level of contribution of the APA to movement performance cannot be ignored in the field of sports. As a conclusion, the present results provide evidence that anticipatory EMG activities in the TAs can contribute to not only creating the conditions necessary to initiate step movement, but also to increasing the step velocity on step initiation. The present findings suggest the necessity of training not only primary but also postural muscles in order to enhance movement performance.

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Original investigation

# Postural stability enhances the effect of dorsal neck muscle vibration on anticipatory postural adjustments when moving rapidly to a tiptoe position from a bipedal stance

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## Abstract

It is little known about how information from sensory systems is processed and combined to determine the setting of parameters (duration and amplitude of descending commands) in anticipatory postural adjustments (APA) which facilitate the execution of the voluntary movement by introducing the propulsive force. We tried to elucidate how sensory afferent inputs with continuous vibratory stimuli to cervical muscles were processed to set the APA associated with a task of standing rapidly on tiptoe from a quiet bipedal stance (ST task). Nine healthy subjects performed seven consecutive ST tasks in a self-paced manner each under four conditions in combination with two factors (vibration of dorsal neck muscles and light finger touch) while eliminating the modifying factors of the APA setting by strictly regulating the initial position of the center of body mass. Prolonged duration of the center of foot pressure in sagittal direction (CoP) in the APA induced by the dorsal neck vibration was lengthened additively when standard deviation of the CoP for the preparatory period for the APA setting (SD of the CoP) was remarkably suppressed by light finger touch. This was suggested that the more static the equilibrium by light finger touch for the preparatory period for the APA setting, the more intense the vibration-induced effects on the temporal parameter of the APA in the ST task. Based on these results, we discussed that modulations in the central processing of proprioceptive signals for the APA setting may be involved in sensory gating system.

**Keywords**　Anticipatory postural adjustments, Vibration, Light finger touch, Postural stability, Standing on tiptoe

## Introduction

Proprioceptive, vestibular and visual systems clearly contribute to postural control in a dynamic motor task. However, little is known about how information from these systems is processed and combined to determine the setting of parameters (duration, amplitude and quantity of descending com-

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mands) in anticipatory postural adjustments (APA) which counteract in advance of mechanical perturbations associated with initiation of voluntary movement from a standing position. A number of studies have demonstrated processing of proprioceptive afferents in feedback postural control using a vibration stimulus which selectively activated muscle spindles and elicits discharges in group Ia afferent fibers. Vibration stimuli could contribute to understanding postural control in at least three ways: by inducing whole-body displacements to measure the magnitude of the vibration-induced falling (VIF) due to tonic vibration reflex responses (Eklund, 1972), by arousing conscious and illusory perception of postural displacement (Kavounoudias et al., 1999), or by producing a condition of postural instability by applying the vibration stimulus to the postural muscles (Lackner et al., 2000). The effects of vibration stimulus on APA have been investigated by few studies (Kasai et al., 2002; Slijper and Latash, 2004) and remain controversial. In a task of forward arm-raising requiring a shift in the center of body mass (CoM) in a backward direction to maintain body equilibrium, one study indicated that the timing of the APA onset in the ipsilateral biceps femoris was earlier during dorsal neck muscle vibration arousing an illusory perception of backward body tilt (Kasai et al., 2002), while another study on APA demonstrated that a significant increase in co-activation of agonist-antagonist muscle pairs in the lower extremities was observed in vibrations applied to the Achilles tendon (Slijper and Latash, 2004). These results have contradicted the concept that greater APA modification is associated with more postural requirements according to afferent inputs originating from the lower extremity muscles and/or cutaneous afferents arising from the foot. For example, a task of standing rapidly on tiptoe (ST task) from a rest standing position involves APAs that move forward to project the center of body mass onto a new small basal support. Therefore, the increase in the actual postural requirement in the ST task, i.e. the backward body tilt, prolonged the APA temporal parameters (Lipshits et al., 1981; Yamashita and Moritani, 1989; Ito et al., 2004). If the illusory perception of the backward body tilt was aroused with vibration to the dorsal neck muscles (Lekhel et al., 1997), the APA would increase more with augmentation of the postural requirement. One of the purposes of this study was to evaluate how the setting of the APAs was modified by changing only illusory perception of postural requirements following vibration of bilateral splenius muscles (non-postural muscles) during the ST task in a condition regulating the initial position of the CoM.

