309. Computerized posturography for data analysis and mathematical modelling of postural sway during different two-legged and one-legged human stance

M. Karpinsky[1] **and N. Kizilova**[2]
[1] M. I. Sytenko Institute of Spine and Joints Pathology, Department of Biomechanics,
61024 Kharkov, Pushkinskaja 80
E-mail: *medicine@online.kharkov.ua,* +38 (057) 704-14-71
[2] V.N.Karazin Kharkov National University, Department of Theoretical Mechanics,
61077 Kharkov, Svobody sq. 4
E-mail: *nnk_@bk.ru ,* +38 (057) 707-52-87

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Abstract. Mechanisms of balance control are investigated on computerized posturography data on vertical two-legged and uncomfortable one-legged stance measured on healthy subjects. Oscillations of the centre of mass in the course of 30 s standing and the corresponding trajectories for a step forward off the force platform have been computed. Spectral analysis of the time series revealed three main harmonics for the studied postures. When a volunteer was balancing standing on one leg, all the harmonics were shifted towards the high frequencies and the sway amplitude was twice increased in comparison with comfortable two-legged vertical stance. Decomposition of the sway trajectories into the rambling and trembling components has been carried out. It was shown that in the course of the one-legged stance the balance control strategy includes ‘scanning’ of the larger area with bigger sway amplitudes in the vicinity of the stable state as compared to two-legged stance. A mathematical model of the body as a multi-link system is considered. Mass and inertia of each body segment and torques in joints are taken into consideration. The calculated own and forced frequencies of the model correspond to the spectral analysis of the posturography data. One-legged stance is proposed as an excellent tool for revealing the balance problems. It is shown that investigation of the oscillations and trajectories of the centre of mass for the step forward off the force platform is perspective for medical diagnostics to distinguish between the spine and joint pathologies.

Keywords: biomechanical modelling, computerized posturography, sway analysis, spectral analysis, medical diagnostics.

Introduction

Computerized posturography is one of the widely used reliable tests for early diagnosis of the vestibular and musculoskeletal pathology. The technique assesses how well an individual integrates muscular torque in joints and sensory information relevant for balance control. Computerized posturography has been used as a clinical tool to diagnostic and study the mechanisms of balance impairments in individuals. Steady stance of a human is supported by somatosensory, vestibular and visual information relevant for balance control. Certain changes in sensory integration determined by age-related variations or specific diseases pose the greatest challenge. In clinical applications posturography is used for assessment, treatment, rehabilitation, and management of individuals with balance problems and implanted prosthesis.

While an individual stands on the force platform, the components of the reaction force $\{\vec{R}_i\}_{i=1}^{n}$ in different parts $n = 1,..,n$ of his/her feet are measured and the positions of the pressure centre (x_p, y_p) and the centre of mass of the body (x_c, y_c) are calculated. The simplest model of the feet includes at least two regions namely the forefoot and the heel of each foot and n=4. Since a wealth of bones and muscles compose the body and the physiological mechanisms with different characteristic times are involved into the balance control, the curves

$(x_c(t), y_c(t))$ exhibit very complex behaviour [1]. Some parameters of the curves and integral indexes are widely used in medicine for diagnostics of the muscular-skeletal and nervous systems, balance control and inner ear pathologies [2,3]. Force platform can be used for training the coordination and balance functions because coordinated movement demands considerable practice in special conditions. Stabilography has gained wide-spread acceptance in rehabilitation of the patients with sclerosis, Parkinson disease, for recovery of the locomotor function and speech after the stroke, for development of the individual training regimes and sport positions of weight-lifters, figure skaters and shoots. Progressive decrease in sway amplitude is observed in the course of training of the sportsmen and the patients with balance impairments on the force platform.

The posture stability may be maintained with respect to a moving preference point rather then a stationary one as it was suggested in [4,5]. When such is the case, the sway amplitude should be bigger and the sway pattern should be more complicated for uncomfortable posture like one-leg standing or balancing on the unstable or moving support. A method of decomposition of the sway into two time series, termed rambling and trembling movements can be used for checking the hypothesis. The rambling component represents migration of the reference point, with respect to which the equilibrium is maintained. When the horizontal ground reaction force equals zero, the so-called instant equilibrium points is reached. Then the reference position at each time interval may be estimated by calculation the coordinates (x_p, y_p) of the centre of pressure [4,5]. The rambling trajectory may be obtained then by spline approximating the consecutive instant equilibrium points. Trembling component represents the oscillations of the centre of pressure around the rambling trajectory. Analysis of the two sway components gives new insight to understanding the balance control in normal and pathological states. In the present paper the computer-assisted posturography is used for analysis of the comfortable vertical two-legged stance and natural uncomfortable one-legged stance of the healthy volunteers.

