DOI 10.1007/s11062-016-9547-0
Neurophysiology, Vol. 47, No. 5,October 2015

Effects of Destabilization of Visual Environment Perception on the Maintenance of Upright Stance by Humans on Different Support Surfaces

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Received July 28, 2014

We compared characteristics of the maintenance of human upright stance under conditions of a real visual environment (VE) and "immersion" into a virtual visual environment (VVE). The foreground of the latter corresponded to the window in the room, while the background was a view of the aqueduct with the adjacent terrain. Destabilization of the VVE was created by "coupling" of the foreground position with oscillations of the subject's body within the sagittal plane. We measured elementary variables calculated according to the trajectory of the center of feet pressure (CFP); these variables were: (i) displacement of the vertical projection of the center of gravity (CGv) and (ii) difference between the positions of the CFP and CGv (variables CGv and CFP – CGv). When standing on a rigid support surface, the root mean square (RMS) of the spectra of oscillations of both variables decreased in the case of an antiphase relation between displacements of the VE foreground with oscillations of the body and increased in the case of an inphase relation between these variables, as compared with the RMS in the maintenance of upright stance under conditions of an immobile VE (ImVE). Under conditions of the inphase relation, however, there were no dramatic disorders in the vertical stance; maximum oscillations of the body in this case did not exceed values typical of the upright stance with the eyes closed (EC). When the upright stance was maintained on a squeezable support, body oscillations increased significantly under all visual conditions, and the difference between the RMS of the CGv spectra obtained for the conditions of the inphase relation and EC became statistically significant. In the case of standing on a squeezable support, RMSs of the CFP – CGv variable at the antiphase relation of the VVE foreground were greater than those at the inphase relation. At the same time, the RMS of the CGv spectra were, *vice versa*, greater at the inphase relation. Thus, upon variation of the conditions for the vertical stance maintenance, the amplitude characteristics of elementary variables (CGv and CFP – CGv) determining the CFP on a support can vary in both a parallel and an independent manner. These variables can be controlled not only by coupled but also by independent (uncoupled) mechanisms controlling their amplitude/frequency parameters.

Keywords: upright stance, stabilography, postural reactions, virtual visual environment (VVE), visual feedback.

INTRODUCTION

The main task for the system responsible for the maintenance of upright stance in humans is aimed at that horizontal shifts of the vertical projection of the center of gravity (CGv) of the body should not go out from a support polygon for the feet on the support surface. This problem is rather complicated because the human body corresponds, in general, to an inverted pendulum. The oscillations of the latter are difficult to predict because the moment of inertia changes continuously. The support reactions, i.e., shifts of the center of feet pressure (CFP) cannot precisely trace changes in the position of the CGv projection. Nonetheless, the human CNS successfully resolves this task by coordinated contractions of the activity of the lower limb and trunk muscles based on information coming from the vestibular, visual, and proprioceptive sensory systems. The result is a relatively stable position of the body, wherein the horizontal displacements of the CGv projection are much smaller than the dimensions of the support contour.

The presence of visual information is not an absolute prerequisite for the maintaining of upright stance; the quality of such maintenance, however, may significantly worsen in the absence of visual signals [1–3]. This phenomenon becomes especially noticeable in some neurological diseases [2, 4–7]. The visual system is involved in stabilization of

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the vertical posture using a variety of mechanisms. On the one hand, vision is directly involved in estimation of the magnitude, speed, and direction of the body oscillations [8–13]; on the other hand, vision affects the system of postural control in a nonspecific mode. The latter statement is confirmed, in particular, by the fact that closing of the eyes in darkness (i.e., under conditions where it is impossible to use vision for stabilization of the posture) may be accompanied by further worsening of the upright stance maintenance [14]. *Vice versa*, when the tested subject stands with his/her eyes open but with spectacles with frosted glasses on (which makes visual spatial orientation impossible), the subject “stands better” than in darkness with the eyes closed (EC) [3].

As is believed [15, 16], nonspecific visual influences are mostly realized via the regulation of the joint stiffness (first of all, in joints of the lower extremities) and mediated by either simple weakening/strengthening of tonic contraction of the corresponding muscles or a decrease in the gain in the vestibular and/or proprioceptive subsystems of postural control. There is some evidence that indirectly confirms these assumptions [16, 17]. For example, Fitzpatrick et al. [17], when comparing postural responses to vestibular stimulation at standing with the eyes open and closed (EO and EC), found that both amplitudes of background body oscillations and magnitude of the reactions to the above stimulation increase in a parallel manner under EC condition. This fact allowed researchers to suggest that differences between the magnitudes of body oscillations under different visual conditions may be related to changes in the joint stiffness automatically adjusted basing on nonspecific influences coming from the visual input.