A model to represent the processing and combining of multisensory input in the balance control process has demonstrated that the postural responses evoked by separate vibration stimuli to two identical or different sensory receptors made a simple summation when the two receptors were stimulated together (Kavounoudias et al., 1999). However, the amplitudes of the somatosensory evoked potentials (SEPs) by simultaneous stimulation of two separate nerves were always smaller than that of the arithmetic sum of the individual SEPs in a condition not requiring postural control (Tinazzi et al., 2000). Consecutive vibration stimuli decreased the movement-related afferents or the excitability of the monosynaptic reflex in the vibration-applied muscle itself in sitting subjects (Hagbarth, 1973), while the vibration-induced effects to leg muscles showed only a minor response during locomotion (Courtine et al., 2001) or were markably reduced in more unstable conditions during bipedal standing (Gurfinkel et al., 1996; Ivanenko et al., 1999). The above may be attributed to a decrease in the afferent inputs through a 'busy-line' or by pre-synaptic inhibition (Hagbarth, 1973). Findings that a higher postural instability level induced a lower vibration effect (Gurfinkel et al., 1996; Ivanenko et al., 1999) have suggested the presence of sensory gating systems to prevent sensory overflow in postural control. Therefore, if lesser inflows of afferent signals, which are attributed to better stability of postural equilibrium, by lightly touching a stationary surface with an index finger (Rabin et al., 1999; Lackner et al., 2000) were imposed on subjects exposed to continuous muscle vibration throughout the preparation of the APA setting, it would supply more artificial proprioceptive information to the progressively stored APA setting. The second purpose of this study was to clarify how the APA was modulated by two proprioceptive signals, i.e.; light finger touch and vibration stimuli, and whether the setting of APA was done on a sensory gating concept basis.

The ST task involves precise control of the resultant force, especially in the sagittal direction, in order to project the center of body mass within the boundaries of a narrow base of support. The APA in the ST task caused a somewhat large forward shift of the center of body mass from the standing position to a new small base of support and was followed by a backward propulsive force almost simultaneously with the onset of the focal movement (Ito et al., 2004). The integrated-area of sagittal shear force indicates antero-posterior velocity on the CoM. Consequently, an excessive difference between the areas of forward propulsive and backward braking forces induces a subject's body to start teetering on his tiptoes after executing a focal movement, i.e. dynamic postural instability. The difference between the areas of forward propulsive and backward braking forces needs to be constant for postural stability in the sagittal plane while standing on tiptoe. The integration of posture and movement are required to achieve the goal of a motor task in a bipedal stance. Without adjusting reactive postural responses during the focal movement according to the vibration-induced APA modification, a loss of body stability would be caused. The third purpose of this study was to investigate whether feedback postural adjustments could correct the APA modification with vibration stimuli.

## Methods

Nine right-handed male subjects, age 22.3 ± 3.5 (mean ± standard deviation) years, body height 168.8 ± 7.7 cm, body weight 61.7 ± 7.0 kg and foot size 25.8 ± 0.7 cm, participated in this study. All were naïve to the effects of dorsal neck vibration, and none had ever participated in a physiological experiment with vibration stimuli. All subjects were free of any known neurological or muscle disorders and of temporary muscle soreness or muscle fatigue. They consented to participate according to the guidelines of the local ethics committee and to the Declaration of Helsinki.

This experimental task given to all subjects was the initiation of the ST task as fast as possible from a static standing position in a self-paced manner. Subjects performed in seven consecutive trials each under four conditions in combination with two factors (vibration and finger touch) in the following order: (1) no finger touch, no vibration (control trial: CTL); (2) finger touch, no vibration (TOUCH); (3) no finger touch, vibration (VIB); and (4) finger touch, vibration (TOUCH & VIB). Before the series of VIB trials, the magnitude of the VIF with dorsal neck vibration for 5 s while quietly standing was measured.

