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Wavelet-Based Dynamic Evaluation of Human Equilibrium Function under Passive Motion

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Abstract: The efficient evaluation of human equilibrium function is important for people with organs degradation and dysfunction. The traditional evaluation of static and dynamic equilibrium function seems efficient, but the prepared participants restricted the experimental results to be objective and genuine. For evaluating the equilibrium function efficiently, we propose a wavelet-based dynamic model of the human body using external excitation. Firstly, we introduce a local linearization method based on the second-order Taylor expansion for simplifying typical linear system model. Secondly, the continuous wavelet transform analysis is applied to process gravity-center data and estimate parameters of the dynamic model. Finally, the settled time of the systemic responding rapidity is evaluated. Furthermore, the index of the equilibrium ability is obtained. Experiment results show the validity and practicability of the proposed method. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Leave dynamic model, Equilibrium ability, Wavelet analysis, Settling time, Passive motion.

1. Introduction

With the advent of the Aging Problem, elderly body equilibrium is an important test for physical condition indicators. The accurate assessment of the elderly equilibrium capacity is a significant research area for predicting risk factors, formulating intervention, rehabilitation measures and the treatment effect, evaluating rehabilitation and treatment, and the differential diagnosis of the disease course [1].

The equilibrium function of the human body is one of the important coordinate functions in a human for the body-organ system. The equilibrium function needs the combined action of the vestibular system, the visual system and the body feeling system to be maintained. The equilibrium ability of the human body can be divided into static equilibrium ability and dynamic equilibrium ability. Static equilibrium ability refers to the ability to keep the body stable position under the condition of stillness. Dynamic equilibrium ability refers to the ability to maintain some kind of action or position on the condition of motion. The corresponding equilibrium test can be divided into static equilibrium test and dynamic equilibrium test.

In this paper, the passive equilibrium test is implemented by exerting force to destroy the original equilibrium of human body. This method belongs to the branch of the dynamic equilibrium test. The dynamic equilibrium test has completely different research branches according to three human sensory systems, which affects equilibrium function of the visual, body feeling and vestibular. These researches can help to determine the cause of the equilibrium disability, and achieve the direction of specific therapy. Compared to the static study method, the dynamic equilibrium test has the vital significance. The Graybial tests posture reaction before and after the flight of the shuttle pilot make the subjects walk in a single track with their eyes opened and closed and qualitatively evaluates the dynamic equilibrium of the human body through observing the time to maintain the equilibrium of human body [2]. Christoph established a complete equilibrium control model of the human body, and proved the trajectory of the gravity center of the human body and the actual acquisition was very similar [3]. Kimura proved that the differential coefficient significantly reduced with increase of age, and when a human closes his eyes, was less than the situation when the eye is open [4]. Nowadays, the dynamic equilibrium is not much researched upon, especially research on passive equilibrium ability; quantificational evaluation method of the equilibrium capacity has not been explored. In the first part of this research, we establish the complete dynamics model in external excitation of human body. Through the principle of local linearization it is reduced to the linear model of typical second order system. In this paper, the thought of passive motion assessment is developed, where a six-degree-of-freedom (6-DOF) motion platform was used as pseudo pulse excitement for human vestibular organ in anterior–posterior directions. Center of pressure (COP) wave was recorded and we choose the wave data with typical second-order damping characteristics. Using the method of wavelet analysis, the natural frequencies and damping were identified, and then the regulating times were calculated. This study proposed that regulating time can be regarded as the evaluation index for equilibrium ability under passive motion. Through participants' experimental research, the effectiveness of the evaluation method is verified and it has good potential in human body recover engineering applications.

2. Passive Motion Model

Consider the motion in the sagittal plane (anterior-posterior) as shown in Fig. 1. At the same time we assumed that the soles of feet and floor of the friction factor is big enough, which makes no sliding between soles of feet and six degrees of freedom platform. In this model, the human body is represented by a single-segment inverted pendulum and the neural controller is assumed to be an optimal controller that generates control torques of ankle according to a certain performance criterion [5, 6].