To verify this assumption, we compared the effects of different visual conditions on the maintenance of upright posture when standing subjects were on different support surfaces, firm and squeezable ones. In the analysis of results, we estimated changes of two elementary variables determining fluctuations of the CFP. The first variable describes displacements of the vertical projection of the center of gravity (CGv) of the body, which is, in fact, a controlled value [18, 19]. The second variable is a difference between the CFP and CGv positions (variable CFP – CGv); its value allows one to estimate changes in the resulting joint stiffness in the ankle joints and in muscle forces correcting oscillations of the body [20, 21].

We used a squeezable support considering the results of the earlier study [23]. It was shown that when a subject stands on such a support under conditions of an immobile visual environment (ImVE), the relative contribution of elementary variables in the maintenance of upright stance was more noticeable and differed somewhat from that on a rigid support. In this study, there were conditions of the absence of visual information (EC) and three conditions of “immersion” of the tested subjects in a virtual visual environment (VVE). The latter environment could be stable or oscillatory, and the respective oscillations were in either inphase or antiphase (IPh or APh, respectively) relations with oscillations of the body of the subject.

METHODS

Tested Subjects. Fourteen practically healthy subjects, 8 men (mean age 42.6 ± 5.6 years) and 6 women (44.0 ± 6.2 years), with no visual pathologies and having no neurological diseases in the anamnesis, took part in the study. In the course of the tests, the subjects maintained a comfortable upright posture, standing on a stabilographic platform (40 × 40 cm; Stabiloplatform-2, KB NIII in Balashikha, Russia). This allowed us to record changes in the CFP position on the platform. The feet of the subject were in a convenient position (angle 20 to 30 deg, distance between the heels 6–8 cm).

Visual Conditions. While maintaining the upright stance, the subjects looked at a screen (height 1.5 m, width 2.0 m), made of a textile having a minimum depolarization degree (silver screen). Using the so-called passive technique [22, 24] a 3D stereo image was formed on the screen; the image was based on the light polarization effect. By means of two projectors (Sharp XR-10X), equipped with polarizing filters oriented orthogonally to each other, two images of the same scene (a view on the aqueduct seen from the room window) were formed on the screen. The subjects and projectors were on the same side with respect to the screen. During the tests, the subjects wore glasses having polarizing filters (3DS-GS Panorama, Stel-Computer Systems, Russia; alternation frequency 120 sec^{-1}), also oriented orthogonally with each other and in a parallel manner with respect to the projector filters. This provided 3D perception of the VVE. The field of vision for the subjects was limited by the glasses and did not exceed the screen area (about 60 deg vertically and 80 deg horizontally). Under such conditions, only a 3D virtual pattern including two plans was perceived by the subject. The foreground corresponded to a view of the room window with the adjacent walls, while the second plan was a view of the aqueduct with the adjacent terrain. The distance to the foreground corresponded to 1.2 m, while that to the outer picture looked as equal to about 20 m. Thus, the subjects could provide visual orientation exclusively within the presented VVE; during testing, they were asked to concentrate on the distant picture and to look approximately at the center of the screen.

We examined the upright stance maintenance under conditions where displacements of the visible VE were associated with oscillations of the body; this provided a full immersion of the subject into the VVE. For this purpose, the position of the foreground of this environment was made dependent on oscillations of the body within one plane (in the present study, sagittal, i.e., anterior-posterior one). Such linkage provided practically synchronous (delay 25 msec) displacements of the VVE foreground with respects to oscillations of the body in these directions; the displacements could be either IPh or APh with each other.

Oscillations of the body in the anterior-posterior direction were estimated according to the signals from a tensometric transducer connected by an elastic thread with the subject's body at the level of the coxal joints. The stiffness of the thread was small (1.4 N/m); i.e., the thread did not practically affect the position of the body [25]. Displacements of the VVE foreground were in correlation with the oscillations of the body within the sagittal plane with the help of a computer program using indications of the tensometric transducer. These signals were then installed in the structure of realization of the VVE displacements in such a way that an experimenter could easily change the direction of displacements of the VVE foreground (IPh or APh) before each testing.

In our study, the coefficient of coupling of the VVE foreground displacements and oscillations of the subject's body within the sagittal plane was equal to 2.0. In other words, when the body shift in the anterior-posterior direction was, e.g., 1.0 cm, the VVE foreground shifted by 2.0 cm. Earlier, we found that the subjects, when correcting their posture under such conditions, unwittingly use the movable VVE foreground as a reference; correspondingly, the posture is destabilized, as compared with that under normal visual conditions [26]. Manipulation of the direction of linkage between body oscillations and VVE resulted in a situation where the tested subjects, according to their verbal reports, perceived, in general, the VE as nonstationary one despite the presence of the still distant picture.

Analysis of Body Oscillations. The CFP trajectory, obtained according to the signals from pressure sensors of the stabilographic platform, was digitized at a 100 sec^{-1} frequency and recorded on a personal computer. In the subsequent analysis, it was converted to a sum of two components, oscillations within the sagittal and frontal planes. The maintenance of the upright posture was evaluated by analyzing changes in the amplitude-frequency characteristics of two elementary variables calculated from the CFP movements on the support surface. These were: (i) CGv trajectory (variable CGv) and (ii) a difference between the CFP and CGv trajectories (variable CFP –CGv). In calculations of these variables, we used the approach proposed by Brenière [27, 28]. This approach has been used many times and described in detail in a number of papers by Rougier et al. [19, 29, 30] and by other researchers. This is why we describe below only its basic statements.

