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EFFECT OF SUPPORT STABILITY ON POSTURAL VIBRATORY RESPONSES IN MAN

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The postural responses to vibration of the leg muscles in standing on a stable and unstable support were compared. Two types of an unstable support were used: a tilting platform shaped like a large paper-weight and a steady support with a soft porolon mat for the feet. Oscillations in the ankle joint were 3 – 10 times greater on a tilting platform than on the hard floor; the average rate of changes on the stabilogram increased 1.6 times, and a high-frequency component appeared on it in the 2 – 3-Hz zone. It was impossible to stand on a tilting platform. Standing on the soft support was characterized by increased (1.7-fold) rate of changes in the stabilogram. The stabilogram level, the angle at the ankle joint, and inclination of the trunk on a tilting support in response to vibration were displaced on average much less than in response to the same vibration effect on a soft or hard stable support. It is assumed that the absence of a marked response to vibration in standing on a tilting unsteady support is due to the changes in the strategy of balance maintenance.

Vibration-induced stimulation of muscles is among the methods for studying the role of proprioception in maintenance of the vertical posture in man [1 – 3]. The response of the muscles and the postural reaction to the effect of vibration depend on the external conditions: the contact of the feet with the support, the angle of tilting of the support surface, and fixation of the upper part of the trunk [3 – 8]. An opinion has been repeatedly advanced that the vibration reactions in a standing person reflect the work of posture control mechanisms. This point of view agrees fully with the fact that change in the conditions of balance maintenance affects the postural responses to vibration. We therefore decided to use vibration-induced effects in investigating the insufficiently studied changes in the mechanism of posture control in standing on a unsteady support. An attempt was made to connect the discovered differences in the responses to vibration with changes in the strategy of balance maintenance and the physiological role of proprioception of the leg muscles.

METHODS

Eight healthy subjects aged from 20 to 40 years were engaged in the study.

The device is represented schematically in Fig. 1*a*. A platform shaped like a big paper-weight that could accomplish a translational-rocking motion served as the unstable platform. Its base was shaped like a semicylinder with a radius of 25 cm. A stabilograph was firmly attached to the top

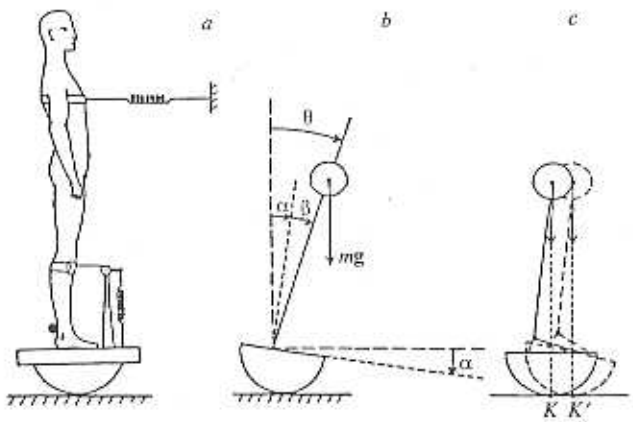

Fig. 1. The general view of the device (*a*), deviations of angles analyzed in the experiment (*b*), and change of balanced body posture in rotation of the platform (*c*). α) Angle of platform rotation; β) angle in ankle joint; θ) angular deviation of trunk from vertical; *K*, *K'*) point of contact of platform with floor. Chosen as the positive direction of all angles was that direction that corresponded to forward inclination of the body (corresponds to the clockwise direction in the given figure).