The following hypotheses are made in order to reasonably formalise and simplify the analyzing process:

Hypothesis 1: The body is stiff and has a mass (kg).

Hypothesis 2: The body centre of mass is located distance (m) from the platform surface.

Hypothesis 3: There is a dynamical equilibrium between the torque of the foot and the forces acting on the 'pendulum'.

Hypothesis 4: There is a stabilizing ankle torque.

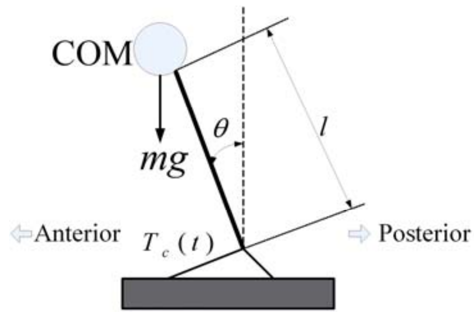

Fig. 1. Inverted pendulum model of human postural dynamics.

The tangential torque equilibrium for a standing person subject to gravitation g, and with a body moment of inertia J, is then

$$J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} - mgl\sin\theta(t) = T_c(t)\,,\ J = ml^2\,, \tag{1}$$

Hypothesis 5: The vibration stimulus n introduces an erroneous input into the stabilizing system, which causes misperception of the position (stretch) and angular velocity (rate). It is assumed that disturbs both stretch and rate perception but at different proportions and, respectively, at this time output control torque of the PD controller can be expressed as

$$T_c(t) = -K_P\theta(t) - K_D\frac{\mathrm{d}\theta}{\mathrm{d}t} + (a_1 + a_2)v(t) \tag{2}$$

Substituting (2) to (1), the close-loop equation of human controlling his equilibrium is

$$J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} - mgl\sin\theta(t) = -K_P\theta(t) - K_D\frac{\mathrm{d}\theta}{\mathrm{d}t} + (a_1 + a_2)v(t) \tag{3}$$

In this research, the passive motion distance under the feet is between 1 cm and 2 cm. For a normal human being, is about 80 cm. The angle is about 1.07 degree. So, for linearised motion around the equilibrium, we let, which means. Then

$$J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} - mgl\theta(t) = -K_P\theta(t) - K_D\frac{\mathrm{d}\theta}{\mathrm{d}t} + (a_1 + a_2)v(t) \tag{4}$$

After Laplace transformation and algebraic simplification, we obtain the transfer function given by

$$\frac{\theta(s)}{V(s)} = \frac{a_1 + a_2}{Js^2 + K_D s + (K_P - mgl)} \tag{5}$$

Thus, it could be seen that the nonlinear close-loop dynamic system can be reasonably simplified as a typical model structure of linear second order systems. And there are mature theories and indexes to evaluate the performances of linear second order system. Therefore, it is an available method to estimate the systemic dynamic process and the performance index. In this research, we chose settling time as the index to evaluate the rapidity of human equilibrium process.

3. Parameters Estimation with Wavelet-based Analysis

For calculating the settling time of a second-order dynamic system, the obvious approach is through analysis method. In case the step-response data of a system were acquired, one can easily get this value by using the adjacent peak values [7], or by other methods. But, there are many uncertainties in the data-acquiring process. Participants could do some unrelated actions carelessly which brings randomness to the calculated results.

The wavelet transform is used as a time-frequency representation for the determination of modal parameters. By this way, the characteristics of non-stationary signals can be more closely monitored and the transient behavior and discontinuities in the signals can be better investigated. Studies have been conducted on the identification of modal parameters including natural frequencies, damping coefficients and mode shapes of structural systems using ambient vibration records without input measurements.

For a typical under damping second order linear system with zero initial condition, the mathematical equation of frequency response signal is:

$$x(t) = Be^{-\varsigma\omega_n t}\cos(\omega_d t + \phi) \tag{6}$$

where ω_n is the natural angular frequency, ς is the damping coefficient, ω_d is the damped oscillation angular frequency.

