Motor Control, 2000, 4, 407-419

Vibration-Induced Postural Reaction Continues After the Contact With Additional Back Support

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Key Words: back support, muscle vibration, postural reference, postural synergy, human

We investigated the development of postural reactions induced in standing subjects by Achilles tendon vibration. We compared vibratory reactions in 3 different conditions: normal standing, standing near support, and when the solid support being protracted forward changed the initial posture. Additional support for the back was placed at subject's sacral or shoulder level. In the easy standing condition, the postural vibration reaction consists of progressive backward upper body movement. When the body contacted the additional support on the sacral level during the vibratory reaction, the movement of the upper body continued in most of the subjects. This was accompanied by an increase of pressure on the toes. When the support was applied at the shoulder level, the body motion reversed its direction in half of the subjects. In this case, backward-forward oscillations occurred near the support. The initial change of body-support interaction did not influence the ensuing, vibration reaction; namely the reaction was similar to that with the support near to the body at the sacral level. Our data demonstrate that the vibration-induced reaction is not a local reaction limited to one joint, but a complex postural synergy that involves both leg and trunk muscles and integrates the information from touch and pressure afferents of the upper body.

Introduction

Intensive investigations of postural responses to muscle vibration began with the pioneering works of G. Eklund (1972, 1973). He demonstrated that vibration-induced muscle activity influences body equilibrium. Vibration selectively activates muscle spindles, predominantly Ia afferents. As a result of this activation, one can observe a contraction of the muscle that is being vibrated (Tonic Vibration Reflex [TVR]; Matthews & Stein, 1969). The vibration-induced postural sway (Vibration

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Induced Fall [VIF]), however, cannot be well explained by tension changes due to a local tonic vibration reflex (Eklund, 1972, 1973). Moreover, many studies have since shown a high dependence of the effect of vibration on the ongoing postural context (Gurfinkel et al., 1992; Hayashi et al.,1981; Popov et al., 1981; Smetanin et al.,1993). For example, vibration-induced postural reactions depend on the distribution of pressure on the feet (Popov et al., 1981) and on the position of the body segments (Gurfinkel &Latash, 1978). Our recent experiments (Ivanenko et al., 1999) have shown that a decrease in postural stability significantly diminishes the effects of Achilles tendon vibration.

In the present experiments, we analyzed whether a support applied to the back influences the development of postural responses to vibration. It is well known that if the body motion is mechanically constrained before the stimulation, the vibration reaction is degenerated into kinesthetic illusions (Lackner & Graybiel, 1978; Quoniam et al.,1990). Moreover the direction of the illusionary body motion depends on the level in which the body is fixed to the external support (Lackner, 1988, 1992). In these studies, the authors usually applied a short period of intensive vibration and also fixed the body prior to vibration onset. In contrast, our present experiment utilized a prolonged vibration of intermediate intensity. Also as opposed to fixing the body in advance, our subjects could contact the external support *during* the development of the postural reaction.

We planned to address the following questions within this study:

1. What is the time course of the postural reaction to the moderate vibration?
2. What are the effects of additional support placed at different position in respect to the body on this reaction?

For this purpose, we compared reactions to Achilles tendon vibration of 20 s in easy standing, in standing close to the additional solid support, and with the support initially protracted forward (resulting in a change in initial posture) at the sacral or shoulder level.

Methods

Subjects

Eight normal subjects, 3 females and 5 males, mean age 33.9 years (±7.3 *SD*), mean weight 70.5 kg (±11.6 *SD*), and mean height 1.76 m (±0.09 *SD*) without any known neurological or motor disorders, took part in the experiment. They gave a written informed consent to the study after the procedure was explained.