Experimental method and procedure

Twenty healthy subjects (weight 65.2±21.2 kg, height 1.75±0.19 m, and age 33±17 years) without pronounced neuromuscular disorders have been asked to maintain quite vertical stance on the force platform during 30 s (Fig.1). The components of the reaction forces $\{\vec{R}_i\}_{i=1}^4$ have been measured for each foot and oscillations of the centre of mass $(x_c(t), y_c(t))$ have been automatically calculated. In the second test the individual has been asked to transfer the body weight onto the right and then on the left leg and stand quietly for 30 s. During the third test the volunteer has been balancing standing on the right foot and then on the left one. The same components $\{\vec{R}_i\}_{i=1}^4$ have been measured for each single foot. In the fourth test the person did a step forward off the force platform onto the board of the same thickness. The trajectory $y_t(x)$ of the centre of mass has been calculated for the right and left foot separately.

As an illustration the time series $(x_c(t), y_c(t))$ obtained for one of the volunteers are presented in fig.2. Oscillations of the centre of mass for the normal vertical two-legged stance (fig.2a), for the two-legged stance when the body weight is transferred onto the right and left leg (fig.2b) and for the one-legged stance (fib.2c) differ significantly in sway amplitude and oscillation pattern. The corresponding trajectories $y_c(x)$ for the listed postures are plotted in fig.3a,b.

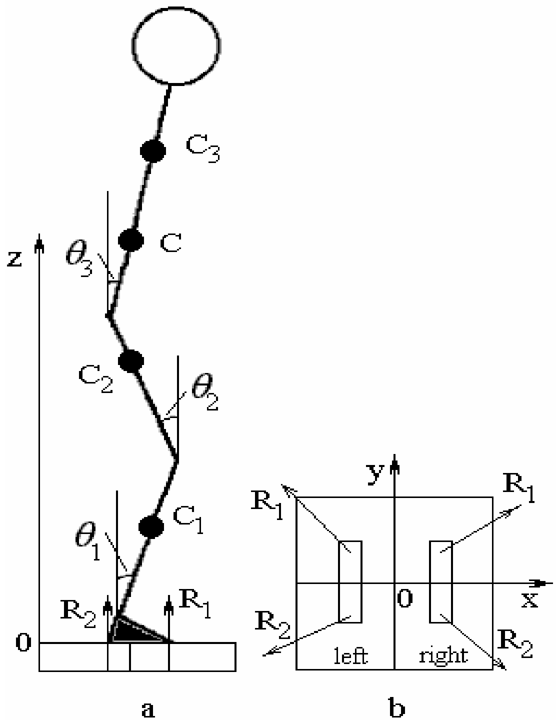


Fig. 1. A three-link model (a) of the standing human on the force platform (b)

The calculated time series $(x_c(t), y_c(t))$ have been then amplified and the low (f<0.01 Гц) and high (f>10 Гц) frequency components have been subtracted using the second order Butterworth filter. Trend of the basic line has been eliminated by shifting of the curves x(t) and y(t) relatively to the mean values $\langle x(t)\rangle_t$ and $\langle y(t)\rangle_t$. The first two-second portions of the data series have been deleted for diminishing the numerical errors [2].

Spectral analysis of the shifted data series has been carried out and the power spectral density (PSD) has been calculated. Some results are presented in fig.4 a,b. The posture sway curves have been decomposed into the rambling and trembling components according to the method described in [4,5].

Two different observed types of trajectories $y_t(x)$ for the first step forward off the force platform are presented in fig.5 for two individuals.