The method for calculation of these elementary variables is based on the presence of a clear frequency dependence of changes in the amplitudes of CGv and CFP oscillations. In particular, it was shown [19, 20, 28, 30] that the ratio between amplitudes of these variables (CFP/CGv) is the maximum (approaching 1.0) at minimum frequencies of oscillations (small fractions of a hertz) and reaches the smallest values (approaching zero) at high frequencies (greater than 3 Hz). It is easy to conclude that the relatively high-frequency oscillations of CFP do not affect the magnitude of CGv oscillations. Indeed, the above-mentioned studies demonstrated experimentally that CFP oscillations with frequencies exceeding 0.5 Hz were practically not reflected in the magnitude of CGv oscillations. According to such interpretation, we used a low-pass filter to obtain the mentioned elementary variables [19, 20]. Before using this filter, we subjected a digitized CFP trajectory to amplitude-frequency decomposition using fast Fourier transform. In such a way, we obtained the amplitude distribution of CFP displacements as a function of the frequency. When the CFP spectrum was calculated, we obtained the CGv spectrum, and the CGv trajectory in the temporal scan was reconstructed by inverse Fourier transform. Then, by subtracting the CFP and CGv trajectories in the temporal scan, we obtained the signal of the CFP–CGv variable and, consequently, the spectrum of the latter. It should be noted that, similarly to what was found in other studies [19, 21, 29], the selected characteristic of the filter does not depend on the anthropometric parameters of the subjects.

Later on, in the analysis of the test results, CGV displacements were interpreted as a controlled variable, while the CFP–CGv difference was considered a variable that reflects changes in the resulting stiffness in the ankle joints and muscle forces correcting oscillations of the body CG [18, 19]. The effects of visual conditions on the vertical stance maintenance were estimated by analyzing changes in the median frequency (MdF) and root mean square value (RMS) of the spectra of oscillations within the ranges of 0–1.0 Hz for the CGv variable and 0–3.0 Hz for the CFP – CGv variable.

The program for frequency filtration of the CFP oscillations providing separation of the CGv and CFP–CGv variables and subsequent calculation of the MdF and RMS spectra for oscillations was written within the MatLab environment.

Procedure of the Tests. In the course of testing, the subject was proposed to look for some object on the immobile background of the VE and to minimize body oscillations. The IPh and APh modes of linkage between the VE shifts and oscillations of the subject's body within the sagittal plane in separate trials were set in a randomized order. Trials with linkage of the VVE foreground shifts and body oscillations were altered with trials of standing in the ImVE and trials with complete elimination of visual control (EC). Under ImVE conditions, the subjects stood in the same stereo glasses, and the field of vision had the same limits as those under conditions of the above-mentioned linkage. The subjects saw the same screen with an image of the same virtual 3D pattern, but both plans of the latter were not linked with the body oscillations.

Testing was carried out when the subject first stood on the rigid support and then on the squeezable one. The latter condition was provided by covering the stabilographic platform by a square 10-cm-thick plate of Porolon (polyurethane foam) covered with a 10-mm-thick plywood plate. The dimensions of the above plates were equal to those of the platform. The pliability of the soft insertion was about 3.5 cm at a pressure of 0.6 N/cm^2.