Apparatus

During the experiment subjects stood on a stabiloplatform close to the wall as it is shown in Figure 1. The signal from the platform was amplified and used to quantify the ankle joint torque in the sagittal plane, hereafter referred to as the ankle joint torque (AT). A mechanical stopper (STOPPER) (contact area of 20x4 cm) was used as a back support. It was equipped with strain gauges to measure the horizontal component of force acting on the additional support. The initial position of the contact surface of the stopper was set at 21 cm from the wall and could be extended for 8 cm more. It could be placed at different heights, which could be

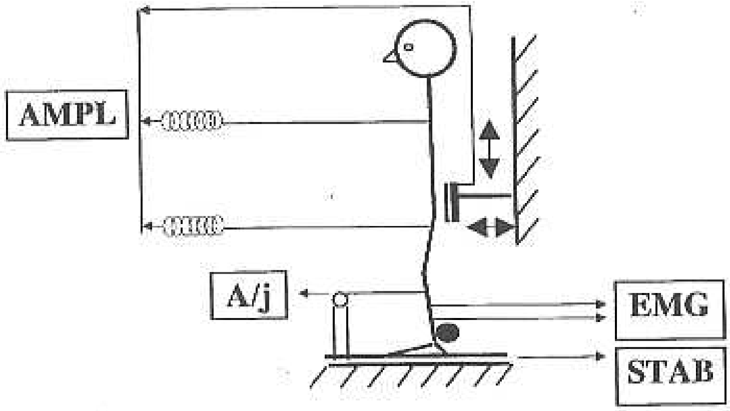

Figure 1 — Schematic diagram of the experimental arrangement used to study the influence of backward support on vibratory reaction in standing subject. Arrows indicate the possibility of up-down and back-forward support displacement.

adjusted individually to fit the subjects' sacral or shoulder level. The back support was removed during the experiment where the postural vibratory reaction in ordinary standing (VIF) was tested.

Two DC-motor based electromechanical vibrators (60–70 Hz, circa 0.5 mm peak-to-peak amplitude) were fixed to the Achilles tendons of both legs by means of elastic bands. The duration of the vibration stimulus used was 20 s. Anterior-posterior displacements of the body segments were measured with two strain gauges connected by elastic threads to the "chest point"(Ch; a point on the midline of the sternum at the level of inter-axial line) and "sacral point" (Sc; at the level of the anterior superior iliac crest). The initial tension and stiffness of the elastic string were small (0.75 N and 7.5 N/m, respectively) so that they did not influence the subject's posture. Ankle joint angle (A/j) was recorded by means of a potentiometer-based goniometer (see also Gurfinkel et al., 1995).

Electromyograms (EMGs) of left m.soleus (SOL) and m.tibialis anterior (TA) were recorded by means of bipolar surface electrodes with an inter-electrode distance of 2 cm placed over the muscle bellies. EMGs were sampled into a PC at 500 Hz and other signals at 20 Hz. All the signals were monitored graphically on-line and stored on the hard disk for off-line analysis.

Procedure

Postural responses to vibration of the Achilles tendons were recorded under three different conditions. In the first condition (VIF), subjects were asked to maintain easy standing with eyes closed on the stabiloplatform. In the second condition (A, B), additional support for the back was placed at the height of the subject's "sacral point"(see above). It was either placed at about 1.5 cm from the dorsal body surface (Condition 2A) or shifted forward in such a way that the increase in the ankle torque due to the forward body displacement was 5 to 10 Nm (Condition 2B). In the third condition (A, B), additional support for the back was placed at the shoulder level similar to Condition 2 with the exception of the back support being situated at the height of the subject's "chest point"(see above).

Before each trial, subjects were asked to place their feet within a contour drawn on the platform surface and assume a standard standing position using visual cues on the PC screen, which displayed the sagittal sway signal. Subjects closed their eyes after fixating a stationary visual target in front of them. Under Condition 2 and 3, the back support was then shifted forwards and fixed in the desired position by means of a screw.

Trial duration was 40 s—10 s before, 20 s during, and 10 s after vibration. The subject stepped off the platform and rested in a chair every three trials. Each of the five experimental conditions was repeated three times in a randomized order. Three of the 8 subjects, who were exposed to the muscle vibration for the first time, were given an introductory trial under Condition 1 to get accustomed to the effects of vibration. After each trial, subjects were asked about their sensation during the trial.

Data Analysis

For every parameter, averages across the three trials at the same task were calculated for each subject, then between-subject analyses were performed. The following was calculated:

In Condition1 (and also in Condition 2B, Condition 3B), we evaluated the effects of vibration as the difference between mean values of the parameters for the last,5 s of vibration and the initial 10 s of the trial. For example, for "chest point" position, the effect of vibration was calculated as follows: ΔCh = mean (Ch [15–20 s]) – mean (Ch [0–10 s]). The change of EMG activity was computed using the rectified and filtered signal.