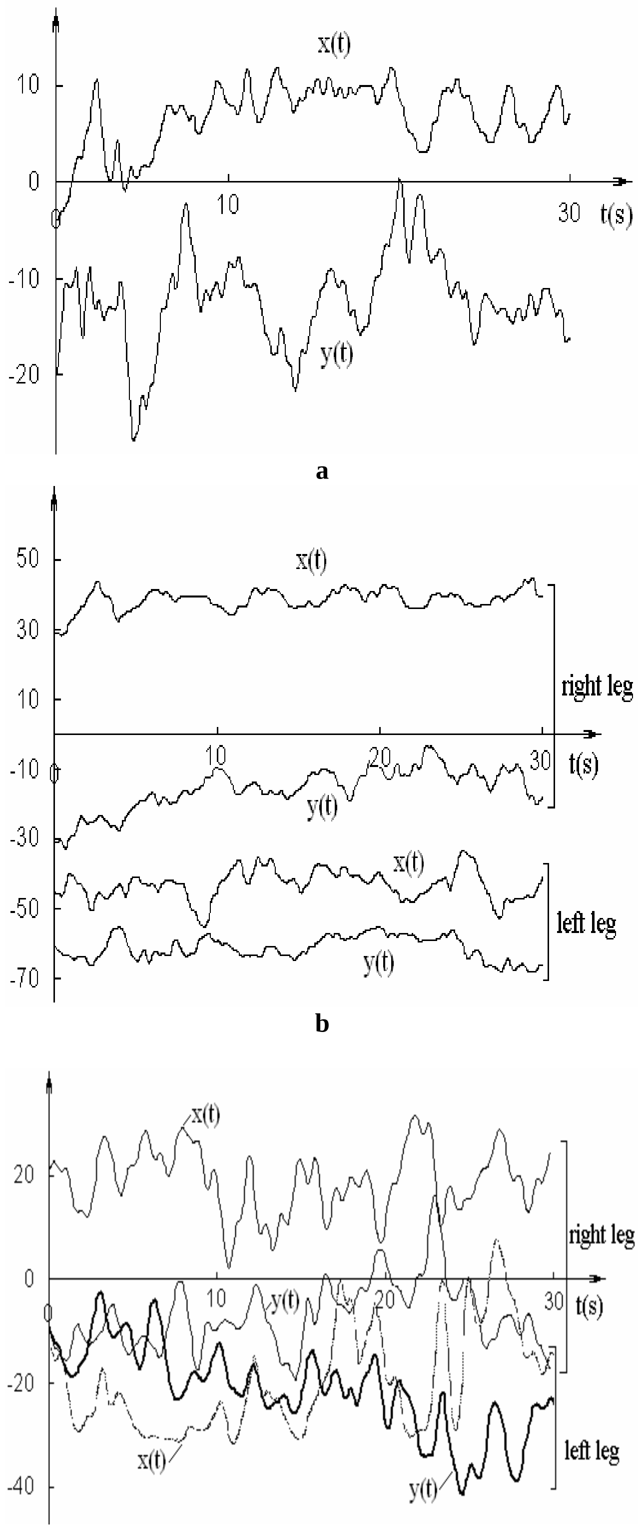


Fig. 2. Oscillation of the coordinates x(t) and y(t) of the centre of mass of an individual in the course of a vertical stance (a), two-legged stance when a body weight is transferred onto the right or left leg (b) and for one-legged stance on the right and left leg (c)

The shapes of the trajectories have been analyzed using some indexes (maximal deflections and some angles as it is shown in fig.5). The results have been compared to the database cumulated in the Institute of Problems of Spine and Joints for patients with osteochondrosis, scoliosis and different joint pathology.

Most part of the individuals exhibit some asymmetry in projection of the centre of mass at the standard comfortable two-legged stance (trajectory 1 in fig.3a) and when the centre of mass has been transferred (trajectories 2 and 3 in fig.3a). The same observation concerns the one-legged stance (trajectories 1 and 2 in fig.3b). The corresponding trajectories have been bounded by rectangular with dimensions h_x, h_y (boxes in fig.3a,b). The maximal sway amplitudes in x and y directions have been calculated as $h_x/2$ and $h_y/2$ correspondingly and the maximal sway amplitude $A = (h_x^2 + h_y^2)^{1/2}$. In all the measurements when the centre of mass has been shifted in the forward/backward direction during the one-legged stance in comparison with bipedal stance, the same direction of the shifting has been recorded for the two-legged stance when the body weight was transferred onto the same leg.