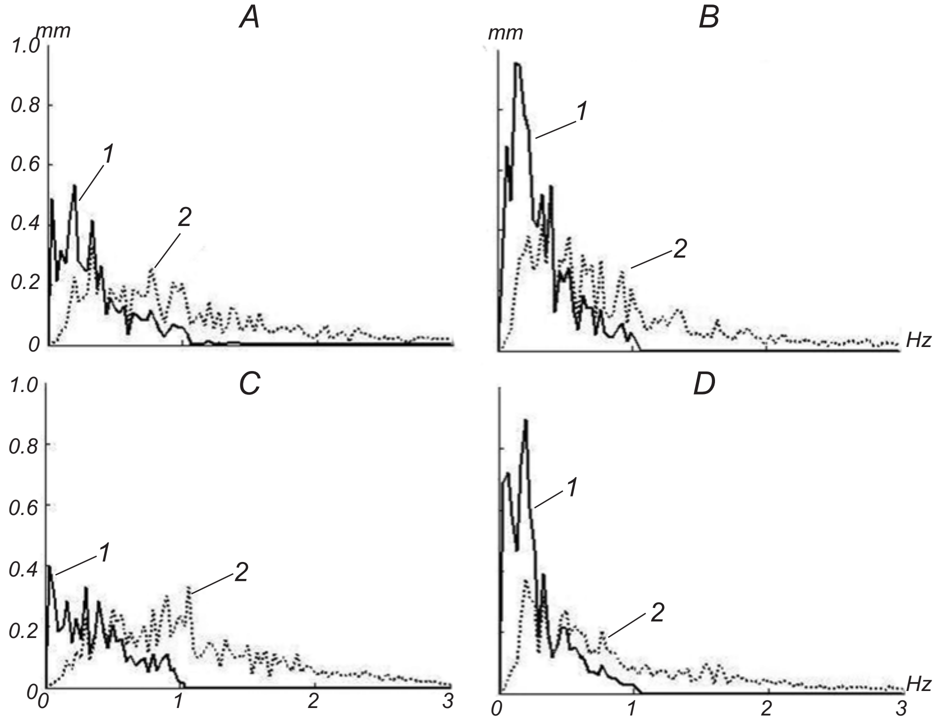
Thus, the examined variables (CGv and CFP–CGv) were evaluated under ImVE and EC conditions, as well as in the presence of APh and IPh oscillations of the VVE foreground linked with body oscillations within the sagittal plane. In the course of testing, the subjects performed 28 trials, 14 on the rigid support and 14 on the squeezable one. Among such 14 trials, there were four trials under APh condition, four under IPh condition, three at the ImVE, and three with the EC. Stabilogram samples in each trial were 40 sec long. The intervals between trials were about 1 min long; after four or five trials, the subjects had an about 3- to 4-min-long rest in a sitting position. Visual conditions in each half of the test series were alternated in a randomized order.

It should be noted that the conditions with introduction of the linkage between oscillations of the VVE foreground and those of the body exerted no significant effect on the maintenance of vertical stance within the frontal plane. This is why we do not describe the results of analysis of body oscillations within the above plane.

Statistical Analysis. The numerical data were averaged over all trials for each visual condition, first for separate subjects and then for the entire group. During the statistical analysis, global effects of the factors "condition of visual control" and "type of support" on the studied variables were estimated using one-way ANOVA. The significance of differences between the RMS and MdF values was estimated using paired comparison of the data, obtained under individual visual conditions, by *post-hoc* analysis using the *t*-test for samplings with unequal dispersions.

RESULTS

The amplitude spectra calculated according to the trajectories of shifts of the CGv and CFP – CGv in the anterior/pasterior direction in tests on a typical subject standing on the rigid support are shown in Fig. 1. It is obvious that different visual conditions exerted different effects on the amplitude spectra of the variables under study. If the spectra of oscillations of the CGv variable were compared, it could be easily noticed that the magnitudes of oscillations were significantly smaller under ImVE and APh conditions than those under EC and IPh ones. In other words, the subject stood more stably under former two conditions. Comparison of the



F i g. 1. Examples of the spectra of two variables, vertical projection of the center of gravity (CGv) and a difference between the positions of the center of feet pressure and CGv (1 and 2, respectively) obtained in the analysis of body oscillations in the course of standing of a typical tested subject on the rigid support under different visual conditions. Abscissa) Frequency, Hz; ordinate) amplitude of oscillations, mm. A) Eyes open, immobile visual environment; B) eyes closed; C and D) shifts of the foreground of the virtual visual environment are linked in antiphase and inphase manners with oscillations of the subject's body, respectively.

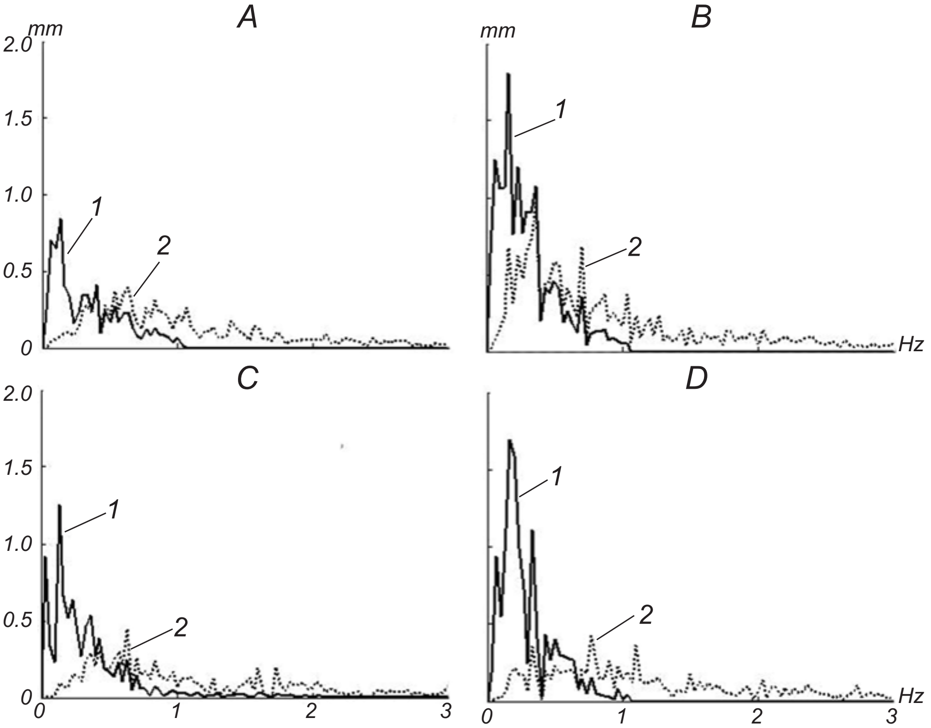
spectra of the CFP – CGv variable showed that the values of oscillations under ImVE, IPh, and APh conditions were close to each other and considerably smaller than those in the case of EC.

