METHODS

Method for Studying the Processes Maintaining Equilibrium at Rest Standing

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According to current concepts, two processes are responsible for the maintenance of body equilibrium: shifts of the reference point caused by changes in the posture and stabilization of oscillations of the center of mass relative to this point. Exact changes in these processes occurring at various forms of locomotor disorders remain unclear. We proposed an original mathematical method allowing separate evaluation of these two processes responsible for the maintenance of body equilibrium.

Key Words: *center of mass; stabilization; reference point*

Study of mechanisms maintaining equilibrium is important for the diagnostics and therapy of diseases accompanied by locomotor dysfunction. The understanding of principles of the maintenance of body equilibrium would allow us to evaluate the pathogenetic mechanisms of various motor disturbances. Until now the changes in the system maintaining equilibrium and posture occurring at various motor disturbances remain unclear. The development of various forms of Parkinson's disease (tremulous, tremulous-rigid, and akinetic-rigid) is probably related to dysfunction of the system regulating movements.

Study of the maintenance of body equilibrium after space flights [4] and during superslow vibrations of the supporting surface [3] suggests the existence of two equilibrating subsystems. System I regulates slow shifts of the reference point within the supporting contour. System II stabilizes position of the center of mass relative to the reference point. Localization of the reference point depends on joint angles that determine posture. Stabilization maintains specified values of these angles. Even at rest standing, the specified joint angles are characterized by slow complex fluctuations and superimposing rapid constituents that reflect stabilization of joint angles relative to the initial state. Transfer tracks for the center of mass reflect these processes in the form of slow transition of the reference point and rapid oscillations of the center of mass around this point. It can be suggested that various components of the system regulating movements provide functioning of these subsystems.

The range of oscillations at rest standing is much low than during vibration of the supporting surface. These peculiarities make difficult to divide visually the track of the center of mass into two constituents and compare the range of oscillations. It was necessary to develop a special mathematical method useful to study functional activity of subsystems in patients with various locomotor disturbances, perform the diagnostics, determine the efficiency of therapy, and evaluate the mechanisms regulating vertical posture and playing a critical role in the development of disorders.

In the present work we developed a new method, which suggests that two constituents characterizing

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shifts of the reference point and stabilization of the center of mass relative to this point are derived from experimentally determined trajectory for the center of mass.

MATERIALS AND METHODS

We examined 5 volunteers maintaining a vertical position of the body at rest standing. The data were recorded at a frequency of 50 Hz for 2 min. The trajectory for the center of mass was calculated from experimental data obtained by means of OPTOTRAK software. Six markers were fixed on the ankle joints, hip joints, and shoulders. Constituents of the trajectory for the center of mass in the sagittal plane were determined as described elsewhere [2].

The developed mathematical method is based on several assumptions. First, the trajectory of the center of mass is the sum of two constituents (rapid and slow). Second, oscillations of the rapid constituent are symmetrical to the trajectory of the slow constituent. Third, these constituents can be described by simple expressions within the time window (2 sec width) comparable to the average period of rapid oscillations. And fourth, rapid oscillations can be expressed as a weighted sum of sin and cos for the current interval of time, while slow oscillations are characterized by the polyenom. Any interval in the trajectory for the center of mass that depends on the time window can be described by means of a local mathematical model with the unknown parameters.

Test parameters were calculated by methods of regression analysis [4]. Using parameters these as the base, study of the reference point (slow oscillations) reduces to calculation of the polyenom. Rapid oscillations of stabilization are the difference between the center of mass and reference point. Evaluation of the trajectory for the center of mass on the local model suggests consecutive transitions of the time window by the trajectory for the center of mass with increments proportional to setting of values and identification of model parameters.