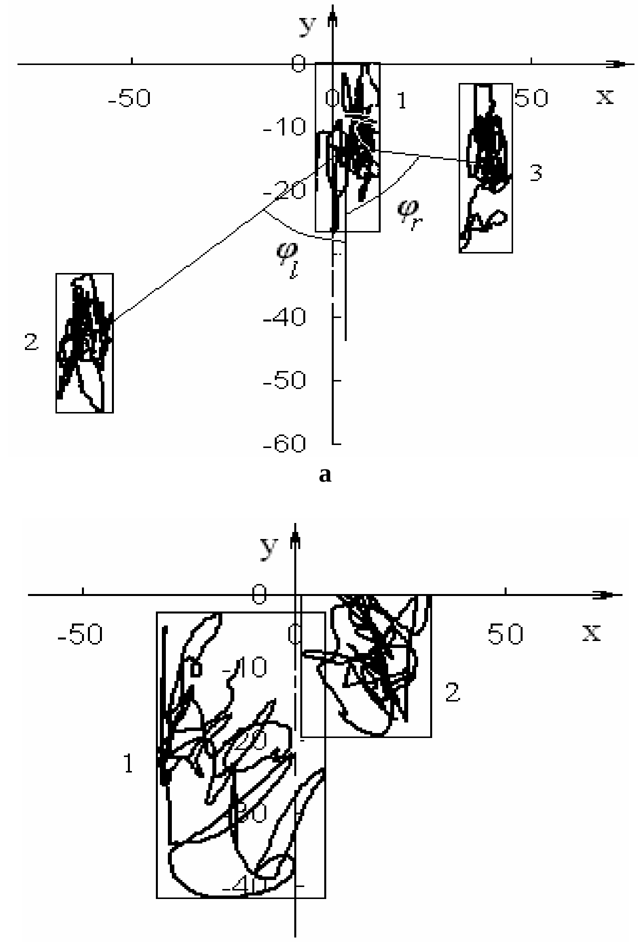
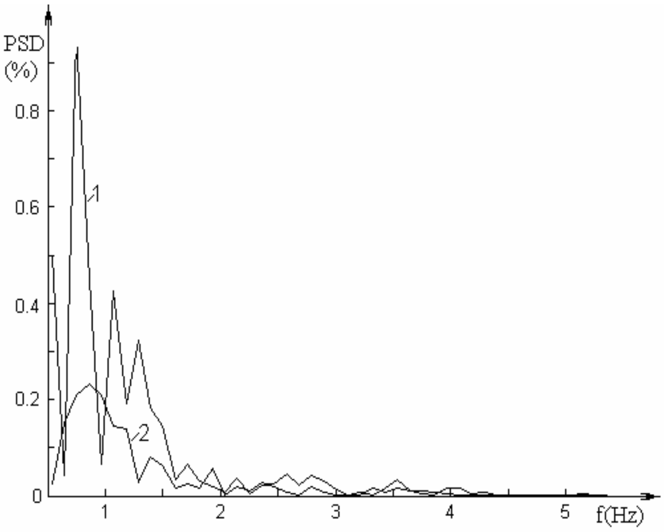


Fig. 3. Oscillation of the coordinates x(t) and y(t) of the centre of mass of an individual standing quietly on his two legs (a) and one of the two legs (b). The curves 1,2,3 in fig1a corresponds to the comfortable stance, two-legged stance when the body weight has been transferred onto the left (curve 2) and right (curve 3) leg. The curves 1,2 in fig1b corresponds to the stance on the left (curve 1) and right (curve 2) leg



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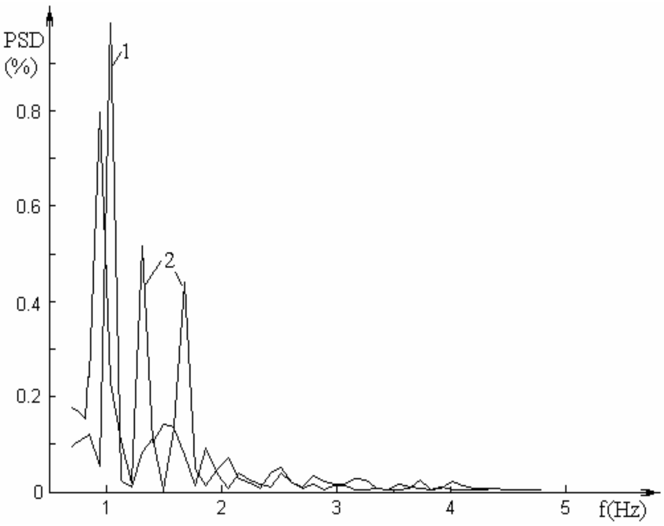

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Fig. 4. Non-dimensional power spectral density PSD of the signals for sway of the body in the sagittal (curve 1) and coronal (curve 2) planes for two-legged (a) and one-legged (b) stance of a volunteer

The shift has been measured by the corresponding angles $\varphi_{l,r}$ between y-axis and the line connecting the s of the corresponding rectangles as it is shown in fig.3a. After the body weight has been transferred the x-coordinate has been shifted into the direction of the corresponding bearing foot but the shifting of the y-coordinate has been connected with individual characteristics of an individual. Comparison to the database obtained during the 15-year experience of the posturographic study of the patients with different muscular-skeletal pathologies applied to the Institution of problems of spine and joints revealed that some patterns of displacement of the projections $y_C(x)$ for different stance corresponds to osteochondrosis and hip joint problems. Since all the measurements have been made for the healthy volunteers, we may conclude that stealthy pathologies of spine and joins are proper even to young volunteers (students and schoolchildren).