Upon standing on a squeezable support, all subjects, including that individual whose data are illustrated in Fig. 2, showed much greater body oscillations. At the same time, visually dependent changes in the spectra of the examined variables, calculated according to body oscillations in the upright stance on a squeezable support, demonstrated, in general, properties rather similar to those under conditions of the rigid support. This is readily visible not only in Fig. 2, but also in subsequent figures (Figs. 3 and 4) where general results of the RMS estimation for the spectra of both variables are shown for the entire examined group.

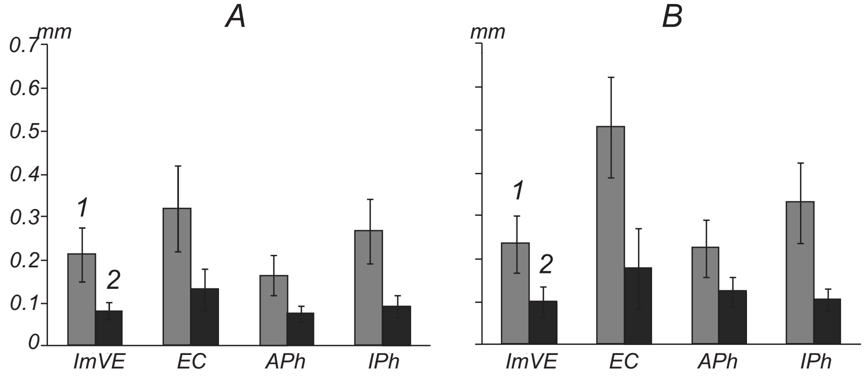
Values of the RMS for the Spectra of Variables Averaged for the Examined Group. Figure 3 shows such values for both variables (CGv and CFP–CGv) calculated for the maintenance of upright stance on the rigid and squeezable supports and averaged over all subjects.

Figure 3 shows that the greatest RMS values for the spectra of the CGv variable were observed in the case of maintenance of the vertical posture in the absence of visual control (EC) and under IPh conditions, while the smallest values were found under ImVE and APh conditions. These differences were confirmed in the course of statistical analysis. In particular, dispersion analysis demonstrated the existence of highly statistically significant effects of the "condition of visual control" factor on the RMS of the CGv spectrum. For the rigid support, the value of the Fisher's criterion $F_{1,\ 159}$ was equal to 30.03 ($P < 0.0000001$), while for the squeezable support $F_{1,\ 159} = 42.3$ ($P < 0.00000001$).

Rigid Support. The calculated RMSs for the CGv spectrum were the smallest under APh condition and significantly differed from those at providing vertical stance in the ImVE ($t = -4.75$, $P < 0.00001$), as well as under IPh ($t = -7.57$, $P < 0.00000001$), and APh ($t = -8.74$, $P < 0.00000001$) conditions. The RMSs of the CG spectrum obtained for ImVE condition differed significantly from the respective values under both EC ($t = -4.79$, $P < 0.00001$) and IPh ($t = -2.92$, $P < 0.001$) conditions. Statistical analysis did not demonstrate significant differences of the RMSs for the CGv spectra when this parameter was compared for EC and IPh conditions.



F i g. 2. Examples of the spectra obtained at standing of the subject on the squeezable support. Designations are similar to those in Fig. 1.

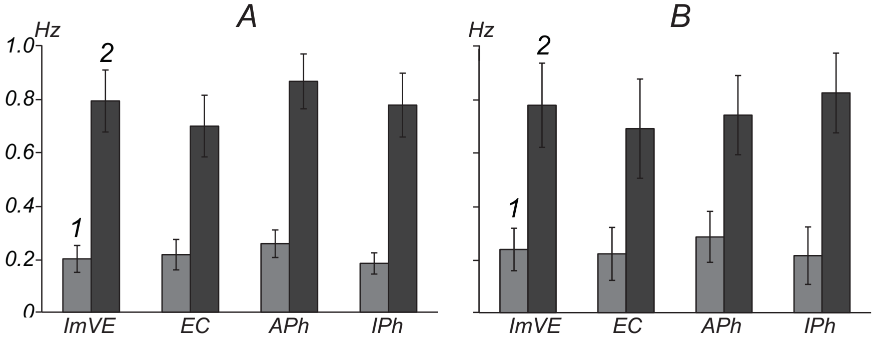


F i g. 3. Averaged root mean square values (RMSs, mm) of the spectra of the vertical projection of the center of gravity (CGv) and of the difference between positions of the center of feet pressure (CFP) and CGv. (1 and 2, respectively) and s.e.m. values calculated corresponding to oscillations of the body within the sagittal plane at immobile visual environment (ImVE), with the eyes closed (EC) in a dark room, and also at antiphase (APh) and inphase (IPh) linkage of shifts of the foreground of the virtual visual environment with body oscillations. Vertical axis) Amplitude of oscillations, mm.