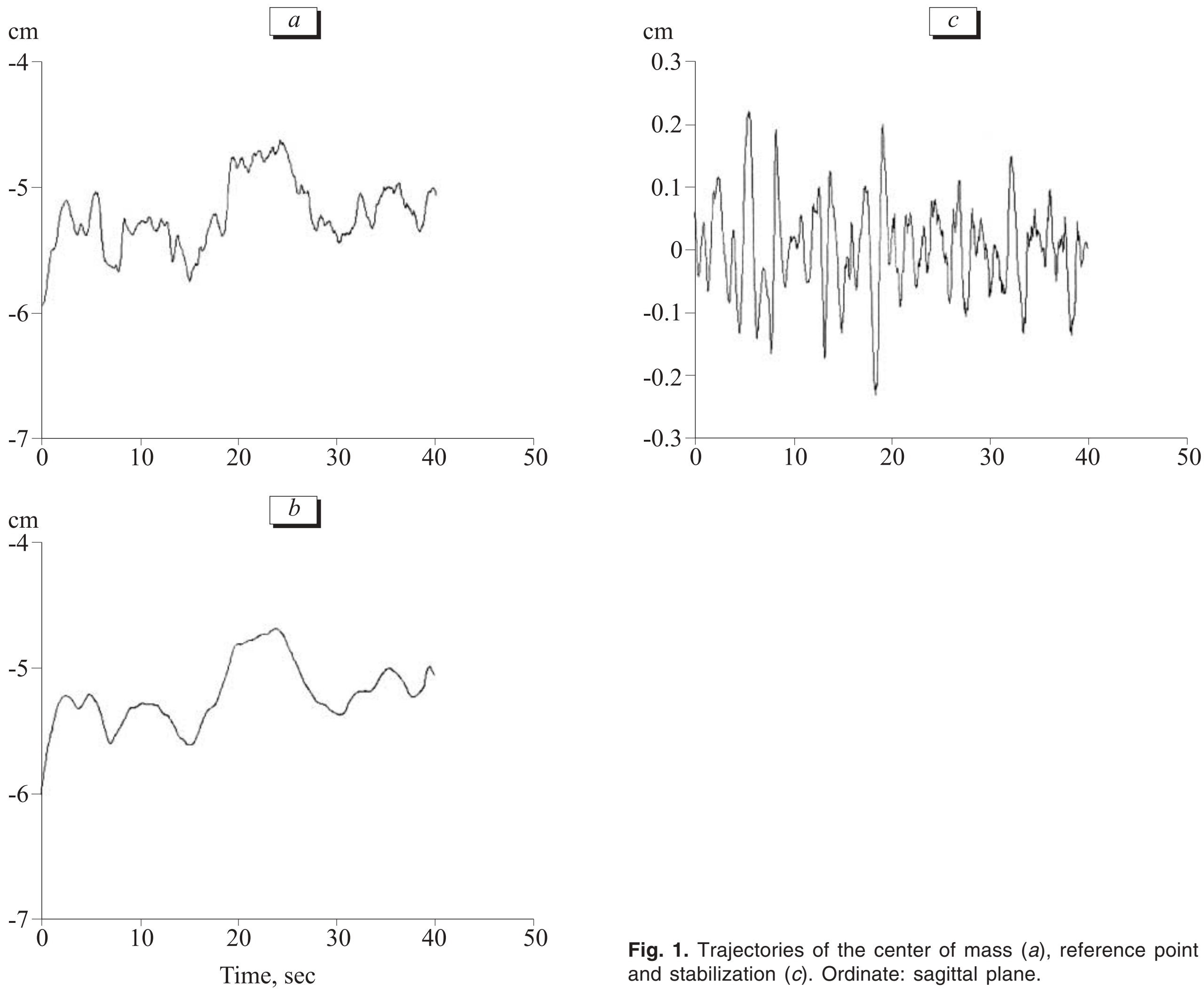

Fig. 1. Trajectories of the center of mass (*a*), reference point (*b*), and stabilization (*c*). Ordinate: sagittal plane.

RESULTS

The local model of trajectory of the center of mass appeared as

$$y(t)=a+b\times t+c\times\sin(\omega t)+d\times\cos(\omega t),$$

where a, b, c, d, and ω are constant parameters. Study of parameters corresponding to the window of the trajectory of the center of mass

$$y(t_i),\ t_i=dt(i\text{-}1),\ i=1,\ldots,\ m,\ dt=\text{const},$$

was performed on the following regression model:

$$y(t_i)=a+b\times t_i+c\times\sin(\omega t_i)+d\times\cos(\omega t_i)+\Delta(t_i),\quad i=1,\ldots,m, \tag{1}$$

where $\{\Delta(t_i)\}_{i=1}^{m}$ is a random component. At the specified values of w, study of parameters a, b, c, and d reduces to the solution of the overdetermined system of linear equations by the least square method. The correlation coefficient of experimental and model values $\{y(t_i)\}_{i=1}^{m}$ served as a criterion to estimate the optimal value of parameter ω. Parameter ω was optimized by enumeration of values at the specified uniform sequence. Accuracy of the measurements was independently evaluated from the mean square of values set by the following equation:

$$(y(\tau_i)\text{-}(\tilde{y}(\tau_i))/y(\tau_i),\ i=1,\ldots,r,$$

were $\{\tilde{y}(\tau_i)\}_{i=1}^{r}$ are $\{y(\tau_i)\}_{i=1}^{r}$ calculated by equation (1), and $\{\tau_i\}_{i=1}^{r}$ are moments of time corresponding to zero velocity of the center of mass.

Calculation of the trajectory of the reference point from the trajectory of for the center of mass was expressed graphically (Fig. 1, *a*). The trajectory of the reference point appeared as slow oscillations with nonstationary amplitude and frequency without clear average values (Fig. 1, *b*). Stabilization looked like oscillations at 1-5 Hz. Its amplitude and frequency were nonstationary, and the amplitude was much lower (Fig. 1, *c*).

TABLE 1. Division of Trajectory of the Center of Mass into Constituents

Volunteer	Period, sec	Correlation	Accuracy, %
1	2.5	0.956	0.032
2	2.2	0.946	0.065
3	2.2	0.937	0.010
4	2.5	0.916	0.009
5	2.2	0.939	0.006

Note. Mean correlation coefficient: 0.939. Mean accuracy: 0.024%.

The trajectory of the center of mass was divided into two constituents, and accuracy of the measurements was evaluated to determine the efficiency of a new mathematical method (Table 1).

The developed mathematical method allows us to study simultaneously two processes maintaining equilibrium. The local model accurately describes the trajectory of the center of mass within the specified window. The accuracy of the method indicates that it is highly efficient. This method can be used in studies of the stabilization of vertical posture under normal conditions and in locomotor dysfunction, for the diagnostics and evaluation of the efficiency of therapy, and for investigation of mechanisms underlying locomotor disturbances of different etiology.

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