Sway amplitude increases significantly when an individual is balanced standing on one of the legs but the contribution of the two components rambling and trembling is different for the one-legged and two-legged stance. It seems that for the one-legged stance when the support area is reduced significantly, the control systems are forced to scan the wider area for checking stability of the posture in the corresponding direction. The more uncomfortable the stance, the bigger initial sway amplitude is necessary for verification the posture stability.

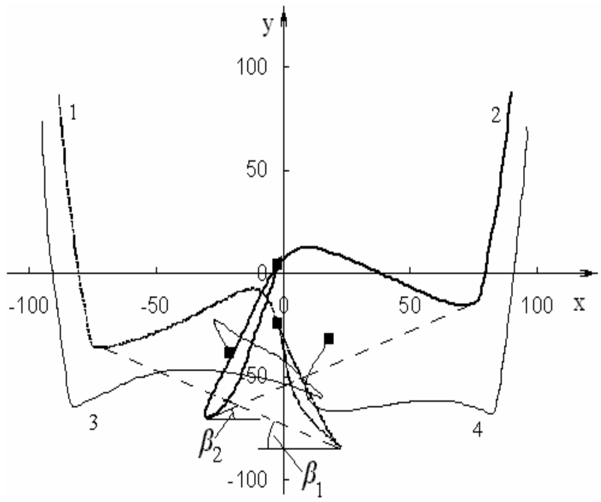

Fig. 5. Trajectories of the centre of mass for the first step forward off the force platform. Curves 2 and 4 (1 and 3) correspond to the right (left) leg of the 2 different individuals

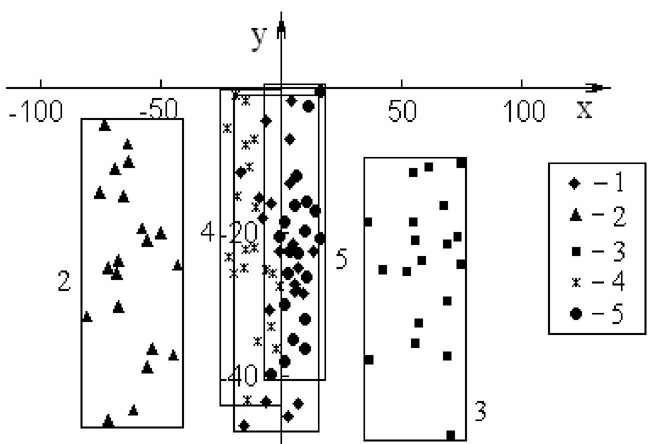

Fig. 6. Coordinates of the centre of mass for the vertical bipedal stance (1), two-legged stance when the body weight is transferred onto the left (2) and right (3) legs and for one-legged stance on the left (4) and right (5) leg

The time-averaged positions of the centre of mass for all the volunteers are plotted in fig.6. During the usual vertical stance the projections are close to the y-axis, but the x-coordinate is slightly shifted towards negative x-values. That means in the comfortable position the centre of mass is a bit transferred towards the heels. All the cases have been described in literature as observed for healthy subjects [1]. When the left leg is chosen as a main support, the centre of mass is more shifted in comparison with the case when the body weight is placed over the right leg.

Comparative study of the maximal sway amplitudes for the two-legged and one-legged posture revealed that the amplitude for the two-legged stance is approximately twice higher then the sway amplitude at the one-legged stance (fig.7). That may be connected with either smaller support area in x-direction rather then in y-direction and with different contribution of the leg segments into the one-legged and two-legged stance or with different role of the lower extremities in maintaining the posture. We may hypothesize that when an individual maintains the vertical stance, the segments of the legs participate in the balance control separately. For the one-legged stance the person uses the free extremity for the posture stabilization as a single segment rather as a two-link one. The suggestion needs to be checked by investigation of the corresponding mathematical model.