The RMSs of the amplitude spectra of the CFP – CGv variable also demonstrated the dependence on visual conditions, although this dependence was considerably weaker. Using ANOVA revealed the effect of this factor on the CFP–CGv variable for the tests on both rigid ($F_{1,\,159} = 10.3$, $P < 0.00001$) and squeezable ($F_{1,\,159} = 16.8$, $P < 0.000001$) supports.

In contrast to the CGv variable, the RMSs for the CFP–CGv variable were the smallest under three visual conditions (ImVE, APh, and IPh) and did not differ significantly from each other ($P > 0.05$). On the other hand, the RMSs of the CFP–CGv spectra obtained for the ImVE, APh, and IPh conditions significantly differed from that of the respective spectrum observed under EC conditions. A comparison of the RMSs under ImVE and EC conditions shows that $t = –3.63$, $P < 0.001$; under APh and EC conditions, $t = –3.51$, $P < 0.001$; and under IPh and EC conditions, $t = –3.27$, $P < 0.002$.

Squeezable support. The RMSs of the CGv and CFP – CGv spectra calculated according to oscillations of the body at standing on the non-rigid



F i g. 4. Group-averaged values of the median frequency of the spectra of two variables, the vertical projection of the center of gravity (CGv) and the difference between positions of the CFP and CGv (1 and 2, respectively) and s.e.m. values calculated under different conditions. Vertical scale) Frequency, Hz. Other designations are similar to those in Fig. 3.

support demonstrated the pattern of their changes related to manipulations with visual conditions, which was, in general, similar to that described above for the rigid support; the differences were insignificant.

The calculated RMSs of the CGv spectrum were the smallest under APh conditions and significantly differed from the values obtained for the IPh ($t = 5.88$, $P < 0.000001$) and EC ($t = –7.41$, $P < 0.0000001$) conditions. In contrast to what was observed in the tests on the rigid support, there were no significant differences between the RMSs of the CG spectra obtained under APh and ImVE conditions ($P > 0.05$). The RMS of the CGv spectra obtained for the ImVE conditions significantly differed from those observed at EC ($t = –7.04$, $P < 0.0000001$) and IPh ($t = –4.92$, $P < 0.00001$). Under conditions of the squeezable support, we found a statistically significant difference between the RMSs of the CG spectra calculated for the EC and IPh conditions ($t = 4.54$, $P < 0.00005$), and this differentiated such results from those of the tests on the solid support.

The RMSs of the CFG – CGv spectra showed the smallest (and close to each other) values under ImVE and IPh conditions, and these values significantly differed from the clearly greater values obtained for the APh ($t = –3.06$, $P < 0.005$ and $t = –2.94$, $P < 0.005$, respectively) and EC ($t = –4.46$, $P < 0.0005$ and $t = 4.29$, $P < 0.0005$, respectively) conditions. The RMSs of the spectra of this variable were the greatest under EC conditions, and the respective value significantly exceeded those obtained under APh conditions ($t = 3.14$, $P < 0.002$).

The factor "type of support" also influenced significantly the RMSs of the spectra of both analyzed variables. While standing on the squeezable support, oscillations of the body were significantly greater. Dispersion analysis demonstrated the global influence of this factor of the RMSs for both analyzed variables. For the CGv variable, the Fisher's criterion $F_{1,319}$ equaled 32.3 ($P < 0.0000001$), while for the CFP – CGv variable $F_{1,\,319} = 30.4$ ($P < 0.000001$).

Paired comparisons of the RMSs for variables obtained at one and the same visual condition gave the following results. There were no statistically significant effects of the factor "type of support" on the RMS of the CGv spectra at standing under ImVE conditions ($P > 0.05$). Under other tested visual conditions, the RMSs of this variable became significantly greater after transition to the squeezable support (for the EC condition, $t = –4.56$, $P < 0.0005$, for APh, $t = –6.91$, $P < 0.00001$, and for IPh, $t = –3.64$, $P < 0.005$).

Unlike the RMSs of the CG variable, the respective values for the CFP–CGv variable calculated for all visual conditions (including ImVE) were significantly smaller when the tested subjects stood on the rigid support. For the ImVE conditions, the index of significance of the differences t was equal to –2.56 ($P < 0.01$), for the EC condition, $t = –02.54$ ($P < 0.01$), for APh linkage, $t = –6.15$ ($P < 0.0001$), and for IPh linkage, $t = –3.61$ ($P < 0.003$).