As for Conditions 2A and 3A, we computed the effect of vibration for: (a) the period from vibration onset until the body contacted the additional support (for example: ΔCh1 = Ch (t0) – mean (Ch[0 – 10s]), identification of t0 see in Results) and (b) the period from the beginning of body contact with the additional support until the end of vibration (for example: ΔCh2 = mean (Ch [15–20 s]) – Ch(t0)). The change of EMG activity was calculated as for Condition 1.

The amount of "non-return" to the initial level was computed as the difference between the mean value of the sagittal stabilogram during the final 5 s of the trial and that during the first 10 s of the trial: ΔAT, fn = mean (AT[35–40 s]) – mean (AT[0–10 s]).

Two-tailed, paired student's *t* test for dependent samples was used to test the differences between initial position in ordinary standing and standing with the additional support protracted forward.

Results

1. Vibration Induced Fall (VIF)

When vibration was applied bilaterally to the Achilles tendons during quite standing, the subject gradually inclined backwards.

We observed three types of VIF-reactions in our subjects (Figure 2). The upper part of Figure 2 (one trial of subject S5) shows a typical case of VIF-reaction: simultaneous backward movement of all body segments during the entire period of vibration. Another type of VIF-reaction is shown for subject S1: The stimulation induced a two-phase backward body inclination—concurrent backward

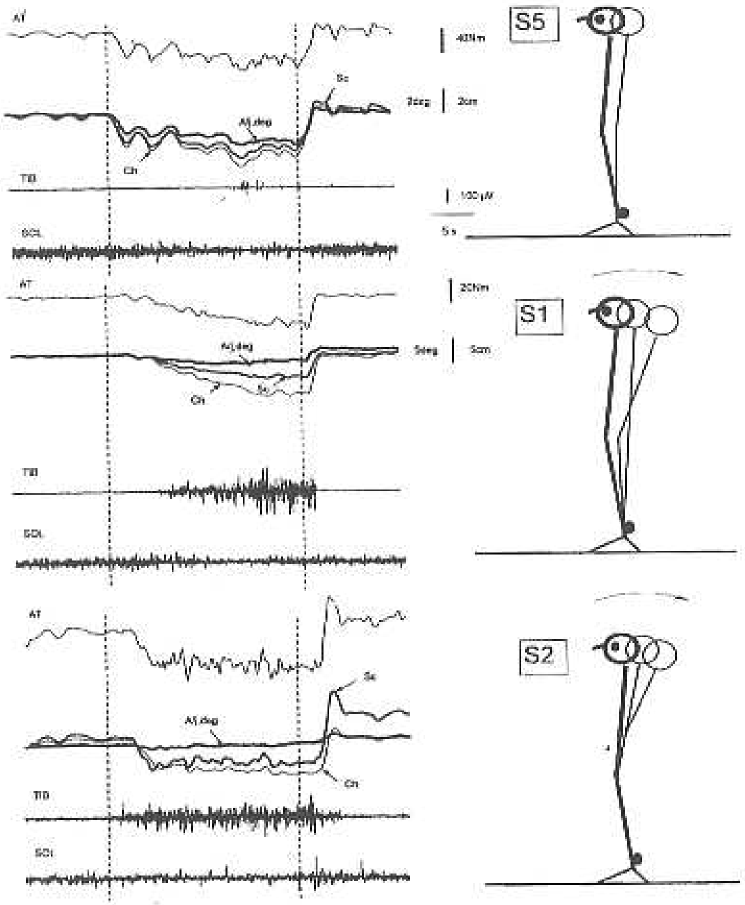

Figure 2 — Three types of postural vibration reaction in normal standing in subjects S5, S1 and S2. In this figure and the following, period of vibration is marked by vertical dotted lines, downward and upward direction of the trace corresponds to backward and forward displacement of the whole body, to increase and decrease of ankle torque (AT) level. If the calibration is not specified see the calibration for previous subject. For further explanation see text.

movement of body segments at the beginning, followed by the ankle-joint movement taking the opposite direction (see the arrow on the A/j-trace). The third type of VIF-reaction is illustrated for subject S2. In this case during the entire stimulation time, the ankle-joint position change was rather small, but the upper body started a backward motion just after the onset of vibration and reached a stationary level in a few seconds. There was an exception for one subject, who exhibited backward upper trunk movements accompanied by lower body movement in the opposite direction immediately after the onset of vibration. This was probably due to the fact that the center of gravity projection in easy standing of this subject was shifted 8 cm backward, whereas for all other subjects, it was displaced about 3 cm forward from the geometrical center of the feet (see also Gurfinkel et al.,1965).