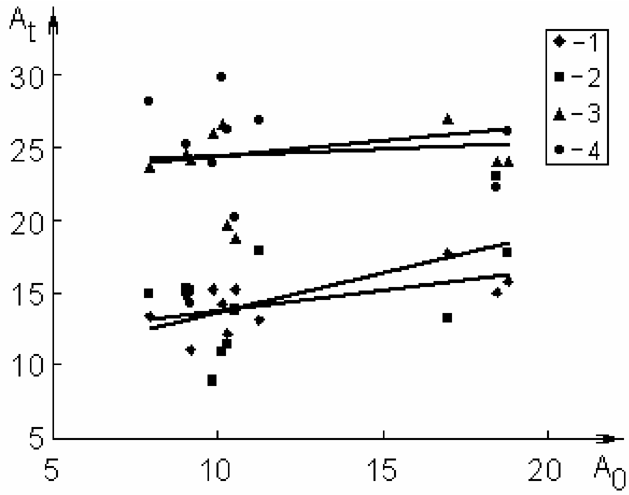

Fig. 7. Sway amplitudes A_t for different stances versus the sway amplitude A_0 of the two-legged vertical stance. The curves 1 and 2 (3 and 4) correspond to the two-legged (one-legged) stance with the main support onto the right (curves 2 and 4) and left (curves 1 and 3) legs

Mathematical model of the body sway in the sagittal direction in the course of two-legged stance

We consider a body as an inverted three-link pendulum (fig.8). The lengths and masses of the segments L_{1-3} и m_{1-3} are known from the measurements on the volunteers. Position of the centre of mass of segments C_{1-3} is determined by distances d_{1-3} from the beginning of the segment along z-axis. The upper extremities are tightly pressed against the trunk so that the trunk together with the head and extremities may be considered as a single segment with composed mass and inertia parameters. Supposing that the bearing area (feet position) is unchangeable, we describe configuration of the pendulum by angles θ_{1-3} between the segments and the vertical line (z axis). Then the motion of the pendulum is determined by Lagrange equations (energy method).

The first body segment (shank) participates in the rotational motional round the fixed point (ankle-joint). The second (thigh) and third (trunk) segments are involved into the rotational motion round their body mass and transportation motion of the centre of mass caused by motion of the previous segments. For the case expressions for the corresponding energies T_j, Π_j of the separate segments can be written in the form:

$$\begin{aligned}
&T_1 = 0.5\dot{\theta}_1^2 (J_1 + m_1 d_1^2), \\
&T_{2,3} = 0.5 J_{2,3}^c \dot{\theta}_{2,3}^2 + 0.5 m_1 V_{2,3}^2, \\
&\Pi_1 = m_1 g d_1 (1 - \cos\theta_1), \\
&\Pi_2 = m_1 g L_1 (1 - \cos\theta_1) + m_2 g d_2 (1 - \cos\theta_2), \\
&\Pi_3 = m_1 g L_1 (1 - \cos\theta_1) + m_2 g L_2 (1 - \cos\theta_2) + \\
&+ m_3 g d_3 (1 - \cos\theta_3)
\end{aligned} \tag{1}$$

where J_j is mass moment of inertia of the j-th segment, V_j is velocity of the j-th segment relatively its of mass. The expressions for the velocities may be easily found from geometrical considerations as

$$\begin{aligned}
&V_2^2 = L_1^2 \dot{\theta}_1^2 + d_2^2 \dot{\theta}_2^2 + 2 L_1 d_2 \dot{\theta}_1 \dot{\theta}_2 \cos(\theta_1 - \theta_2) \\
&V_3^2 = L_1^2 \dot{\theta}_1^2 + L_2^2 \dot{\theta}_2^2 + d_3^2 \dot{\theta}_3^2 + 2 L_1 L_2 \dot{\theta}_1 \dot{\theta}_2 \times \\
&\times \cos(\theta_1 - \theta_2) + 2 L_1 d_3 \dot{\theta}_1 \dot{\theta}_3 \cos(\theta_1 - \theta_3) + \\
&+ 2 L_2 d_3 \dot{\theta}_2 \dot{\theta}_3 \cos(\theta_2 - \theta_3)
\end{aligned}$$