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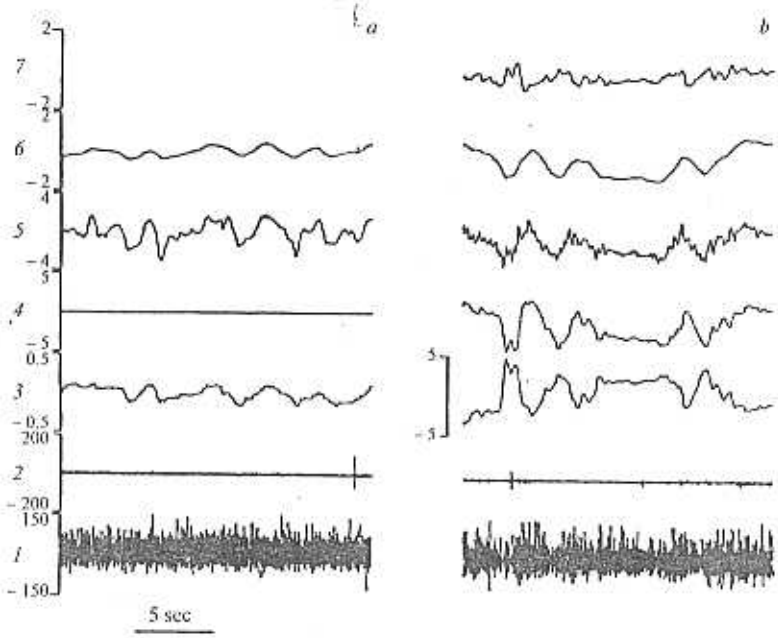

Fig. 2. Balance maintenance on a steady (*a*) and unsteady (*b*) support. *1*) SM EMG, μV; *2*) PTM EMG, μV; *3*) oscillations in ankle joint, deg.; *4*) oscillations of platform, deg.; *5*) sagittal stabilogram, N · m; *6*) horizontal displacement of thoracic point in immobile coordinate system, cm; *7*) horizontal displacement of thoracic point in system of coordinates of unsteady support, found from curve 6 after subtracting from it curve 4 with a coefficient of 0.44 (since inclination of the platform by 1° is attended with horizontal displacement of the point of contact between the platform and floor by 0.44 cm). Attention should be paid to the 10-fold difference in calibration of the angle at the ankle on an unsteady and steady support.

of the base. The upper surface of the stabilograph was 23 cm from the floor. The platform together with the stabilograph weighed 10 kg. The subject stood with opened eyes and his upper limbs hanging freely along the body. Control measurements on a steady platform were taken in firm fixation of the platform in a horizontal position.

The position of the feet on the support may differ. Since the center of gravity is unambiguously determined by the point of contact between the platform and the floor (see further), the position of the feet depends on the distance from the axis of the ankle to the projection of the center of gravity, i.e., the force moment. It is well known that displacement of pressure to the front or back of the feet changes the tonic activity of the postural muscles [9] and may alter the direction of the vibratory responses [4]. So, before recording began, the subject was told to move his feet in the antero-posterior direction so that the primary force moment in the ankle joint (stabilogram level) on the tilting support would approximate that in usual standing on the firm floor. Accordingly, the level m. of soleus muscle (SM) EMG activity was also approximately equal.

Records were taken of the force moment in the ankle joint (sagittal stabilogram), platform angle of rotation, angle at the ankle joint, horizontal displacement of the upper part of the trunk on the chest level, and surface EMG of the soleus muscle and anterior tibial muscle (ATM). The angle of inclination of the platform and displacement of the thoracic point were measured with a tensometer, and the angle at the ankle with a potentiometric pick-up. In some cases (to check Eq. (1)) the estimated horizontal displacement of the thoracic point was used in calculating the trunk angle of rotation in relation to the vertical. The signals obtained through the ACP were set into an IBM PC/AT computer for subsequent processing. The frequency of myogram and mechanogram digitalization was 500 and 20 Hz, respectively.

It is noteworthy that the thoracic point pick-up measured the displacement of the upper part of the trunk in the immobile coordinate system. To find the horizontal displacement of the thoracic point in relation to the platform, the horizontal translational component of the support movement had to be taken into account. Inclination of the platform (25-cm radius) by 1° caused horizontal displacement of the point of contact between the platform and the floor by 25/57 = 0.44 cm.

Vibration of the Achilles tendons and tendons of the anterior tibial muscles of both lower limbs was accomplished with vibrators. The amplitude of the oscillations was 1 mm, and frequency ranged from 60 to 70 Hz [3]. The experiment consisted of 6 tests on average on a stable and unstable platform, each lasting 90 sec. Vibratory stimulation lasted 30 sec. In the intervals (2 – 3 min) between the tests, the subject sat on a chair without displacing his feet in relation to the platform.

