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Human Postural Responses to Different Frequency Vibrations of Lower Leg Muscles

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Summary

We analyzed human postural responses to muscle vibration applied at four different frequencies to lower leg muscles, the lateral gastrocnemius (GA) or tibialis anterior (TA) muscles. The muscle vibrations induced changes in postural orientation characterized by the center of pressure (CoP) on the force platform surface on which the subjects were standing. Unilateral vibratory stimulation of TA induced body leaning forward and in the direction of the stimulated leg. Unilateral vibration of GA muscles induced body tilting backwards and in the opposite direction of the stimulated leg. The time course of postural responses was similar and started within 1 s after the onset of vibration by a gradual body tilt. When a new slope of the body position was reached, oscillations of body alignment occurred. When the vibrations were discontinued, this was followed by rapid recovery of the initial body position. The relationship between the magnitude of the postural response and frequency of vibration differed between TA and GA. While the magnitude of postural responses to TA vibration increased approximately linearly in the 60-100 Hz range of vibration frequency, the magnitude of response to GA vibration increased linearly only at lower frequencies of 40-60 Hz. The direction of body tilt induced by muscle vibration did not depend on the vibration frequency.

Key words
Postural responses • Vibration frequency • Lower leg muscles • Man

Introduction

The postural system consists of several sensory systems (proprioceptive, visual and vestibular), the motor system, and a central integrating control system which involves complex interactions among multiple neural systems (Horak and MacPherson 1996). Tendon or muscle vibration generates proprioceptive information which is not congruent with actual body position. The proprioceptive input induced by muscle vibration has been shown to alter spatial body orientation within seconds (Lackner 1988, Roll *et al.* 1989). The primary muscle spindle endings that are highly sensitive to mechanical stimuli are responsible for the response to muscle vibration (Roll *et al.* 1989). Vibration of lower leg muscles induces spatially oriented body tilts, with a tendency to fall during bilaterally applied vibration (Eklund 1969). Unilateral muscle vibration of the tibialis anterior muscle generates body tilt forwards and in the direction of the stimulated leg, while unilateral muscle vibration of the triceps surae (lateral and medical gastrocnemius and the soleus muscle) causes a backward

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tilt which is opposite the side of the stimulated leg (Hayashi *et al.* 1981, Hlavačka *et al.* 1996). The functional character of two lower leg muscles – tibialis anterior (TA) and gastrocnemius (GA) – differs. While the TA is a muscle which shows very little activity during normal standing, GA is a muscle with more or less constant activity during stance. We predicted that these differences would affect the response characteristics of each muscle to variations in frequency of vibration. A linear dependence between induced body tilt magnitude and vibration frequency was found for vibrations applied to both plantar sole zones (Kavounoudias *et al.* 1999). Likewise, the enhanced motor evoked potentials to vibration applied to extensor carpi radialis muscle varied with changes in vibration frequency (Siggelkow *et al.* 1999). We can expect a similar dependence of magnitude of postural response on vibration frequency of lower leg muscles.

The aim of our research was to characterize the human postural sway response (forward-backward and left-right stabilograms) to vibrations of different frequency (40-100 Hz) applied to lower leg muscles (tibialis anterior, gastrocnemius).

Methods

Fifteen healthy volunteers (8 females and 7 males) aged 19-28 years (mean age 23.3±2.6) served as the subjects. Informed consent was obtained from all of them. To ensure that the subjects had normal balance control, we performed a balance screening test with them before the experiment. The data from the screening test were compared to the physiological range of stabilometric parameters in the human upright posture (Hlavačka *et al*. 1990).

Vibrations were generated by a small DC motor with an eccentric weight of 5 g. The DC motor was enclosed in a plastic tube 9 cm high and 5 cm in diameter to allow safe application to the skin overlying the muscles. The vibrator was fixed in place with an elastic sling and was applied directly on the muscle (not tendon), for a more adequate response of muscle receptors to the vibration frequency (Roll *et al*. 1989).