In order to reconstruct the relative positions of the three body segments (ankle, hip, upper body) at the end of the vibration period, taking into account the individual anthropometrical data, we assumed the initial position of the segments for all subjects to be as follows: forward inclination of the shin segment from the vertical, 6°; knee angle, 176°; and upper body position, vertical. The result of this calculation showed that the difference in angular position between chest and ankle of 7 subjects was more than 1°, –5.5 ± 3.6° (mean ± *SD*); and between the chest and sacral points, –3.8 ± 2.1°. One subject moved the body backward as a whole.

Despite the difference in the dynamics of the response (Figure 2), the vibratory reaction in all subjects had one common feature: monotonous backward movement of the upper body (–5.4 ± 3.4 cm) in contrast to the lower limb motion. This corresponded to a decrease in the AT level of all subjects (–33.9 ± 16.7 Nm) and a suppression of SOL activity and increase of TA activity. The amount of AT change during vibration over the trials correlated with the angular difference between the upper and lower body ($r = -0.5$), which could implicate a compensatory function of this postural synergy during vibration.

When vibration ceased, there was a fast forward displacement with an overshoot beyond the initial position (mean value of ΔAT, fn was 4.6 ± 3.5 Nm). (For example, see the trial of Subject S2 on Figure 2.)

2. Back Support on Sacral Level

2.1. Back Support Near the Body on Sacral Level. All subjects displayed the standard VIF reaction until their back touched the additional support (Figure 3).

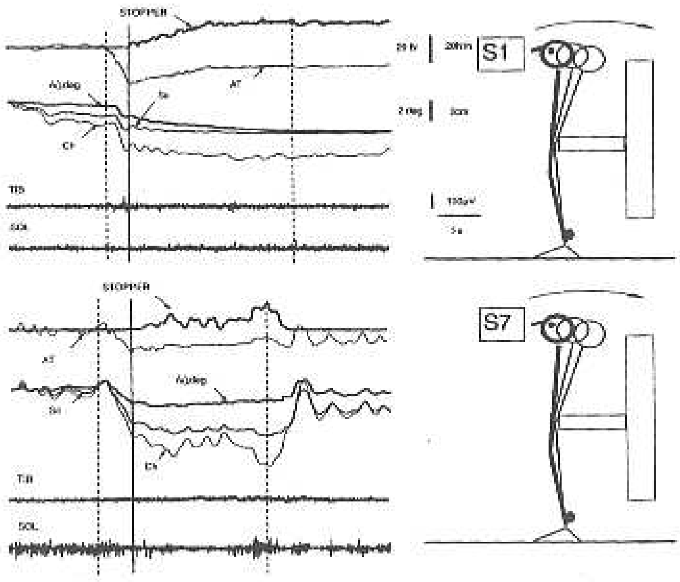

Figure 3 — Two types of postural responses to Achilles tendon vibration of subjects S1 and S7 standing near the additional support placed on sacral level. In this figure and the following, moment of contact with additional back support is marked by a solid vertical line.

The moment t0 was defined as when the body touched the additional support after the beginning of the vibratory reaction (solid vertical line on Figure 3). T0 was determined as the moment of a sharp change of direction on the AT-trace. On average, the time from backward inclination until contact with the support lasted for 3.5 ± 2.6 s. After that, when the contact force reached about 1 N or less, the pressure on the toes started increasing gradually. This was accompanied by a backward tilt of the upper body in 6 out of 8 subjects. The mean backward displacement of the upper body after the contact was −1.1 ± 1.1 cm.

There were long delays in the return of AT and mechanogram to initial levels after the end of vibration. In fact, 3 subjects remained in contact with the additional support until the last 10 s of the trial (as for subject S1 in Figure 3).