In an additional series of experiments, a soft porolon mat 5 cm in width and 30 g/dm^3 in density was used as the unstable support. Under the subject's weight the thickness of the porolon decreased to 1 cm. The postural responses to vibration of the Achilles tendons were studied on such a pliable soft support in 4 persons.

To compare oscillations of the body on a stable and unstable platform, the root-mean-square deviation of the recorded mechanograms from the mean value was estimated. The steadiness of standing was assessed by calculating the mean rate (according to the absolute value) of change of the stabilogram. The fast Fourier transform was employed for analysis of the stabilogram frequency characteristic. The response to vibratory stimulation was judged from the change of the mean level of the mechanograms and EMG-activity. The last 20 sec of the vibration period were compared with a similar preprocedure period. Thus, the transitional process, which in tests on a support usually took several seconds, was not taken into account in calculating the mean values. The average level of EMG-activity was determined after its straightening. The numerical data are presented in the work as mean ± root-mean-square deviation.

RESULTS

Peculiarities of Balance Maintenance on a Stable and Unstable Support

It is well known that when standing on a steady support, the human body in a first approximation is a single-link overturned pendulum with mobility at the ankle joint [10]. Rigidness in the other joints is much higher while the loads experienced are less; as a result the small slow deviations of the center of mass in the sagittal plane are compensated by the leg muscles [11].

On an unstable rocking support, just like on the hard floor, the main mobility takes place in the ankle joint. If that is so, and movements at the other joints are small, then the trunk angle of inclination must be equal to the angle of rotation of the platform plus the angle of inclination of the leg (Fig. 1*b*):

$$\theta = \alpha + \beta. \quad (1)$$

Satisfactory approximation of the experimental curve of the trunk angle of inclination could indeed be obtained by adding the current values of the inclination angle of the platform and the ankle angle in accordance with Eq. (1). Such approximation provided accuracy up to 1°, while oscillations in the ankle joint reached 5 – 10°.

Figure 2 illustrates standing on an immobile and mobile support of one of the subjects. Differences are most apparent on goniograms of the angle at the ankle. First, oscillations of this angle were 3 – 10 times more in standing on an unsteady platform than in standing on the hard floor (more than tenfold in the case of the subject shown in Fig. 2). On the whole, in the group the oscillations (root-mean-square deviation) in the ankle joint were equal to $0.18 \pm 0.06°$ in standing on a steady support, and $0.93 \pm 0.37°$ in standing on an unsteady platform. Secondly, though in both cases the mechanograms changed in phase one with another, on an unsteady platform the change in the ankle angle was contrary to displacement of the upper part of the trunk. Forward displacement of the upper trunk on an unsteady platform was attended by shortening of the gastrocnemius muscle. In large movement amplitudes (as in Fig. 2), increased EMG-activity of the soleus muscle in its shortening, but not in stretching, was apparent.

Note that in standing on an unsteady platform, the support is always displaced horizontally due to its translation-rotation motion (rocking). Balance was maintained on an unsteady platform largely due to displacement of the support under the feet to the side of the inclining center of mass of the body (Fig. 1*c*). The conditions for balance in this case require that there is no tilting moment of the force of gravity in relation to the point of contact between the platform and the floor, i.e., that the projection of the center of mass is within the supporting contour of the feet and coincides with the point of contact of the platform with the floor. This condition for balance maintenance is shown schematically in Fig. 1*c*. Experimentally this conclusion was confirmed by the small