Vibration was applied to lower leg muscles (TA and GA) of standing subjects at four different frequencies: f_1 = 40 Hz, f_2 = 60 Hz, f_3 = 80 Hz and f_4 = 100 Hz. Each lower leg muscle (TA right or left, and GA right or left) was vibrated individually.

The postural response was measured by the force platform (center of foot pressure exerted by the body on the platform surface – CoP). The CoP in forward-backward and left-right direction were recorded on line with a laboratory computer at 100 samples/s during 20-s trials. The postural responses were quantified by measuring the position of CoP relative to the initial position in both directions. The subjects stood upright on the platform with their eyes closed and their hands along the body during the experiment. The heels were together with feet opened at an angle of 30°.

The experiment consisted of 20-s trials under 16 different conditions (four muscles x four vibration frequencies) and was divided into 4 blocks (4 repetitions) of 16 trials during 2 days with 2 blocks per day. Each trial lasted 20 s and consisted of a 2 s baseline without vibration, an 8 s period of vibration and a 10 s period following the end of vibrations. The 16 different conditions were randomized to avoid prediction, habituation and fatigue, and were repeated 4 times each. For comparison to normal variability of body sway, one 20-s trial with control situation (no stimulation with eyes closed) was performed.

The obtained data were analyzed and evaluated in MATLAB. Paired t-tests with p=0.05 significance level served for statistical analysis.

Results

Lower leg muscle vibration evoked body tilts from the vertical axis in all subjects. Direction of the body tilts depended on which muscle was vibrated: postural response amplitude, but not the time course, varied with vibration of different frequencies (Fig. 1). CoP responses to vibration of lower leg muscles started with a small body shift opposite to the direction of final body tilt. The main body tilt reached a new position at 1.5 to 2.5 s after vibration onset. The velocity of main body tilt varied with the frequency of vibration. Another, smaller increase of body tilt followed, mostly in a forward-backward direction, which was accompanied by a slight CoP oscillation until the end of vibration. Vibration cessation was followed by a short small amplitude CoP tilt increase. The body then returned to the initial position, stabilization being reached during 2 s after the end of vibration. Some subjects demonstrated an overshoot of the initial body position, but this overshot was not evident in the grand average of all data**.** The mean values of CoP in control condition with no vibratory stimulation and eyes closed were small and near to the initial position. The value in the forward-backward direction was –0.18±0.43 cm and for lateral direction 0.04±0.26 cm.