2.2. Back Support on Sacral Level Shifted Forward. The forward shifting of the back support at the sacral level induced a significant initial increase of AT level for all subjects ($p < .05$), accompanied by a tendency of SOL increase ($p = .3$). The onset of vibration caused an increase in AT level corresponding to an increase of SOL activity and backward movement of the upper body in 7 out of 8 subjects. The magnitude of the ankle joint position change varied across subjects. The AT increase corresponded to the amount of force applied to the additional support. The force applied to the support gradually increased towards the end of vibration to a level of 15–20 N. Following the end of vibration most of the subjects overestimated their initial position (mean value of ΔAT, fn was 3.5 ± 6.4 Nm).

3. Back Support at the Shoulder Level

3.1. Back Support Near the Body at the Shoulder Level. In this condition, there were two typical reactions. In 4 subjects, the movement of the body ceased when the back touched the support. The backward inclination lasted for 2.5 ± 0.8 s until the support was contacted and the mean upper body inclination was −1.4 ± 0.8 cm. After the body motion stopped, the increase of SOL activity (see one trial by subject S6 in Figure 4) and AT level (8.8 ± 6.8 Nm) became apparent.

In 4 other subjects, the back support contact induced a reversal in the body movement. This ensuing forward movement was changed back to the usual backward movement soon after the body lost contact with the support (Figure 4, subjects S7 and S5). This behavior gave rise to alternating forward-backward movements of the whole body that is to oscillations in the sagittal plane (at 0.6–0.8 Hz).

To determine whether the support was only lightly contacted or was instead relied upon to support the body weight, we performed the following estimation. At the moment when the body started to go forward from the additional support, it was estimated that the body contacted the support at a height of about 1.4 m (middle high of shoulder where additional support was placed). For a subject weighing 75 kg inclined backward about 1.4 cm, a force greater than 7 N ($75 \times g \times 0.014 / 1.4 = 7.4$ N, where g is acceleration of gravity) would be required to support their weight. If so, at times our subjects were physically supported by the mechanical stopper (as evidenced by forces greater than 7 N; see the two initial body tilts of subject S7 on Figure 4). At other times they were not (forces smaller than 7 N; see body oscillation of subject S7 in the middle of vibration period and also vibration reaction of subject S5). In this latter situation, stopper contact did not physically support the body weight.

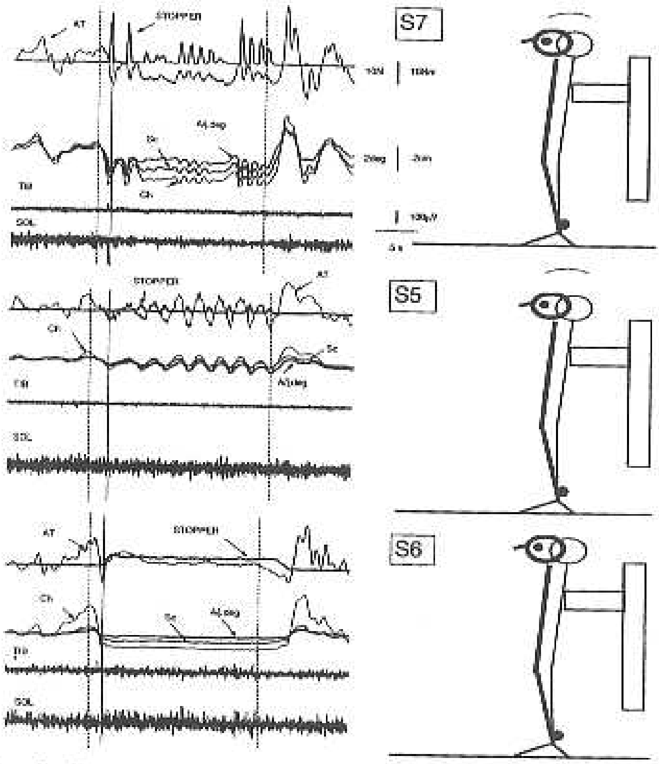

Figure 4 — Cyclic reactions of subjects S7 and S5 and isometric reaction of subject S6 standing near the additional support, placed on shoulder level.

After the end of vibration most of the subjects exhibited a prominent forward after-reaction (3.3 ± 3.5 Nm).