For the average amplitude and frequency modulation signal

$$x(t) = A(t)\cos(\theta(t)), \tag{7}$$

The wavelet transform coefficient [8, 9] is

$$W_\psi(a,b) = \frac{\sqrt{a}}{2} A(b)\Phi^*(a\theta'(b))e^{j\theta(b)} \tag{8}$$

Assuming

$$A(t) = Be^{-\varsigma\omega_n t}, \tag{9}$$

$$\theta(t) = \omega_d t + \phi \Rightarrow \theta'(t) = \omega_d, \tag{10}$$

The free response signal of wavelet transform [10] is:

$$W_\phi(a,b) = \frac{\sqrt{a}}{2} Be^{-\varsigma\omega_n b}\psi^*(a\omega_d)e^{j(\omega_d b+\phi)}. \tag{11}$$

Let $a = \omega_0/\omega_d$,

$$\left|W_\phi(a,b)\right| = \frac{\sqrt{a}}{2} Be^{-\varsigma\omega_n b}\left|\psi^*(a\omega_d)\right|. \tag{12}$$

Taking the logarithm:

$$\ln\left|W_\phi(a,b)\right| = -\varsigma\omega_n b + \ln\left(\frac{\sqrt{a}}{2}B\left|\psi^*(a\omega_d)\right|\right) \tag{13}$$

$$x_1 = \frac{\mathrm{d}(\ln\left|W_\phi(a,b)\right|)}{\mathrm{d}b} = -\varsigma\omega_n. \tag{14}$$

$$\angle(W_\phi(a,b)) = \omega_d + \theta. \tag{15}$$

$$x_2 = \frac{\mathrm{d}\angle(\ln\left|W_\phi(a,b)\right|)}{\mathrm{d}b} = \omega_d. \tag{16}$$

$$\omega_n = \sqrt{{x_1}^2 + {x_2}^2}, \tag{17}$$

$$\varsigma = -x_1/\omega_n. \tag{18}$$

Apparently, the regulating time for approximate calculation is

$$t_s \approx (4 - \ln\sqrt{1-\varsigma^2})/\varsigma\omega_n. \tag{19}$$

According to the Eq. (19), one can obtain the settling time, and use this value as the quantitative evaluation of the human body equilibrium ability index.

4. Equilibrium Evaluation and Results

4.1. Construction of the Evaluating System

The systemic construction is presented in Fig. 2. In this system, the eforce plate consists of three force strain sensors, which are mounted onto the bottom plate. The data acquisition is performed by a special computer-centered software and AD card, impulse from multiple directions are carried out by a six-degree-of-freedom (6-DOF) parallel motion platform, with the evaluated human standing on a force plate. The 6-DOF platform outputs the desired position steps in space. Under this impulse when the human gravity center (GC) is disturbed suddenly because of feet friction the instinct of cerebra would try to adjust human GC to the origin of force plate. The adjusting process would reflect body equilibrium ability.

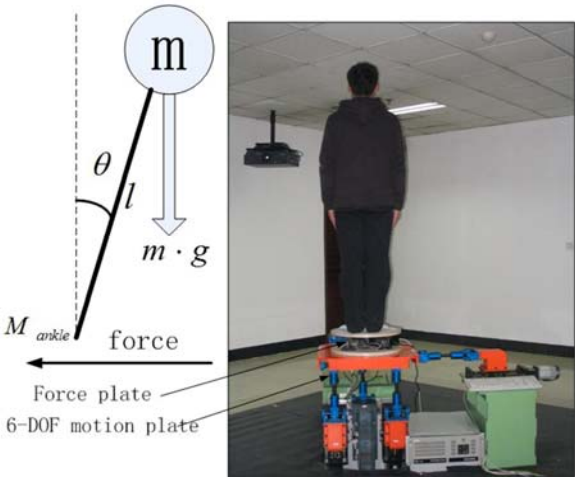

Fig. 2. The experiment device.