Frequency Characteristics of Oscillations of the Examined Variables. Figure 4 illustrates the group mean values of the MdF of the amplitude spectra for the CGv and CFP–CGv variables calculated for the maintenance of upright posture on the rigid and squeezable supports. As can be seen, the MdF of the CG spectra on both types of supports was greater under conditions of APh linkage and the smallest in the case of IPh relation. Analysis of the variance demonstrated the existence of a statistically significant effect of the factor "visual control condition" on the MdF of the CG spectrum. For tests on the rigid support, the Fisher's criterion

$F_{1,\ 159}$ equaled 14.37 (P < 0.000005), and the respective value for the squeezable support was equal to 4.36 (P <0.006).

Rigid support. The calculated MdFs for the spectra of the CG variable were the greatest under APh conditions, and these values differed significantly from those in the case of IPh linkage (t = 6.77, P < 0.0000001), ImVE (t = 4.32, P < 0.0002), and EC (t = 2.89, P <0.003). Statistical analysis revealed significant differences between the MdFs for the CG variable in comparisons of these values under IPh and EC conditions (t = 2.52, P < 0.01).

Squeezable support. The calculated MdFs for the CGv spectra appeared the greatest under APh conditions, similarly to what was observed on the rigid support. These values significantly differed from those measured at standing with IPh linkage (t = –3.15, P < 0.002), under ImVE conditions (t = 2.37, P < 0.02), and with the EC (t = 2.74, P < 0.004). Statistical analysis showed no significant differences between the MdFs for the CGv spectra in comparisons of other pairs of visual conditions.

The MdF of the spectra of the CFP – CGv variable acquired the smallest values during the maintenance of upright stance with the EC and the greatest values in the case of APh linkage between oscillations of the visual foreground and those of the subject's body (t = 6.11, P < 0.000001). In general, the factor "condition of visual control" exerted a statistically significant effect on the MdF of the CFP – CGv spectrum. For the rigid and squeezable supports, the Fisher's criterion $F_{1,159}$ equaled 11.75 (P < 0.000001) and 2.74 (P < 0.05), respectively.

Rigid support. Comparison of the effects of visual conditions on the MdF of the CFP–CGv spectra revealed significant differences between values of this parameter for the following pairs of conditions: APh and IPh, t = 3.42 (P < 0.001), ImVE and APh, t = 2.66 (P < 0.01), ImVE and EC , t = 3.04 (P < 0.005), and APh and EC, t = 3.84 (P <0.001).

Squeezable support. The visual dependence of the MdF of the CFP–CGv spectra calculated for the conditions of this support was somewhat weaker than that in the tests on the rigid platform. Nonetheless, a pairwise comparison of the effects of visual conditions on this frequency still demonstrated significant differences between the respective values at ImVE and EC (t = 1.91, P < 0.05), EC and IPh (t = 2.71, P < 0.005), and APh and IPh (t = 2.02, P <0.05).

The factor "type of support" was also significant with respect to the MdFs of both spectra (CGv and CFP–CGv). Dispersion analysis allowed us to identify the global impact of this factor on the MdF of the CGv spectrum (Fisher criterion $F_{1,\ 319}$ = = 7.96, P < 0.006), whereas there was no statistically significant influence of a change of the rigid support to the squeezable one with respect to the MdF in the CFP – CGv spectra.

Pairwise comparisons of the spectra of the CGv variable, obtained under identical visual conditions, on different supports revealed the following relations. The MdF values differed statistically significantly from each other under conditions of ImVE (t = 2.27, P < 0.02), APh (t = 1.75, P <0.05), and IPh (t = 2.01, P <0.03).

Despite the absence of the global influence of the factor "type of support" in transitions to standing on a squeezable support, the mean group value of the MdF of the CFP – CGv spectra was considerably smaller under conditions of APh (t = 3.00, P < 0.002) and greater under IPh conditions (t = = –1.72, P < 0.05).

DISCUSSION

Vision probably plays at least a double role in the stabilization of vertical stance in humans. On the one hand, visual signals inform the CNS about oscillations of the body with respect to the surroundings; on the other hand, the visual system evaluates the degree of stationarity of the environment *per se*. In this regard, it is important to understand how effective can be the contribution of visual signals, which contain information on body oscillation, in the control of vertical posture of the subject under conditions where the stationarity of the visible surrounding is disturbed, e.g., in some neurological diseases [2, 4-7] or when there are difficulties in using such environment as the reference. Our study allowed us to find some facts that, as we believe, bring us closer to an understanding this situation.

We compared the maintenance of vertical stance by humans under conditions of ImVE with that in situations in which the subjects were immersed in a non-stationary visual space. The nonstationarity of the visible VE was created by linking the position of the foreground of this environment to oscillations of the subject's body within the sagittal plane. The results obtained demonstrated the following.