After substitution (1) into Lagrange equations, using power expansions of the trigonometric functions in the small angles θ_i and neglecting the terms smaller than θ_i^2, we obtain the following system of linear differential equations in the matrix form:

$$M \cdot \frac{d^2}{dt^2} \vec{\theta} + N \cdot \vec{\theta} = 0 \tag{2}$$

where $\vec{\theta}^T = (\theta_1, \theta_2, \theta_3)$, sing T denotes transposition,

$$\begin{aligned}
&M_{11} = J_1 + m_1 d_1^2 + (m_2 + m_3) L_1^2, \\
&M_{22} = J_2 + m_2 d_2^2 + m_3 L_2^2, \quad M_{33} = J_3 + m_3 d_3^2, \\
&M_{12} = M_{21} = m_2 L_1 d_2 + m_3 L_1 L_2, \\
&M_{13} = M_{31} = m_3 L_1 d_3, \quad M_{23} = M_{32} = m_3 L_3 d_3, \\
&N = \begin{pmatrix} m_1 g (d_1 + 2L_2) & 0 & 0 \\ 0 & m_2 g (d_2 + L_2) & 0 \\ 0 & 0 & m_3 g d_3 \end{pmatrix}
\end{aligned}$$

Let us investigate the system (2) and determine the own frequencies of the pendulum substituting

$\theta_j = \alpha_j \sin(\omega t + \psi)$ in (2), where α_j, ω, ψ are amplitude, frequency and phase of the oscillations. Then we obtain the system of linear equations for the frequencies $\bar{\alpha}^T = (\alpha_1, \alpha_2, \alpha_3)$ in the matrix form:

:

$$(M\omega^2 + N)\cdot \bar{\alpha} = 0 \qquad (3)$$

The solvability condition of the system (3) is $\det\left|M\omega^2 + N\right| = 0$ which leads to a polynomial equation for computation of the own frequencies ω. Solution of the equation may be easily obtained by numerical methods when all the parameters of the model are determined.

Mathematical model of the body sway in the sagittal direction in the course of one-legged stance

Another three-link inverted pendulum is considered as a mathematical model for one-legged stance (fig.8). The individual stands on the straightened bearing leg having another leg straightened too and using it for balance maintaining.

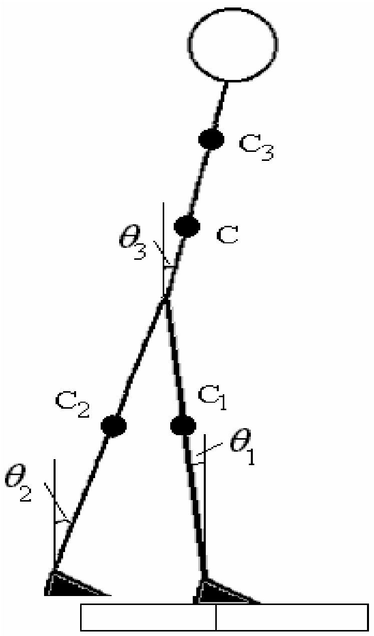

Fig. 8. One-legged stance of a human: a three-link model

The angle θ_2 of the free leg may change but the positional relationship of the separate segments of the free leg is unchangeable. Mass, position of the s of mass of the segments are introduces in the same way as in the previous model. We suppose that the left and right extremities are similar and their length, mass and distance to the centre of mass are L_1, m_1, d_1. The motion of the pendulum in the case will be described by Lagrange equations where the expressions for kinetic and potential energy of the first segment possess the same form and for the segments i=2,3 we will obtain

$$T_{2,3} = 0.5J^c_{2,3}\dot{\theta}^2_{2,3} + 0.5m_1V^2_{2,3},$$
$$\Pi_2 = m_1g(d_1 + d_1\cos\theta_2 - L_1\cos\theta_1),$$
$$\Pi_3 = m_3g(L_1 + d_3 - d_3\cos\theta_3 - L_1\cos\theta_1) \qquad (4)$$
$$V_2^2 = L_1^2\dot{\theta}_1^2 + d_1^2\dot{\theta}_2^2 + 2L_1d_1\cos(\theta_1+\theta_2)\dot{\theta}_1\dot{\theta}_2,$$
$$V_3^2 = L_1^2\dot{\theta}_1^2 + d_3^2\dot{\theta}_3^2 + 2L_1d_3\cos(\theta_1-\theta_3)\dot{\theta}_1\dot{\theta}_3$$

Substituting expressions (4) into Lagrange equations, making power expansions of the trigonometric functions and neglecting the small terms of the same order of magnitude as in the previous case, we obtain the system of differential equations in the form (2) where

$$M_{11} = J_1 + m_1d_1^2 + (m_1+m_3)L_1^2, \qquad M_{22} = J_2 + m_1d_1^2,$$
$$M_{33} = J_3 + m_3d_3^2, \qquad M_{12} = M_{21} = m_1L_1d_1,$$
$$M_{13} = M_{31} = m_3L_1d_3,$$
$$M_{23} = M_{32} = 0,$$
$$N = \begin{pmatrix} m_1g(d_1+L_1) + m_3gL_1 & 0 & 0 \\ 0 & m_1gd_1 & 0 \\ 0 & 0 & m_3gd_3 \end{pmatrix}$$

In the case it is also worth to investigate the free oscillations of the pendulum and compare the results for the one-legged and two-legged stance. Solution of the system can be obtained by the same numerical procedure.