3. 2. Back Support at the Shoulder Level Shifted Forward. Having shifted forward the additional support at the shoulder level we initially increased the ankle torque of all subjects ($p < .05$), accompanied by a tendency of SOL to increase ($p = .1$). The onset of vibration caused an increase of AT and of SOL-activity in 6 out of 8 subjects. The change of ankle joint angle and position of the hip segment varied for each subject. No cases of oscillation appeared under this condition.

The return to the initial position, according to the AT parameter, was 0.3 ± 5.3 Nm.

From these data, it can be concluded that the initial change of body-support interaction did not influence the ensuing vibration reaction at either the sacral or the shoulder level.

Kinesthetic Illusions

In Condition 3B, 3 out of the 8 subjects reported sensations such as "the heels dove into the floor" or " my foot moved backward and the body forward." Under

Condition 3A, the illusion of one subject was "forward bending." For Condition 2A and 2B, 2 out of 8 subjects reported illusions such as "the stopper moved forward, and the velocity of this movement was so high that I was surprised to observe my true small inclination after the trial." The subjects who had cyclic reactions in Con.3A did not have any illusions in any of the conditions.

Discussion

Our data have allowed us to suggest the following answers to the questions formulated in the Introduction:

1. The postural reaction to prolonged Achilles tendon vibration consists of progressive backward upper body movement. The amplitude of this motion, the lower body position, and the magnitude of ankle muscle EMG activity varied across the subjects.

2. The additional support situated near the body changed the ongoing postural vibration reaction. Particularly when the body contacted the support on the sacral level, the movement of the body continued in most of the subjects. When the support was applied at the shoulder level, the upper body motion reversed its direction in half of the subjects. In this case, backward-forward oscillations occurred near the support.

Note that large inter-individual differences in the effects induced by muscle vibration have been previously shown and well accepted (Eklund & Hagbarth, 1966). This is probably due to the fact that postural vibration reactions can be voluntarily suppressed (Eklund, 1972). Therefore, the effects of vibration depend partly on the relaxation state of the entire subject.

Postural Vibration Reaction in Ordinary Standing

Using prolonged vibration of low intensity in easy standing, we have shown a wide range of reaction types, but one basic characteristic of postural reaction remained consistent across subjects: backward bending of the upper body (Figure 2). This response was quite similar to a voluntary backward body inclination (Babinski, 1899; Crenna et al., 1987) with one exception: the velocity of upper body movement in our experiment was about 0.4 cm/s, approximately two orders less than the slow voluntary movement in the experiment of Crenna et al. (20 cm/s). The overall structure of both reactions was similar: backward movement of the upper body and displacement of the lower body to prevent the body from falling, indicating a standard pattern of postural synergy in both cases. The most impressive difference between the voluntary tilt of the body and the backward inclination occurring due to vibration was the continuation of the backward movement of the upper body, while the lower body stopped (subjects S1, S2; Figure 2). It is possible that this phenomenon was due to the remote influences of muscle vibration from the leg to the back muscles, as was proposed by Gurfinkel et al.(1992). The authors found upper body inclination was produced by Achilles tendon vibration during unstable sitting, while during stable sitting, the same vibration elicited knee extension.

Postural Vibration Reaction With Additional Support

The progressive backward upper trunk movement during muscle vibration was recorded both while subjects were in a normal standing position and with the support close to the body at the sacral level. The additional support placed close to the back at the shoulder level led either to cessation of the movement accompanied by an increase of SOL activity, or to a change in direction of the vibratory reaction, followed by oscillations of the whole body in the sagittal plane near the support.

Such a periodic inversion of the postural vibration reaction was also shown by Popov et al.(1981), in which the forward body movement under TA-vibration inverted after forward displacement of the center of pressure (CP) under the feet. In this case, the cyclic reaction appeared in one subject, who moved forward during TA vibration so much that he raised on his toes. After that, the inversion of the reaction occurred and he began to move backward (frequency of oscillation 0.1Hz). The displacement of CP in that experiment did not change to the opposite the reaction to Achilles tendon vibration. Occasionally, in our study the afferent signal from the shoulder did invert this reaction in some subjects and induced oscillations with a frequency of 0.6-0.8 Hz. Regarding the oscillation frequency as an informative parameter, reflective of the typical timing of changes in the reference frame when the source of information is changed (Kelso 1998), one can consider these oscillations as a good example of a combination of feedforward and feedback loops (see also Fitzpatrick, 1996). Further studies are required to better understand this phenomenon.