Each subject wearing fitted shoes (Moon Star BioLT-01, Japan) stood on a force platform (AMTI OR-6-6-2000, USA) with the upper arms vertical and the right elbow flexed at 90 degrees (the center panel in Fig. 1). We imposed biomechanical constraints on the subject's initial posture with regard to feet position to eliminate the modifying factors of the APA (Ito et al., 2003; Ito et al., 2004; Slijper and Latash, 2004; Azuma et al., 2007). As shown in Fig.1, the subject's feet, positioned exactly along outlines on a foot-template drawn on the force plate, were placed 10 cm apart in parallel, and the subject was blindfolded with an eye-mask. Then, the subject started to superimpose the center of foot pressure (CoP) on a regulated position at rest (rest CoP position; a position 45% of foot length from the heel point: ref. Ito et al., 2003) according to an experimenter's verbal instructions as feedback information. One of the experimenters instructed the blindfolded subject to correct direction and distance by judging the deviation from the position of an intersection point on an X-Y plotter system (TEAC es8, Japan) indicated as the regulated rest CoP position (the left panel in Fig. 1). The direction and distance shown on the X-Y plotter was adjusted to be consistent with the actual values on the force platform. The sequence of the preparation stated above was carried out before each trial throughout the experiment. Each subject voluntarily initiated the ST task with a delay of approximately 2 s after the sequence of the preparation had been completed (without providing any feedback on the subject's CoP by the experimenter). All subjects were instructed to quietly maintain the standing posture on tiptoe for about 3 s after they finished performing the focal movement. During the CTL trial, subjects maintained right elbow flexion, but did not contact the touch device. This was the protocol for the CTL condition.

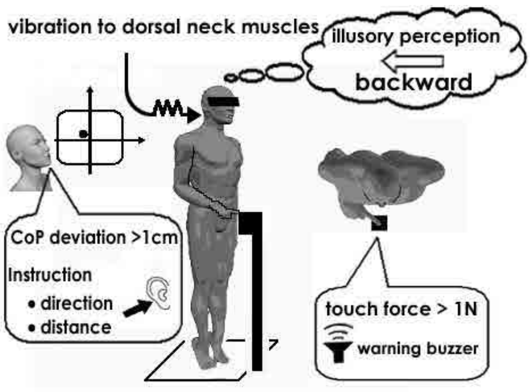


Fig.1
A schematic illustration of the experimental procedures in standing rapidly on tiptoe (ST task) with vibration to dorsal neck muscles (vibration condition) and light touch of index finger (touch condition).

For the TOUCH condition, subjects maintained light contact with a stationary touch device with the right index finger through each trial. The level of the touch device surface, including a small force platform (Kyowa LP-100KSA29, Japan) 5 cm wide by 5 cm long by 3 cm thick on a sturdy tripod, was adjustable to the subject's waist height to maintain right elbow flexion of 90 degrees while quietly standing. All subjects were instructed that the touch force detected in vertical direction should not exceed 1 N during each trial. A warning-buzzer from a PC informed the subject of exceeding the vertical touch force limit.

The experiment for the VIB condition employed two electromechanical vibrators consisting two DC motors with an eccentric on the shaft embedded in a plastic tube 3 cm in diameter and 5 cm long. Vibrators were tightly fixed to bilateral splenius muscles (3 cm lateral from C3-4) by elastic tape. The vibrator at a frequency of 100 Hz produced a peak-to-peak force of 5 N, and amplitude of 0.4-0.5 mm. Vibratory stimuli were applied about 5 s before the APA onset and were stopped after standing on tiptoe for 3 s. Subjects could easily overcome the tonic vibration reflex due to vibration stimuli, and their

CoP position could be adjusted to the rest CoP position regulated by experimenter instructions before each trial.

If large deviations (> 1 N in the touch force downward and/or > 1 cm from the rest CoP position regulated strictly in the anterior-posterior direction) occurred, the trial was rejected and an additional trial was done.