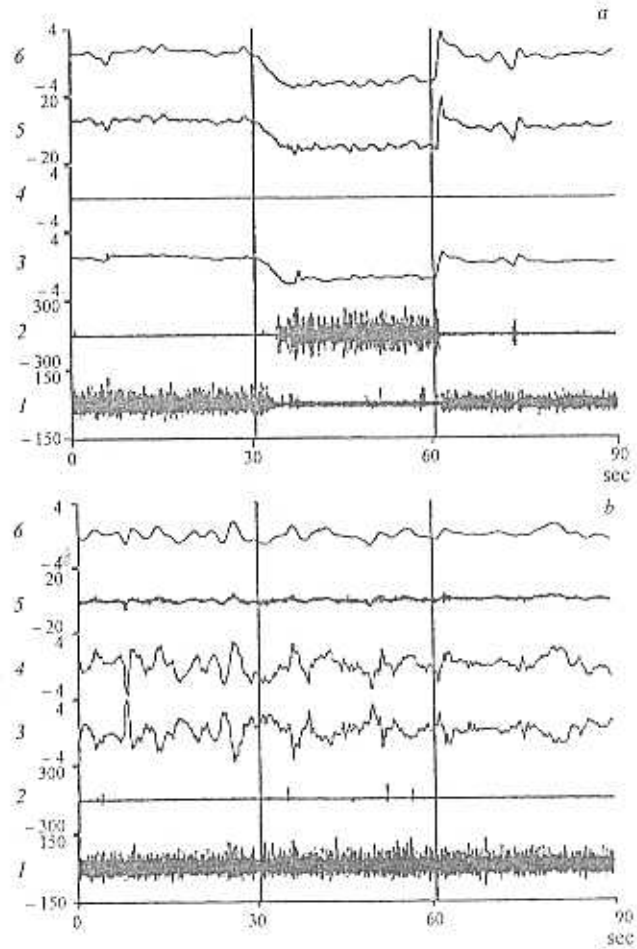

Fig. 3. Vibration of the Achilles tendons on a steady (*a*) and unsteady support (*b*). Designations the same as in Fig. 2. Vertical marks at 30 and 60 sec correspond to the beginning and end of vibration.

deviation of the trunk from the vertical, i.e., by the small horizontal displacement of the thoracic point in relation to the mobile support. Displacement of the thoracic point in the immobile coordinate system was actually about 2 – 4 cm (curve *6* in Fig. 2) but in relation to the platform the deviations were smaller (curve *7*). On the whole, horizontal movements of the thoracic point displacement (root-mean-square deviation) in the group came to 0.58 ± 0.21 cm in a steady system of coordinates and to 0.29 ± 0.05 cm in relation to the platform (0.37 ± 0.09 cm on a steady support). The small horizontal movements of the upper trunk were the result of the oscillations in the ankle joint occurring in the phase opposite to that of the rotation angle of the platform (curves *3* and *4* in Figs. 2, 3*b*).

The stabilogram mean level changed insignificantly (curve *5*); the root-mean-square deviation was 1.4 ± 0.4 (1.7 ± 0.6 N · m on a hard support). A peak was seen on the frequency characteristic of the stabilogram in the zone of high frequencies (2 – 3 Hz) which had also been found earlier [12]. The mean rate of change in the stabilogram on an unsteady platform was 1.6 times that on the hard floor.

Thus, while balance was accomplished mainly due to the leg muscles, precise stabilization of the angle at the ankle joint was not a problem of its maintenance. Balance was possible whatever the inclination of the platform and the angle at the ankle, respectively, if only the projection of the center of mass coincided with the point of contact of the platform and floor (Fig. 1*c*). Therefore, in the case of an unsteady support, the value of the ankle angle cannot be an unambiguous absolute reference point. Moreover, displacement of the trunk on an unsteady and steady support was attended by differently directed change of the angle at the ankle (e.g., a forward movement of the trunk was accompanied with plantar flexion in the first and dorsal flexion in the second case). Standing on an unsteady support differed from standing on the hard floor in the contribution of various sources of sensory information. For instance, most subjects could not stand on it with their eyes closed. Due to growing accelerations at the head level [12], an increased role of the vestibular apparatus also cannot be excluded. It may be assumed that the character of employing information from the muscle spindles in maintaining the posture on an unsteady support changes, which in turn allows differences to be expected in the postural responses to vibration of the leg muscles as compared to those in standing on a hard support.

