Spectral analysis and mathematical model of human postural sway in sagittal and corollary planes

Natalya Kizilova[1], Julius Griškevičius[2], Michail Karpinsky[3], Elena Karpinskaya[4]

[1]Kharkov National University, Ukraine
[2]Vilnius Gediminas Technical University, Lithuania
[3, 4]M.I.Sytenko Institute of Spine and Joints Pathology, Ukraine
E-mail: *[1]n.kizilova@gmail.com, [2]julius.griskevicius@vgtu.lt*

Abstract. Trajectories of the center of pressure (COP) of human body during different stances measured on healthy individuals and patients with spine and joint diseases have been measured. Fourier and continuous wavelet transforms have been used for statistical analysis of the trajectories and 3d representation of the spectral power density (SPD) in both frequency and time domains. The corresponding multilink models have been analyzed and the influence of fixation or pathology of separate joints have been studied. Novel indexes for clinical diagnostics of joint pathologies have been proposed.

Keywords: posturography, postural sway, spectral analysis, biomechanics, clinical diagnostics.

Introduction

Postural sway is important determinant of human locomotor, balance and nervous systems [1]. Sway analysis is used for differential diagnostics of muscular, skeletal, vestibular, nervous, auditory and visual pathology, age-related changes, and emotional state of the individual and alcohol uptake [2, 3]. Body sway in the sagittal plane is quite well studied as an inverted multilink pendulum [1–3], while sway in the corollary plate is not well studied.

Experimental measurements

Posturographic measurements have been done in M.I. Sytenko Institute of Spine and Joints Pathology (Kharkov, Ukraine) on young healthy volunteers and a group of patients with different spine and joint diseases using the force platform (Statograph-M05/28). The series of tests include 2-leg and 1-leg stances with open and closed eyes, normal and fixed joints. Experimental setup is described in [2, 3].

Data analysis

The trajectory $Y_{COP}(X_{COP})$ of the centre of pressure have been computed from the measured time series $(X_{COP}(t),Y_{COP}(t))$. The data have been amplified and the low ($f<0.01$ Hz) and high ($f>10$ Hz) frequency components have been subtracted using the 6-th order Butterworth filter. The 30 s test was split into 4 consequent periods to study the sway amplitudes a_1, a_2, a_3, a_4 and stance regulation at the beginning and at the end of the test. It was shown the body sway amplitude in both sagittal and coronal plate is twice bigger when the eyes are closed and visual control is absent. It was also shown in young healthy individual sway amplitude in bigger in the sagittal plane while in elderly patients with locomotor problems the sway amplitude in the corollary plane may exceed the amplitude in the sagittal plane. Fourier and continuous wavelet transforms have been used for statistical analysis of the trajectories and 3d representation of the spectral power density in both frequency and time domains (Fig. 1). The area A_r of rectangle surrounding the trajectory, trajectory spot area A_s, axes and asymmetry parameters have been computed as well as dynamic velocities dX_C/dt, dY_C/dt and accelerations d^2X_C/dt^2, d^2Y_C/dt^2. According to the second law of dynamics acceleration is proportional to the resulting force produced by the muscles that participate in the balance control.

Mathematical model

Human body is modelled as an inverted 4-link pendulum (Fig. 2). The lengths L_{1-4} , masses M_{1-4} , moments of inertia I_{1-4}, and positions of the centre of mass C_{1-4} determined by distances d_{1-4} in the local coordinate system connected with each segment has known from measurements and tables. Position of the pendulum is determined by angles θ_{1-4} (Fig. 2). Oscillations of the pendulum are described by Lagrange equations. Kinetic and potential energy have been computed for each segment and substituted in Lagrange equations. Supposing the small variations of the angles θ_{1-4} and setting $\sin(\theta_j) \sim \theta_j$, $\cos(\theta_j) \sim 1$ and neglecting terms $\sim (\theta_j)^2$ one can obtain the system of ODE governing oscillations of the links

$$M \cdot \frac{d^2}{dt^2}\vec{\theta} + K(\frac{d}{dt}\vec{\theta},\vec{\theta}) + N \cdot \vec{\theta} = \vec{u}(\frac{d}{dt}\vec{\theta},\vec{\theta}) \qquad (1)$$

where $\vec{\theta}^T = (\theta_1,\theta_2,\theta_3,\theta_4)$, sing T denotes transposition, M is the mass-inertia matrix, K is centrifugal matrix, N is gravity matrix, $\vec{u}$ is the control function which is usually supposed to be proportional to deviations of angles and velocities.

Components of the matrices M, K, N are long complex expressions which are not presented here. Nonlinear system (1) has been solved and amplitudes and frequencies of body oscillations have analyzed.

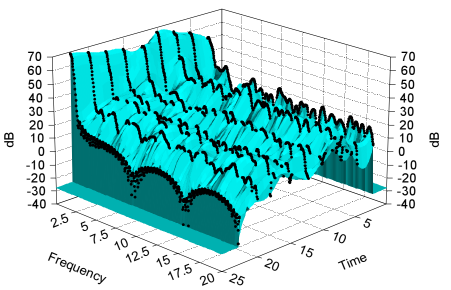

Fig. 1. Dependence of SPD on frequency and time

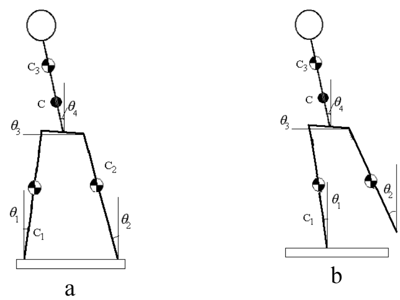

Fig. 2. Multilink models of the human body for the 2-leg (a) and 1-leg (b) stances

Results and discussions

Good agreement of the computed frequencies and measured by spectral analysis of the experimental data have been obtained. It was shown in the young healthy patients a good approximation of the computed results to the measured data is given by the control function determined as $u_j(t) = a\theta_j(t) + bd\theta_j(t)/dt$ while in the elderly patients $u_j(t) = a\theta_j(t-\tau) + bd\theta_j(t-\tau)/dt$ and time delay τ correlates with both age and pathology level. It is shown the parameters A_s/A_r, a_1:a_2:a_3:a_4 and SPD_1:SPD_2:SPD_3:SPD_4 for 4 consequent test periods gives important information for early diagnostics of postural disorders.

References

[1] **Zatsiorsky V.M., Aruin A.C., Selujanov V.N.**, *Biomechanics of human locomotor system,* Moscow, 1981.

[2] **Karpinsky M.Yu., Kizilova N.N.,** *Computerized posturography for data analysis and mathematical modelling of postural sway during different 2-legged and 1-legged human stance*, J. Vibroeng., 2007, 9, 118–124.

[3] **Kizilova N., Karpinsky M., Griskevicius J., Daunoraviciene K.**, *Posturographic study of the human body vibrations for clinical diagnostics of the spine and joint pathology*, Mechanika, 2009, 6, 37–41.