The motion platform can output not only infliction quantitative impulse to anterior canal, horizontal canal and posterior canal of vestibular organ in three rotational directions, but also infliction impulse to utricle and saccule in three linear directions. So by using this platform the whole equilibrium-related performance of vestibular organ could be excited and shown. By using the force plate the adjusting process of COP is detected and recorded in real time as in Fig. 3. When the process finishes the data could be analyzed off line, and setting time of response process is evaluated through the methods presented in this research, which could be used as the assessment value to evaluate equilibrium ability.

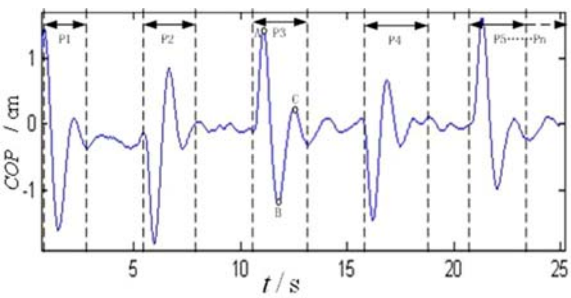

Fig. 3. COP graph under pulse incentive.

4.2. Data Acquisition, Processing, and Evaluating Results

In actual case the human equilibrium-keeping model is nonlinear, as in Eq.(1). In this research, the model is linearized and the order is reduced, which makes the outer impulse amplitude very important in the process of data collection. If it is much less, human equilibrium-keeping dynamics could not be excited enough; if it is much more, the dynamic would step into nonlinear region and the evaluated participant might fall down.

In order to obtain the linear region, we performed a test. Four participants were chosen and ordered to stand on the motion platform respectively.

We let the platform to output step straight motion with the amplitude of 2 mm, 4 mm, …, 20 mm, as excitation signals with 2 mm step value on every participant. After we obtained the data, the settling time of everyone under every excitation was calculated. The results were plotted in the following Fig. 4.

In Fig. 4, Ts(s)_x (x=1,2,3,4) indicates the settling-time distribution of participant x under different excitation. This figure shows that the approximately same settling time can be obtained under different pulse excitation for a given participant, which is one of the basic properties of a linear system, and the reasonable range is from 8 mm to 20 mm. This conclusion is treated as an evidence to use settling time as an index to reflect human equilibrium ability.

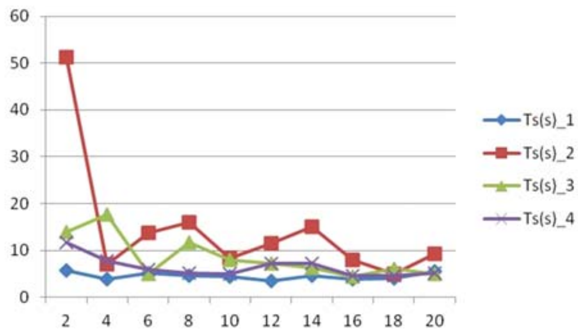

Fig. 4. Settling time distributions of 4 students.

4.3. Model Fitting Degree

In order to compare the described methods in this paper, i.e. analytical and wavelet-based, and to conclude whether the wavelet-based method is a better, we calculated their damping coefficients, the regulating times and the model fit degrees, which is a (scalar) measure of how well a particular model is able to “explain” or “fit” to a particular data set [11]. The results are listed in Table 1. In this table, represents the damping coefficient of model, is the regulating time of dynamic process, and is a measure of the model fitting the data; [x:y] means the data we used to compare, where x is the starting datum, and y is the end.

Table 1. Comparison experimental results.

Research methods	[1275:1650]			[2146:2750]			[6253:7000]		
	ς	$t_s(s)$	fit	ς	$t_s(s)$	fit	ς	$t_s(s)$	fit
Wavelet	0.2010	4.4236	94.53%	0.2154	4.3122	81.05%	0.2144	4.4622	82.39%
Analytical	0.2228	4.5068	85.37%	0.1927	5.3387	34.135%	0.1613	9.6067	-15.37%

The results show that we can obtain a much better fit degree through the wavelet method. The consistent results of the assessing process also indicate that the wavelet method can extract higher precision equilibrium value, which ensures the credibility of the method. More information in more measuring cycles is considered by the wavelet method, which makes the calculation results more objective. From the view of clinical applications, the regulating time can be more useful to evaluate the human body equilibrium ability.