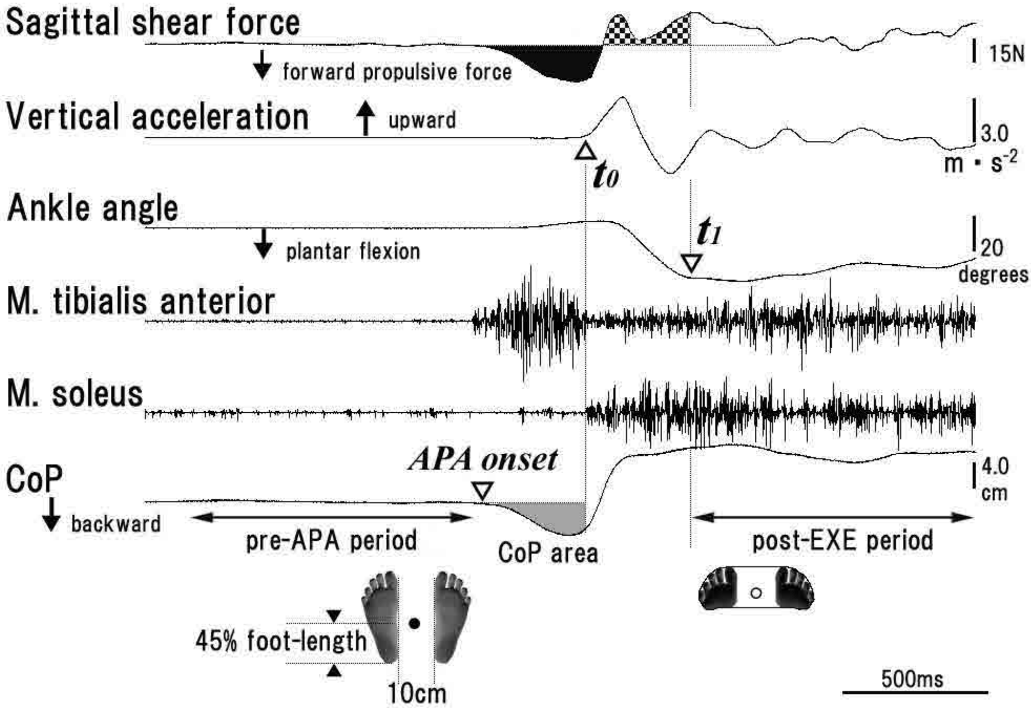


Fig.2

Examples of a representative data (average of three control trials) involved anticipatory postural adjustments (APA) during standing rapidly on tiptoe. Three open triangles show onset of backward displacement in the center of foot pressure (CoP), which corresponds to onset of the APA (APA onset), onset of an upward acceleration on the center of body mass, which is identical to onset of executing a focal movement (t0), and point in end time of the plantar flexion (t1), respectively. Lower-left footprints illustrated show the subject's initial foot positions and the CoP position (closed-circle) strictly regulated before the APA onset. The open circle in the lower-right footprint indicates the mean CoP position projected on a new basal support area at t1. Forward propulsive force around the anticipation phase is indicated as a black-shaded region and backward braking force during the execution phase is represented by the square-dots region.

No analysis was made of the electromyogram (EMG) signals, although EMG signals from the tibialis anterior and soleus muscles were measured for observation of a local APA (cf. Fig. 2). The global APAs were calculated from kinetic data, i.e., the moments around the frontal (Mx) and sagittal (My) axes and the force in the sagittal (Fy) and vertical (Fz) directions recorded using a force platform. Displacement of the CoP in the sagittal directions was computed using the equation: CoP = Mx / Fz. Response of the

CoP and sagittal shear force in the ST task were quantified as follows: (1) root mean square (RMS) and standard deviation (SD) values of the CoP in bipedal stance for 1 s (pre-APA period) before the APA onset or of the CoP while standing on tiptoe for 1 s (post-EXE period) after the termination of plantar flexion (t1; termination of executing a focal movement) to evaluate the static postural instability before and after the focal movements, respectively: (2) area, duration and peak values in the CoP from the APA onset to the onset of upward acceleration on the center of body mass (t0; onset of a focal movement): (3) postural instability in sagittal direction at t1 (dynamic postural instability; DPI-index) calculated from data of the forward and backward propulsive force between the APA onset and t1 during the ST task as follows: DPI-index (%control) = [(forward propulsive force integrated for the APA phase) − (backward braking force integrated to execute the focal movement)] / (average of the DPI-index of the CTL condition) × 100. The DPI-index reflected the concept that the ST task involved the precise and constant control of the resultant force, especially in the sagittal direction, in order to shift the center of body mass within a narrow basal support, i.e., to maintain posture while standing on tiptoe. The goniogram of the ankle joint was detected by a flexible potentiometer (Penny & Giles M110, UK). All mechanical signals were sampled at 1 kHz.

The APA onset, which corresponded to the onset of the CoP change indicating an increase of ≥ 3 mm for the first 30 ms, and the t0, which corresponded to the onset of the upward acceleration indicating an increase of ≥ 0.05 $m \cdot s^{-2}$ for the first 30 ms, were measured carefully by two skillful analysts.

One- and two-way analysis of variance (ANOVA) were simultaneously used to indicate significant differences among the four experimental conditions, and to determine the main effects and interaction of two independent factors (vibration and finger touch), respectively. The degrees of freedom for one- and two-way ANOVAs were 1 and 248, and 3 and 248, respectively. When ANOVA indicated significant differences among the conditions, comparisons of each condition were performed using the Bonferroni's post hoc test. A statistical significance level of $P < 0.05$ was chosen.