Numerical results and discussion

Investigation of the free oscillations of the models has been carried out by numerical methods. The lengths of the segments have been obtained during the measurements on the volunteers and mass, moments of inertia and position of the centre of mass of the segments have been calculated basing on the statistical data [1,7]. Mass and inertia of the segments are considered as an association of the separate segments basing on the mass theorem and using the measured values of the height and weight of the body of an individual [7,8]. The same calculations have been made for the one-legged stance when the low extremities have been considered as single links consisted of two separate segments. The computational results of the own frequencies are presented in table.1. Comparison of the computed values to the measured posturography data and the data presented in literature has revealed that the calculated own frequencies f_{1-3} correspond to three main oscillation ranges I-III of PSD (fig.4) that for the averaged posturography data gives $f \in [0.2;0.4]$ (I), $f \in [0.4;1]$ (II), and $f \in [1;1.4]$ (III) for sway in 0y direction, and $f \in [0.2;0.3]$ (I), $f \in [0.3;0.9]$ (II), and $f \in [0.9;1.3]$ (III) for sway in direction of 0x axis. The low frequency component corresponds to mechanical oscillations and the high frequency component corresponds to the physiological tremor [1].

Numerical results for the model of the one-legged stance give the values for the own frequencies which are slightly bigger then the corresponding frequencies for the two-legged stance and relate to the same frequency ranges I-III. The computation results on variations of the own frequencies in the two-legged to the one-legged stance are in agreement with posturography data.

The computed data conforms with the mentioned hypothesis that any decrease in the support area in both longitudinal and transverse directions leads to an increase in instability of the posture [6]. At definite critical values of the supporting area an individual may lose the posture stability. In that case the sway amplitude increases in both sagittal and coronal planes and the low frequency rambling component changes its behaviour, namely the average “free path length” increases that leads to significant increase in maximal sway amplitude. The pattern of the trembling component is changed in a different way.

Table.1. Own frequencies of the human body oscillations for the two-legged stance

N	Height (m)	Weight (kg)	f_1	f_2	f_3
1	1.82	80.75	1.51	1.88	4.95
2	1.56	52.45	1.35	1.83	4.98
3	1.72	60.95	1.38	1.83	4.98
4	1.80	61.1	1.41	1.88	5.63
5	1.69	55.7	1.35	1.91	5.57
6	1.90	84.75	1.51	1.98	6.65
7	1.74	61.5	1.41	1.89	5.65
Mean value	***1.75***	***65.3***	***1.42***	***1.89***	***5.49***

Conclusions

Results of the posturography study of several sorts of two-legged and one-legged stances revealed that the patterns of oscillations of the centre of mass and the corresponding trajectories $y_c(x)$ are different for different healthy volunteers. Since some relationships in displacement of positions of the of mass for the vertical stance and for the first step off the force platform are the same as have been obtained during the 20 year experience of measurements of posturography data for the patients in the Institute of Spine and Joints Pathology, it implies the state of the even young volunteers (students, schoolchildren) is far from the real healthy and the stealthy spine and joint chronic pathologies have been observed in many cases.

Single-meaning visual interpretation of the posturography data is usually impossible so the mathematical models and biomechanical analysis and interpretation of the data are extremely important. Maximal and mean sway amplitudes may be proposed as separate diagnostic indexes for the two-legged and one-legged vertical stance. Spectral power density is an important characteristic of the own and forced sway frequencies.

Mathematical model of the human body as an inverted pendulum allows computation of the own frequencies and describes correctly the increase in frequency values when an individual transfers from the two-legged to the one-legged stance. The model can be generalized for different joint pathology and for incorporation the feedback control mechanisms.

A comparative study of the posturographic data for the two-legged and one-legged models is a promising way of medical diagnostics, because one-legged stance allows stimulation of the neuromuscular system controlling the body balance that may be significantly changed in entirely different ways at the expense of the age-related and pathological processes.

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