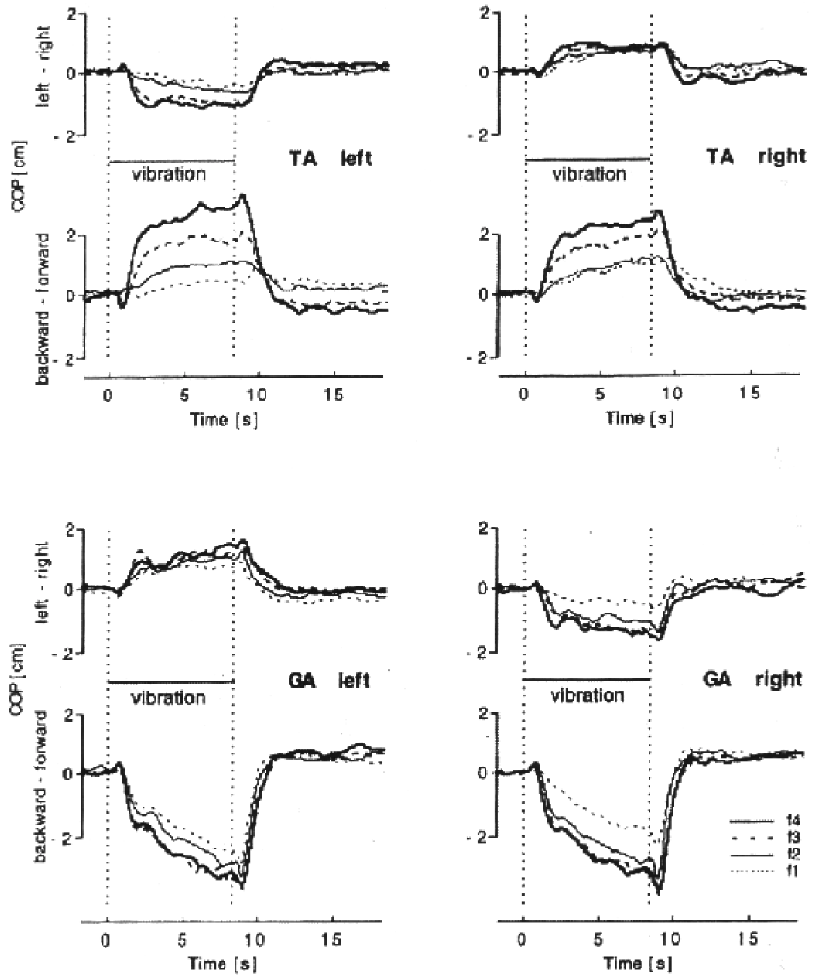

Fig. 1. *Forward-backward and left-right time records (CoP) of grand average postural responses of all subjects to different vibration frequencies. The oriented body tilts evoked by vibration were dependent on the muscle stimulated (TA or GA). Body tilt magnitude depended on the frequency and increased from f_1 (40 Hz) to f_4 (100 Hz).*

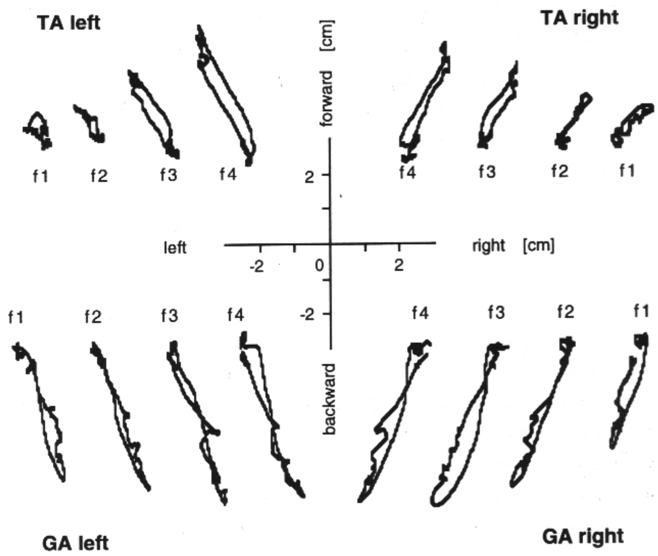

Fig. 2. *Grand average CoP responses of all subjects in the form of an xy-record. Representation of direction and magnitude of postural response to different frequency vibrations.*

Representation of grand mean CoP responses of all subjects in the form of xy-records (Fig. 2) illustrates the effects of vibration frequency on response direction and response magnitude. Vibration of TA evoked a body tilt forwards and in the direction of the stimulated leg, while vibration of GA evoked body tilting backwards and in the opposite direction to the stimulated leg. Responses were larger during GA vibration. We characterized the evoked direction of body tilt by using polar plots, where 0° was defined on the right hand side and 90° in front of the subject. The result show that increasing frequency has no influence upon the direction of the evoked body tilt (Fig. 3). Average angle of body tilt direction for the left TA was 111.5±18.1°; for the right TA 68.5±14.7°; for the left GA 289.7±11.3° and for the right GA 248.3±11.2°. These facts clearly indicate that directions of body tilt are symmetrical for muscles of the left and right leg. The average angles of body tilt directions from all frequencies (bold arrows) are presented in Figure 3, next to the icon identifying the vibrated muscle. Angles of the body tilt direction of individual subjects are also depicted. Statistical analysis showed that the evoked body tilt direction is determined only by the vibrated muscle and is not dependent on the vibration frequency.