## Results

When applied to standing human subjects, the vibration stimuli evoked a stereotyped whole-body postural response in the forward direction in all subjects. Mean magnitude (± SD) of the VIF from the regulated rest CoP position was 5.65 ± 3.67 cm further to the front. In the initial CoP position at APA onset, the sagittal deviations from a reference CoP position across conditions were constant (one-way ANOVA: $F = 0.86$, $P = 0.46$: CTL 2.8 ± 5.6 mm, TOUCH 3.1 ± 7.5 mm, VIB 1.2 ± 6.0 mm, and TOUCH & VIB 2.7 ± 6.4 mm with slightly backward tilts). The momentum of the ankle joint in the ST task was in a range of mean rotation angles between 41.1-41.4 degrees and did not show significant differences among conditions (one-way ANOVA: $F = 0.05$, $P = 0.99$) .

A deflection in backward CoP and forward propulsive force occurred prior to the onset of a focal movement (t0) in all trials as shown in Fig. 2. The upper panel in Fig. 3 shows that the backward CoP in the APA confirmed a significant increase in the area in the TOUCH & VIB conditions than that in the CTL and the TOUCH conditions (one-way ANOVA: $F = 2.77$, $P < 0.05$). The APA area constituted both the duration and amplitude parameters. The APA durations of the CoP in the VIB and the TOUCH & VIB conditions were significantly longer (approximately 40 ms) than that in the CTL (one-way ANOVA: $F = 4.54$, $P < 0.01$: the center panel in Fig. 3), whereas there was no significant difference in the peak CoP amplitude among all conditions ($F = 1.79$, $P = 0.15$: the lower panel in Fig. 3).

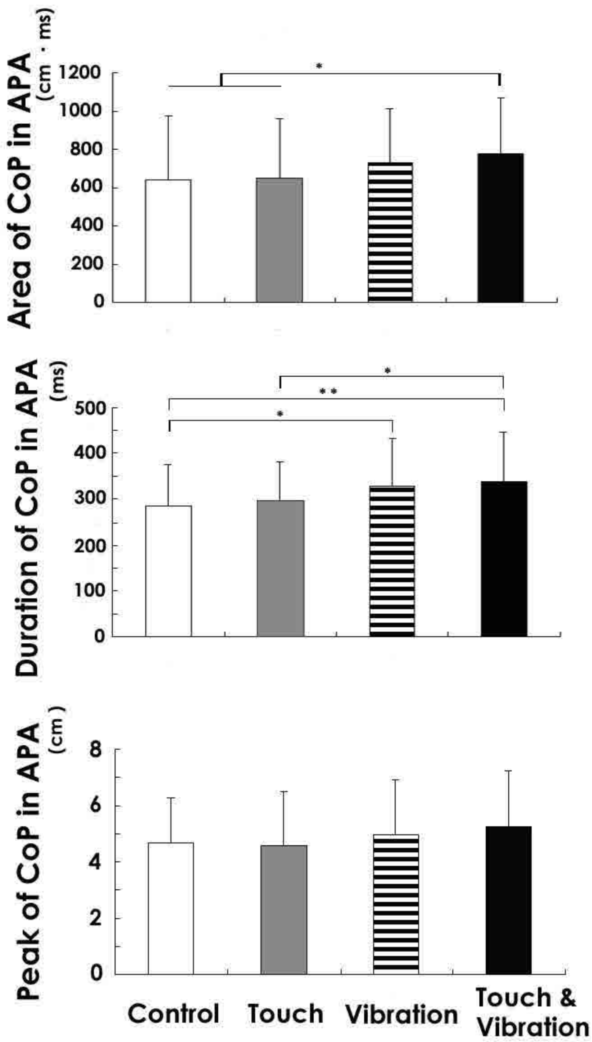


Fig.3

Differences of mean values of the center of foot pressure (CoP) in the anticipatory postural adjustments (APA) among the four experimental conditions (control, touch, vibration and touch & vibration conditions). Error bars are standard deviations. Significant changes of individual differences using post-hoc test were denoted with an asterisk ($P < 0.05$) or two asterisks ($P < 0.01$).