Postural Vibration Responses on a Steady and Unsteady Support

Vibration of the Achilles tendons in a subject standing on a hard support caused the trunk to incline backwards (Fig. 3*a*), which was described for the first time by Eklund [5]. On average, in 8 subjects the stabilogram level was displaced by 18 ± 8 N · m and the angle at the ankle joint by $1.5 \pm 0.5°$. In some of the subjects, mild extension at the hip joint was encountered in small deviations of the upper trunk, while the change in the ankle joint occurred in two phases: at first the angle of inclination of the trunk and the angle at the ankle joint changed in parallel, then, while the trunk continued deviating slowly to the back, the change in the angle at the ankle took place more slowly or even reversed.

When the support under the feet becomes pliable, stabilization of the vertical body posture deteriorates, which is displayed in increased amplitude and rate of mechanogram changes [13]. In our experiments with a soft porolon mat, a statistically significant 1.7-fold increase of the mean rate of stabilogram changes occurred, which was evidence of more active contribution of the leg muscles to stabilization of body balance [14]. The size of oscillations of the angle of inclination of the leg in relation to the vertical (which in standing on an easily distorted support is unambiguously related to the angle at the ankle) increases 1.6-fold as compared to that in standing on a hard support. The response to vibration of the Achilles tendons on a soft "immobile" support, however, persisted, i.e., backward deviation of the body was demonstrated (the stabilogram level was displaced by 10 N · m on the average).

The vibration effect usually hardly changed the pattern of standing on a mobile support (Fig. 3*b*), although switching the vibrators on or off affected the character of the oscillations in many cases. They could increase or, in contrast, decrease. Some subjects noted that they found it easier to stand during vibration. Differences could occur between the first and the next tests (because the subject had become accustomed to the procedure). On the whole, the mean value of the ankle angle in the group of subjects did not change (Table 1).

The myographic patterns of balance maintenance on a steady and unsteady support were similar in many respects. The level of SM activity was moderate, the ATM was poorly active in most cases. After vibration had been switched on, EMG-activity of the soleus muscle on a hard support diminished by 46% on average. In some of the subjects (as in Fig. 3*a*) it was damped almost completely. On an unsteady support SM activity did not decrease and even increased in some subjects. The increase in SM activity on an unsteady support in a constant stabilogram level (the moment of force in the ankle joint) was apparently compensated for by the other muscles.

In vibration of the ATM tendons on a hard support the body deviated to the front. There was no response on an unsteady support (Table 1), and the EMG-activity level of the SM and ATM hardly changed.

DISCUSSION

The results of the experiments show that change of the conditions of balance maintenance in standing on an unsteady support leads to the disappearance of marked vibration responses that occur on the hard floor. In principle, the opposite effect could also be expected. The absence of a store of stability could have possibly caused serious balance disorders during vibration. Nevertheless no significant changes were encountered, and balance was not disturbed and some subjects even found standing easier. On the other hand, if the postural vibration-induced responses consisted of activation and shortening of the vibrated muscles, then a marked change in the angle at the ankle joint and the angle of inclination of the platform in balance maintenance could not be excluded (Fig. 1*c*). However, the mean level of the angle at the ankle in the group as a whole did not change.

With what may the disappearance of the vibration-induced responses on an unsteady support be connected? One of the causes may be suppression of the reflex excitability of the motor neurons. This suggestion is based on the results of work [15] in which the authors found that the H-reflex was suppressed in a person walking on a narrow unsteady beam. Nevertheless this explanation cannot be considered exhaustive. The case that we studied differed from the usual condition in that maintenance of balance on an unsteady support amounted to positioning the support under the deviating center of mass and not to minimizing deviations of the center of mass in relation to a steady support. In comparison with the

TABLE 1. Change of Mean Stabilogram Level and Angle in the Ankle Joint ($\Delta\beta$, mean $\pm\sigma$) in Vibration of the Achilles Tendons and Tendons of the Anterior Tibial Muscles