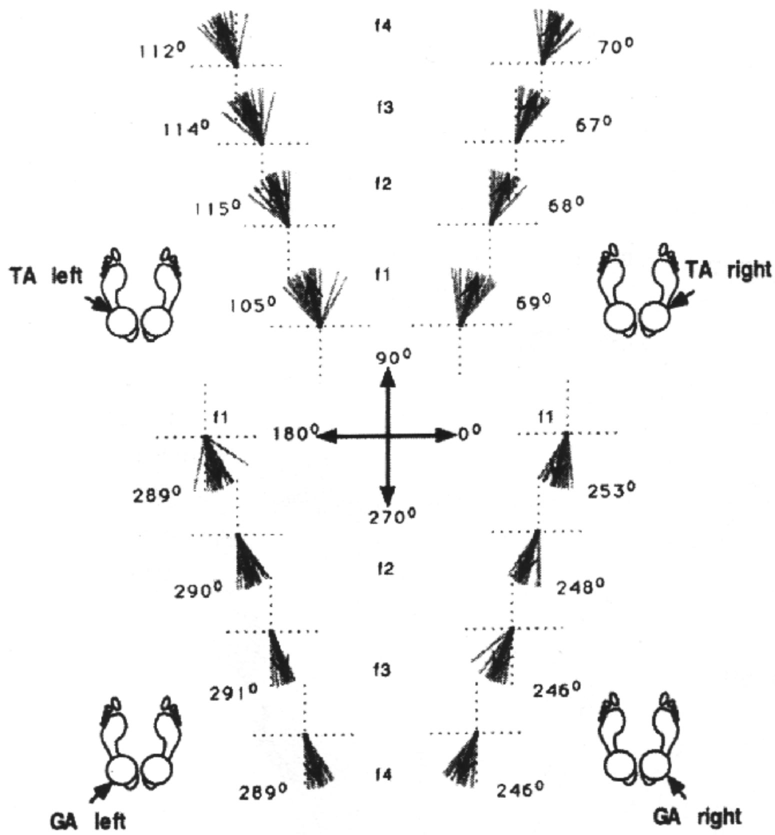

Fig. 3. *Body tilts angle values of each subject for all vibrated muscles. Bold arrows show average body tilt angles of all subjects. Average values for each muscle are not significantly different across vibration frequencies (significance level p= 0.05).*

Body tilts evoked during TA and GA vibration are performed mostly in the forward-backward direction (Fig. 2). We obtained evoked body tilt magnitude from grand average CoP values measured during 3-8 s of vibration for both forward-backward (My) and lateral (Mx) directions by Mcop = sqrt(Mx*Mx + My*My). The dependence of the magnitude of body tilts on vibration frequency is presented in Figure 4. During TA muscle vibration, body tilting increased approximately linearly with frequency range from f_2 (60 Hz) to f_4 (100 Hz). Tilting with the frequency f_1 (40 Hz) is not significantly different from the tilt at frequency f_2 (Fig. 4). We recorded an approximately linear increase of tilt magnitude during the GA vibration only with lower frequencies from f_1 to f_2 for both muscles (left and right) and with frequency from f_2 to f_3 for the left GA (Fig. 4). The magnitude of tilting was unaffected by increasing the frequency from f_3 to f_4. Comparison of the response increase with ascending frequency during TA and GA vibration is represented in Figure 5. The different character of the increases for both vibrated muscles (TA and GA) is evident.