Two-way ANOVA in the SDs of CoP, which corresponded to the static postural instability for pre-APA period (the left panel in Fig. 4), showed a significant decrease in postural instability with a light finger touch (main effect in the TOUCH factor: $F = 12.89$, $P < 0.001$) and a significant interaction between the TOUCH and VIB factors (F= 6.02, P < 0.05) were found. No main effect of the VIB factor was found in the SDs of CoP for the pre-APA period ($F= 0.09$, $P = 0.76$). Meanwhile, the SDs of CoP for the post-EXE period while standing on tiptoes significantly decreased with the light touch (main effect in the TOUCH factor: $F = 32.78$, $P < 0.001$) and without the vibration stimuli (main effect in the VIB factor: $F =$

4.95, $P < 0.05$), and no significant interaction between the VIB and TOUCH factors was found ($F = 0.33$, $P = 0.57$). No significant changes in the RMS of the CoP were observed in any conditions or periods.

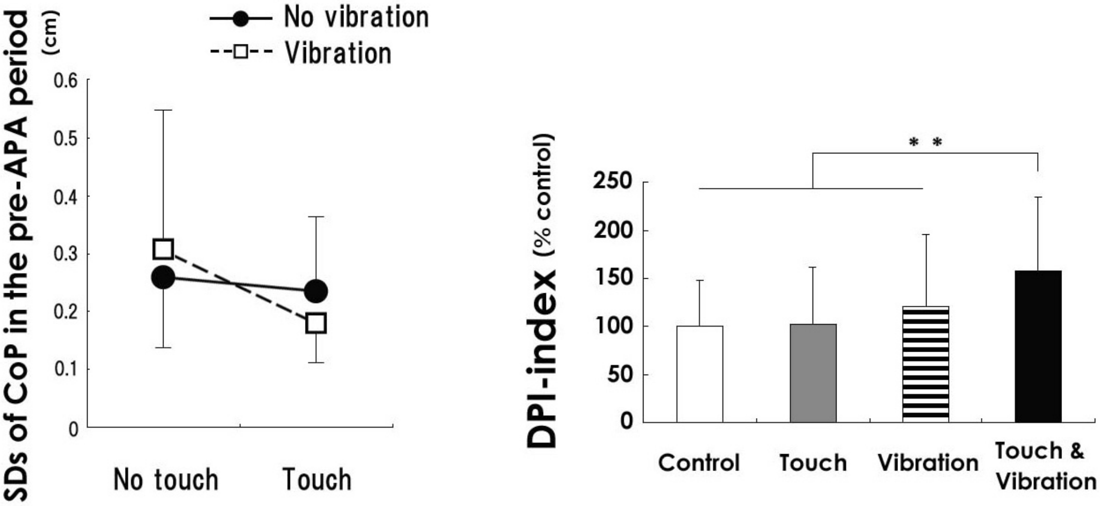


Fig.4

Effects of vibration and light finger touch in static (left panel) and dynamic postural instability (right panel). Error bars shows standard deviations. Two asterisks indicate $P < 0.01$.

The increase in backward CoP area in the APA corresponded approximately to the augmentation of the resultant force for forward propulsion in the APA, as in a previous study (Ito et al. 2004), in the ST task (Pearson's correlation coefficient in the present study, $r = 0.774$, $P < 0.001$). The integrated-area of the forward propulsive force in the TOUCH & VIB condition was larger than the other conditions (one-way ANOVA: $F = 5.14$, $P < 0.01$), while the area of backward propulsive force generated to execute a focal movement remained unchanged across conditions ($F= 0.39$, $P = 0.76$). Therefore, dynamic postural instability, indicated by the DPI-index, increased more significantly in the TOUCH & VIB than in the other conditions (one-way ANOVA: $F= 10.46$, $P < 0.001$: the right panel in Fig. 4).