Subject	Vibration of Achilles tendons				Vibration of tendons of anterior tibial muscles			
	steady support		unsteady platform		steady support		unsteady platform	
	stabilogram, N · m	$\Delta\beta$, deg.	stabilogram, N · m	$\Delta\beta$, deg.	stabilogram, N · m	$\Delta\beta$, deg.	stabilogram, N · m	$\Delta\beta$, deg.
M. L.	−31	−1.8 ± 0.3	0	0.4 ± 0.8	12	1.5 ± 0.4	−2	1.5 ± 1.1
V. G.	−30	−1.4 ± 0.5	1	−0.2 ± 1.1	35	5.4 ± 1.9	0	−1.0 ± 1.9
Yu. I.	−19	−2.2 ± 0.5	−1	−0.6 ± 0.5	24	3.5 ± 0.1	0	−0.6 ± 1.1
Yu. L.	−13	−2.0 ± 0.6	−1	0.9 ± 0.1	35	2.8 ± 0.6	−1	0.4 ± 0.2
L. D.	−13	−1.3 ± 0.6	−1	1.5 ± 1.5	8	1.7 ± 0.9	2	−0.3 ± 1.4
I. B.	−13	−0.7 ± 0.2	0	−0.7 ± 0.3	13	3.4 ± 0.4	−1	0.7 ± 0.9
L. T.	−12	−1.1 ± 0.3	0	0.5 ± 0.9	3	1.0 ± 0.3	1	0.5 ± 1.9
V. T.	−11	−1.1 ± 0.4	0	−0.2 ± 0.5	12	1.1 ± 0.3	−1	−0.3 ± 0.5
Mean	−18	−1.5	0	0.2	18	2.6	0	0.1

Note. Direction corresponding to forward inclination of the body was accepted as positive.

normal position of a person on a hard floor, standing on a mobile, unsteady support requires higher levels of control.

We believe that the absence of a response to vibration of the leg muscles may be attributed to a change in the way proprioceptive information is used in maintaining balance on a mobile support. It may be assumed that on a firm support the system of posture control uses the concept of the vertical, which is based to a great measure on proprioceptive information, including information from the receptors of leg muscle stretching. The current control takes place in relation to this referent posture. Vibration-induced stimulation of the muscles produces a false additional signal, which causes displacement of this referent posture. As a result the body deviates forward or backward and control is accomplished in relation to a new level. This hypothesis is supported by the fact that the response to vibration of the leg muscles involves not only these muscles but the remote muscles of the trunk as well, and the fact that when trunk movements are prevented by fixation, vibration produces the illusion of its inclination [3, 7, 8].

The subjects practically could not stand on an unsteady support with the chosen parameters if their eyes were closed. This means that to maintain a vertical posture under these conditions the visual vertical must be used. This may be due to the difficulty of using proprioceptive information for formation of the reading system in the case of a mobile rocking support whose tilting changes continuously at quite high rates. In particular, inclination of the body on the hard floor and on porolon can be judged by the change in the force moment in the ankle joint, but in experiments on an unsteady platform the situation is different (see the results). The change from a proprioceptive to visual vertical alters the response to the effect of vibration. The vibration-induced signal from the muscle receptors is no longer interpreted as displacement of the referent posture and does not induce the response of deviation of the body. This does not exclude changes at the level of the operative control (in stabilogram oscillations, EMG modulation, etc.).

Thus, these data are evidence in favor of the notion that postural vibration-induced responses in standing are basically determined by central rather than by local segmental mechanisms.

CONCLUSIONS

1. Comparison of standing on a steady support and on an unsteady rotator support showed the main mobility in balance maintenance to be in the ankle joint. However, on an unsteady support oscillations in the ankle were 3 – 10 times greater, the mean rate of changes in the stabilogram grew 1.6-fold, and a high-frequency component appeared on the stabilogram (2 – 3 Hz).

2. The strategy of balance maintenance on a "paperweight" was related to the horizontal mobility of the platform and consisted in displacement of the support in the direction of the deviating body mass center.

3. The force moment and the angle at the ankle joint changed in response to vibration on an unsteady support much less than in response to a similar vibration effect on a soft or firm steady support.

4. It is suggested that the absence of a marked response to vibration of the leg muscles in standing on a mobile unsteady support is due to changed strategy of balance maintenance.

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