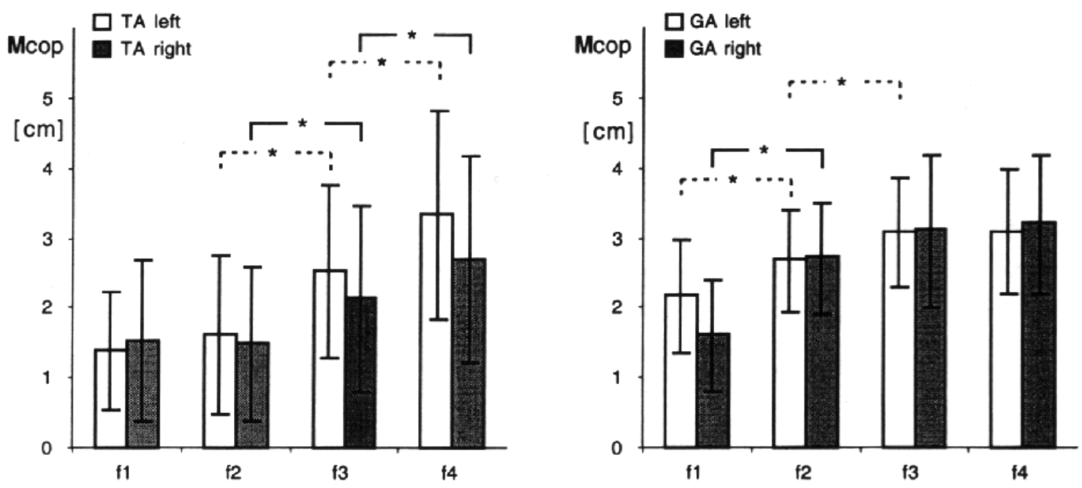

Fig. 4. *Comparison of total magnitude of body tilts (Mcop) evoked during (3-8) s period of each muscle and all vibration frequencies (f_1=40, f_2=60, f_3=80, f_4=100 Hz). The asterisk denotes significant differences (p= 0.05). Values Mcop are grand averages with error bars ± S.D.*

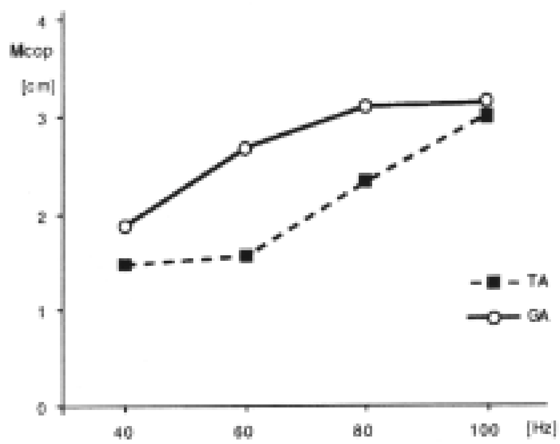

Fig. 5. *Comparison of TA and GA response sensitivity (quantified as Mcop) related to the range of vibration frequency (abscissa in Hz).*

Discussion

The results of our experiment show that the magnitude of postural responses (body tilt, leaning) to leg muscle vibration can be modulated by the frequency of the vibratory stimulus (Figs 1 and 2). The frequency of vibration does not influence the direction of body slope (Fig. 3). The direction of the postural response was determined only by the muscle stimulated. Body tilting occurred in all our subjects with lower leg muscle vibrations which is consistent with prior reports concerning the postural orientation during muscle or Achilles tendon vibration (Eklund 1972, Hayashi *et al.* 1981, Roll and Vedel 1982).

Recent work on human postural control during combined leg muscle vibration and galvanic vestibular stimulation (Hlavačka *et al.* 1995, 1996) suggests that the maintenance of vertical orientation of the body in an upright standing position with eyes closed is under the continuous control of vestibular and leg proprioceptive inflow. Each sensory system contributes to the establishment of a reference system for maintaining the vertical position of the body. The control of human upright posture requires both operative control assigned for compensation of body deviations from a reference position and a conservative control system which elaborates this reference using kinesthetic inputs with participation of body scheme mechanisms (Gurfinkel *et al.* 1995).

It is reasonable to assume from our results that the magnitude of the body tilt determined by the frequency of muscle vibration is involved in operative postural control. The reference setting is always updated as sensory conditions change. In our experiment, a new body position was set each time when the muscle vibration (proprioceptive input) started or the vibration frequency was changed.

Body tilts evoked by vibration of each muscle maintained the same direction. This indicates some special and defined role of the muscle as an element of human body scheme. As a response to proprioceptive stimulation of a freely standing person on a stable support, each muscle involved in the human body scheme is always given the same special direction of evoked body tilt.

Different changes in the magnitude of body tilts during stimulation of GA and TA are interesting and can be related to two facts. First, anatomical locations are different – TA in the front and GA in the back of the leg. Second, and probably more important, is the different functional role of these muscles in standing posture. GA, which is continuously active during normal upright posture, is responsive to lower vibration frequencies and its activity during vibration increases from an already active level during forward body tilting. In contrast, TA is inactive during upright posture and must increase its activity during backward body tilt from zero level.

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