## Discussion

The present experiment with the vibration stimuli confirmed that the APA increased with augmentation of the postural requirement by changing the illusory perception. Feed-forward control, APA, can occur after setting its gain and duration according to a variety of circumstances during a period of preparation while quietly standing (Cordo and Nashner, 1982; Massion, 1992). For instance, the ST task from a quiet stance with a backward body tilt was associated with earlier onset of APA to compensate for the increase in postural requirements (Lipshits et al., 1981; Yamashita and Moritani, 1989; Ito et al., 2004). The present results showed that not the spatial, but rather the temporal parameter of the APA was scaled according to the virtual postural requirements mimicked by the vibration stimulus. This modulation of the temporal parameter was consistent with previous results in the APA with actual postural changes (Lipshits et al., 1981; Yamashita and Moritani, 1989; Ito et al., 2004). In the ST task, it has been calculated that the APA duration increases by approximately 120 ms per cm of backward displacement of the initial CoP position using a regression line for the relationship between the two variables (Ito et al., 2004). Our results indicated, however, that the modulation of the APA duration by artificial sensory inputs is less effective (increase of approximately 40 ms in the APA duration to illusory perception which is equivalent to a 5.7 cm postural reaction in the VIF with vibration during quiet stance) than that by the actual sensory inputs when the body position changes. This implies that the combined information from foot plantar cutaneous afferents, afferent inputs from dynamic fusimotor signals and spindle secondary terminations from the lower-extremity muscles, afferents from the Golgi tendon organ and joint capsule receptors are monitoring the actual posture requirement and have a greater influence on APA setting than the illusory perception for no weighting of the availability of visual information with blindfolded-eyes and in the vestibular sensory channels during quiet stance (Fitzpatrick et al., 1994).

The observation that light touch contact by the index finger against a stable external object suppressed the SD of the CoP fluctuation during the preparation period for the APA setting with or without vibratory stimuli is consistent with previous reports in the upright stance (Clapp and Wing, 1999; Rabin et al., 1999; Lackner et al., 2000). Surprisingly, light finger support during vibratory stimuli (TOUCH & VIB condition) had a significantly lower CoP fluctuation than the TOUCH condition without vibration (the left panel in Fig. 4). Most subjects gave experimenters feedback that they felt more comfortable controlling unidirectional deflection in the TOUCH & VIB than multidirectional fluctuation in the CTL or TOUCH, even though they were forced to push the whole-body forward with the dorsal neck vibration. This depression of postural sway is probably due to the effectiveness of finger contact in the unstable plane caused by the vibration stimuli (Rabin et al., 1999).

Our results provide a novel finding that this haptic cue augments the effect of vibrations to dorsal neck muscles on the temporal parameters in the APA. In contrast, Slijper and Latash (2004) reported that co-activation in the leg agonist-antagonist muscle pairs during vibration to the postural muscles involved in the APA was buffered by a light finger touch. A crucial difference between the two reports is the intended use of the vibration tool. We employed the vibration stimulus as a non-postural synergist to arouse the conscious and illusory perception of a postural requirement; therefore, there was no significant difference between the CTL and VIB conditions in the SD of the CoP fluctuation during the preparation period for APA setting. This vibration-stimulus method without postural destabilization and providing a regular CoP position allows the confounding factors in the manipulation of postural stability and position sense to be removed from the APA setting.

It is very likely that the APA facilitation with the haptic cue is attributable to a significant interaction between the VIB and TOUCH factors in static equilibrium. The present results for feed-forward postural control are consistent with the finding that the higher the postural stability level induced, the more effective the vibration in reactive postural adjustments (Gurfinkel et al., 1996; Ivanenko et al., 1999). However, vestibulospinal reflexes were much larger with decreasing availability of visual and proprioceptive information, namely ‘sensory re-weighting’, to compensate for the postural instability (Day et al., 1993; Welgampola and Colebatch, 2001). This contrary result cannot be explained by the characteristics of the sensory weighting in the somatosensory system. With the eyes blindfolded in this experimental condition, equilibrium-evoked afferent discharge would arise from vestibular and somatosensory inputs. However, the vestibular system, which has the greatest influence in the detection of large and fast body sway, is not critical in the quiet stance for APA setting assembled progressively (Fitzpatrick et al., 1994). Moreover, although the vibratory stimuli to the cervical muscles require processing of vestibular signals in terms of head position to whole body posture as a central interpretation between the proprioceptive and vestibular input (Lekhel et al., 1997), the cervical muscle afferents play a dominant role over the vestibular afferents (Magnusson et al., 2006). A strong dependency and convergence only on the somatosensory system may force a sensory processing and gating different strategy.

It is possible that the compound of the artificial Ia afferent inflow with the proprioceptive information for postural control under equilibrium instability; i.e. 'sensory overflow', is responsible for blocking the vibration-induced afferent flow. Gurfinkel et al. (1996) implied that the central nervous system (CNS), which decodes proprioceptive signals, might be able to distinguish natural afferent inputs to monitor changes in muscle length concerned with postural stability from artificial information generated by vibration. Hatzitaki et al. (2004) suggested that the CNS can selectively discard tonic and artificial afferent inputs which are less able to threaten postural stability. Our results also indicated that excess ascending afferent inflows with the vibration and postural destabilization, in part, were filtered in the somatosensory system.