In order to test the feasibility of the described equipment and method, 100 healthy students or graduate students were selected as samples to participate in the testing process. They were ordered to stand on the center of force plate with two legs, close their eyes, open legs to 45 degree with closed heels. Considering the equilibrium between affordability and better exciting results everyone received impulse excitation from straight-line motion along axis y with the amplitude of 15 mm, under which case participators would adjust their gravity center to origin. The period was settled at 10 seconds. After measuring and storing the data of COP to hard disk in real time, every participant's data is ready to be analyzed offline.

By using the wavelet-based and analytical methods respectively, the settling time of every human under different excitement was calculated and shown dotted in Fig. 5, where the horizontal axis indicates the number of human and vertical axis indicates the settling time of adjusting equilibrium with unit of second. Fig. 6 shows the results only using wavelet method.

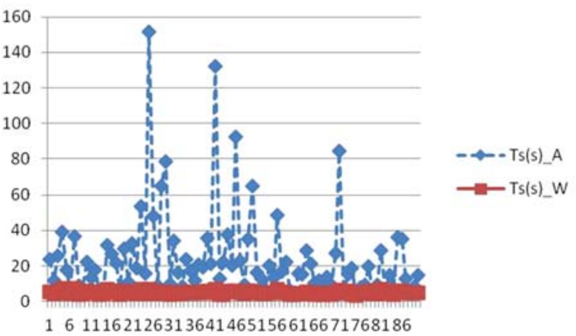

Fig. 5. Result comparison between wavelet-based method and analytic one.

In Fig. 5, the dashline curve indicates the result of analytic method, and the solidline curve indicates the result of wavelet method. These results show the uniformity when using wavelet method to evaluate the settling time of human equilibrium dynamic. Then it is a more impersonal candidate to evaluate the human equilibrium ability.

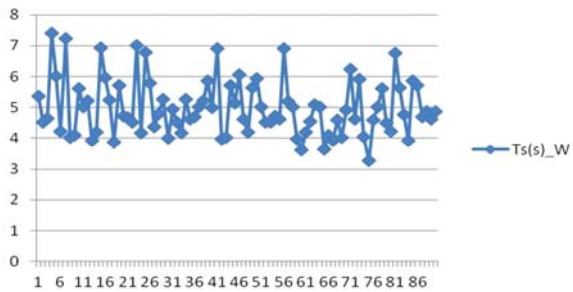

Fig. 6. Results with wavelet-based method.

Since all participators were healthy and young, from Fig. 6 we can conclude that if the settling time of an individual lies in the range of 3-8 s, then he/she has a sound equilibrium ability; otherwise, his/her balance ability should be considered to improve.

5. Conclusions

Through the human anatomy and neural model research, the inverted pendulum model is established based on the PD controller. Through the local linearization method it can be simplified to typical second-order system model, which could be used to abstract the equilibrium-related index expediently. In this paper the wavelet principle is introduced to estimate the coefficients of human dynamic model. Based on several experiments the feasibility of this method was tested and verified, and it weakens the influence of uncertainty factors such as noise. Because excitement of the motion platform could have very high accuracy and repeatability, and it is based on passive motion, this method would be more credible.

More importantly, in the system the multi-dimensional motion platform is used to test and provide incentives. In this way, it can eliminate the randomness and individual differences introduced by the human interference. Therefore, the incentives for the patients are more objectivity and uniformity. Furthermore, if the balanced postures of patients were disturbed by the interference of external forces, patients will try their best to maintain balance. In this way, the system can be used to increase the training strength of the patient's balance ability, and at the same time, the testee can supervise and observe the real-time changes of their own center of gravity. By using this visual feedback adjustment mechanism, patients can be allowed by various active and passive rehabilitation training. However, this research only deals with the situation of anterior and posterior motion. Left and right motion of human being would be considered in the further research.

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