At standing on the rigid support, the RMSs of the spectra of both of the above variables changed in a more or less parallel manner. These values decreased under conditions of APh linkage of the visual foreground with oscillations of the body and increased in the cases of IPh, compared with the RMSs calculated for ImVE conditions. This result can be interpreted in such a way. The tested subjects, when maintaining upright stance, showed rather noticeable reactions to oscillations of the visual foreground despite the instruction "to use the immobile backward plan (landscape) as the reference." They unconsciously corrected their posture according to the direction of the respective shifts. In the case of APh, such a reaction resulted in the following: correctional muscle efforts evoked antiphase shifts of the foreground, whith visually corresponded to the above shifts. This, finally, led to a slight decrease of postural oscillations. In the case of IPh, however, the subjects, in the course of correctional effeorts, obtained no visual information on the expected decrease in the shifts of the VVE foreground; *vice versa*, they saw that such shifts acquired even a greater magnitude. Therefore, under IPh conditions, visual signals on the foreground movements interfered significantly with use of the signals from muscle/joint and vestibular receptors and also of visual signals with respect to the immobile backward plan, which would be adequate to the current posture and could be used for the formation of necessary muscle correction. This situation probably was the reason for additional destabilization of the vertical posture. At the same time, it should be noted that maximum oscillations of the subject's body under SPh conditions did not exceed values typical of standing with the EC. This circumstance allows us to suggest that the subjects were able to overcome, to some extent, the effect of "incorrect" visual signals, related to oscillations of the foreground, and exerting destabilizing influences on the posture.

Under conditions of maintaining the upright stance on the squeezable support, oscillations of the body CGv increased significantly at all versions of visual conditions. In this case, such oscillations in the IPh case became significantly smaller than in the complete absence of visual information (EC) (Fig. 3). This result indicates that, on the squeezable support, signals from nonvisual sensory sources that bring an adequate estimate of the body position in space increased their influence on the process of formation of postural corrections.

In contrast to the spectra of the CGv variable, RMSs of the CFP–CGv spectra, calculated for the conditions of standing on the rigid support, were rather close to each other under three visual conditions, ImVE, APh, and IPh. This is why we can conclude that, under the above conditions, the effects of visual signals on the foreground shifts, which destabilize the posture, were not realized directly via the mechanism controlling the stiffness in the ankle joints. This mechanism is, however, activated at standing on the squeezable support because RMSs of the CFP–CGv spectra obtained for the APh and IPh conditions were dissimilar. It should be noted that RMSs of the spectra of the above variable under APh conditions were greater than those under IPh ones. At the same time, the RMSs of the CGv spectra were, *vice versa*, significantly smaller under APh conditions. This fact directly demonstrates that the amplitude characteristics of the basic variables (CGv and CFP–CGv) can change not only in a parallel manner (as in the case of the rigid support), but also in different directions (at certain changes in the conditions of maintaining upright stance).

Changes in the frequency characteristics of the spectra of both variables were not so clearly pronounced as changes in the amplitude characteristics. At the same time, the MdF of the spectra, as follows from the results obtained, also demonstrated certain dependences on both conditions of visual control and type of the support surface (Fig. 4). First of all, it should be noted that there were differences between changes in the MdF of the CFP – CGv spectra related to transition from APh conditions to IPh ones. At standing on the solid support, such transition led to a decrease in the MdF of these spectra; at the same time, tests on the squeezable support demonstrated a decrease in the mentioned parameter. In this case, the MdF of the CGv spectra changed in the same way; regardless of the characteristics of the support, transition from the APh mode to the IPh one resulted in a decrease of this parameter.

In general, we can conclude that the results obtained in our research contradict, to a definite extent, the hypothesis proposed earlier [16, 17]. This hypothesis stated that differences in the magnitudes of body oscillations observed under different conditions could be related to changes in the joint stiffness automatically adjusted according to nonspecific influences on the neuronal structures of postural control, which come from the visual input. If such interpretation was correct, we should expect strictly parallel increases or decreases in the amplitude and frequency characteristics of the spectra of both analyzed variables after changes in the visual conditions, independently of the support type (rigid or squeezable). We have found, however, that parallel changes of the spectra of both variables (e.g., in the case of transition from standing with the EC to ImVE condition) could be accompanied by a significant disturbance of the above-mentioned parallel pattern. Thus, our findings allow us to postulate that both analyzed variables can have either interrelated mechanisms of control of their amplitude/frequency characteristics or separate, i.e., mutually independent, control mechanisms.

Acknowledgment. This work was supported by the RFBR (grant No. 14-04-00950).

All stages of the research corresponded to the statements of the Helsinki Declaration (1975, editions 1996-2013). All subjects were previously informed of the pattern and procedure of the tests and gave their written consent.

The authors of this paper, B. N. Smetanin, G. V. Kozhina, and A. K. Popov, confirm the absence of conflicts of any kind related to commercial or financial interests, relations with organizations or persons that could in any way be related to the study, and interrelations between the co-authors of the article.

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