How can the analysis of postural vibratory reactions contribute to an understanding of the control of upright posture itself?

1. The Non-Local Response of the Muscle Vibration. Muscle vibration is now a common method for studying the non-local responses, which depend on the central mechanisms of posture regulation. Achilles tendon vibration evokes backward body inclination. It must be pointed out that when vibration was applied, there was no primary activation of SOL (Figure 2). It is unclear whether the decrease in SOL activity was due to or the consequence of the body inclination. One can suggest that Achilles tendon vibration produced the SOL activity and resulted in body inclination. When a considerable inclination developed, the muscle activity was inhibited to prevent a fall. Thus, the inhibition of SOL activity can be considered a consequence of the backward body inclination. The cause of this inclination remains unclear. It is possible that the onset of the vibration causes a small amplitude of TVR, undetectable as SOL EMG, and this TVR is sufficient to disturb posture and to cause a backward body inclination. However, it was shown earlier by Gurfinkel et al.(1974) that elasticity of the active shin muscles is excessive due to antagonist coactivation. Therefore, small changes in SOL activity are not likely to disturb balance. On the other hand, it can also be suggested that the backward inclination of the body was caused by the activity of the *trunk* muscles. If this were the case, the vibratory reaction is substantially defined by a change of "reference system" of vertical pose (see Gurfinkel et al., 1994; Massion, 1994), apparently connected with the upper, most massive part of the body (together with hands and head, about 63% of total weight).

2. The Role of Somatosensory Information. The inclination under vibration by itself disturbs balance. The cessation of the backward movement in our experiment occurred well within the stability limits and therefore gave rise to oscillations around the "neutral level" (far from the range of possible motion; Figure 4). We believe that here, even a weak signal from somatosensory sources of the upper body appeared to be capable of changing the direction of the postural vibration reaction.

Experimental data concerning the role of additional touch and pressure cues in postural control are quite scarce. The role of fingertip contact in the postural regulation was most widely covered in the latest experiments of Jeka et al. (1994, 1997). Analyzing medial-lateral body sway in the tandem Romberg posture with additional hand contact, they found that the contact of the fingertip with a frontally moving bar leads to synchronization of the entire body to the frequency of the touch-bar movement. It is also known that a subject being rotated about the Z-axis of his body while horizontal feels himself inverted by changing the pressure on the top of his head to the pressure on the soles of his feet (Lackner, 1992). In animal experiments, it was shown that cats, wearing a vest fitted to their shaved trunk, tend to keep their limbs extended at a roughly constant orientation relative to a platform tilted in the sagittal plane rather than relative to the vertical (Lacquaniti & Maioli, 1994). This behavior may result in a loss of balance with platform tilt changes. The importance of somatosensory stimuli to postural regulation was also suggested by Bernstein in 1947, who observed that the locomotion in the patient diagnosed with "tabes dorsales" was improved thanks to a special heavy belt giving the intermediate pressure to the abdomen skin. Therefore, the experimental results suggest that the increase of postural stability could be a result of the sensory source (cue) at finger and body surface as well.

Conclusions

1. It was shown that the vibratory stimulation of ankle muscle afferents initiates the whole body inclination associated with the center-of-mass displacement. The constant feature of this synergy is the backward tilt of the upper body, while the changes in the position of the lower body and legs varied between subjects.

2. A mechanical stopper placed at different levels did not terminate the vibratory reaction: it continued, although these reactions were different from the usual VIF. Body contact with a support at the sacral level during the vibration reaction (developed at one third from maximal) induced the contraction of a muscle being vibrated, which can be accompanied by an upper body backward inclination. Moreover, the additional support placed at shoulder level could invert the direction of the postural reaction.

3. The present data demonstrate that the postural vibration reaction is not a local reaction limited to one joint, but a complex postural synergy involving both

leg and trunk muscles, which also integrates the information from touch and pressure afferents of the upper body.

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Acknowledgements

This work was supported by the RFFI grant # 98-04-48935. We thank Prof. V. Gurfinkel Dr. Y. Levik, and Dr. O. Kazennikov for their critical discussion, and also the two anonymous reviewers for helpful comments.

Manuscript submitted: February 1, 1999
Accepted for publication: March 21, 2000