Ascending afferent inputs from the lower limbs are modulated by gating in the cortical (centripetal gating or centrifugal inhibition) and/or by the peripheral system (peripheral receptor or spinal reflex) (Brooke et al., 1997). However, a gain in spinal stretch reflex remained unchanged even when maintaining balance was threatened by a postural perturbation (McIlroy et al., 2003). This implies that the depression of the vibration-effect in the APA under postural instability cannot be accounted for only by pre-synaptic inhibition of group Ia fibers or by a 'busy-line' phenomenon at the spinal level. In contrast, evidence has been provided that somatosensory gating, which reduces amplitude in the SEPs from the scalp (Staines et al., 2001), occurs in a postural instability situation, but not in a stable equilibrium (McIlroy et al., 2003). There are possible mechanisms in the CNS to explain these phenomena, often known as sensory processing and gating or facilitation of task-relevant information. Patients with stroke damage involving the ventroposterior thalamus or its cortical connections have compromised capacity to inhibit or facilitate the ascending paths carrying the confounding sensory inflow to extract task-relevant information (Staines et al., 2002). The thalamocortical loop of the rat somatosensory system involves the ascending pathway, which has projections from the brainstem reticular formation to the thalamus ventral posterior medial nucleus (VPM), reticular thalamic nucleus (RTN) and layer IV of the primary somatosensory cortex (SI), and the descending pathway, which has excitatory projections from the SI to the thalamus and had an inhibitory influence from the SI to the RTN due to GABAergic neurons (Nicolelis and Fanselow, 2002). These corticothalamic feedbacks have a role in increasing the center excitability and surrounding suppression to sharpen thalamic receptive fields (Alitto and Usrey, 2003). Here, the decreasing attention (Rosenkranz and Rothwell, 2004) to risk of fall by maintaining better postural stability with the haptic cue may cause the VPM receptive fields to become large enough to receive the irrelevant vibratory-inputs.

The integration of posture and movement are required for achieving the goal of motor tasks in the bipedal stance. The DPI-index in the TOUCH & VIB condition being significantly greater than those in the other conditions (the right panel in Fig. 4) showed that the backward velocity on the CoM during the execution of the focal movement did not increase to counteract the excess forward body velocity generated during the APA. This suggests that the information on APA setting did not flow into the execution system of the focal movement and was not utilized for that system. With respect to the relationship between the control processes of the APA and focal voluntary movement, it has been controversial, regarding the dependent (single) and independent (parallel) control processes (Massion, 1992). When a forefoot is lifted from the four-legged stance in a quadruped (cat), the animal's weight is supported by the contralateral forelimb and ipsilateral hindlimb prior to the lift-off of a foot. This diagonal stance in the quadruped was also observed when directly stimulating a part of the motor cortex related to the lift-off of a forefoot (Massion and Gahery, 1979). Meanwhile, the APA amplitude parameters had a positive and significant correlation with a performance of the focal movement in the ST task in humans (Ito et al., 2004). These results imply that the neural circuit between posture and execution controls appears to reside in the CNS as a dependent (single) control process. On the other hand, the independent (parallel) control process in the APA was confirmed by the observation of a strong temporal dissociation between the onset of the APA and of the voluntary reaching movement in the cat (Schepens and Drew, 2003). The absence of coordination in the sagittal resultant forces to suppress dynamic postural instability in human subjects also implies that the posture and execution components might be set independently of each other in the context of this experimental task and conditions.

We conclude that the temporal components of the APA were set according to the postural requirement generated by artificial proprioceptive inputs with vibrators, and could be enhanced by better postural stability with the haptic cue during quiet stance before APA onset. These findings indicate the possibility that APA modulation by combining equilibrium conditions with vibration stimuli could lead to a brief, noninvasive and quantitative method for measuring the degree of the impaired inhibitory integration of afferent inputs; i.e. 'sensory overflow', in stroke involving the VPM (Staines et al., 2002), dystonia, and Huntington's and Parkinson's disease (Abbruzzese and Berardelli, 2003).

Personal Note:

It is with deep regret that we have lost our collaborator, Dr. Noriyoshi Yamashita. We send sincere condolences to his family.

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