The Affect of Multi-source Time Delay to the Human Balance Based on Robust Control Model

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Abstract

Time-delay is a prevalent phenomenon in human body during standing and locomotion, and it is one of the main factors to affect human balance ability. The purpose of this study is to design a human balance control model, and to analyze the human possible posture control mechanism with multi-source delay considered. Based on an inverted pendulum with the ankle joint model, we derived and proved that the human body existed multi-source time delay, and then designed a robust state feedback controller with an observer for the generalized system, which is with delay state and delay control inputs in continuous time. This controller can be considered as the central nervous system (CNS) for the human balance controller mathematical model. Finally, applying simulation software, we obtained the balance regulation kinematics responses to anterior and posterior (A/P) surface translations, and discussed the effect on the dynamic response of the human body to different kinds of the time-delay. The robust controller can stable the human system within larger interference and larger time-delay. This paper provides a useful method for analyzing the impact of the multi-source time delay on the human balance system.

Keywords: *human balance, multi-source time delay, robust controller, surface translation.*

1. Introduction

The phenomenon of time-delay happens prevalently in human body during standing and locomotion, and it is one of the main factors to affect human balance ability [1]. In reality, accident or aging may result in the increase of delay time, and the specific performances include slow motion, reaction time extension or sensory organ insensitivity [2, 15]. Since the human body is not statically stable, maintaining upright posture requires continuous action of tonal adjustments in the antigravity muscles [15]. The time-delay which comes from different organs of the body, has adverse effects to balance ability of the human body [4, 9]. So it is necessary to analyze various delays impacted on body balance capacity objectively and efficiently.

Engineering models have been developed that effectively describe aspects of human balance [3,4]. Some scholars [5] model the human body as a single segment, single joint inverted pendulum that rotates about the ankle joint; Jiang and Kimura [6] model it as a more complex dynamic model including five joints; Gawthrop, Loram, and Lakie [14] model it as an inverted pendulum that is balanced by an active muscle working in series with a tendon; Robert J. and Schilling, Senior purposed a phase-locked loop model of the response of the postural control system to periodic platform motion[13].

Standing posture control strategies now are commonly believed to be a fundamental motor skill learned by the central nervous system (CNS) [9]. The behavior of the human postural control system was approximated by various systems such as feed forward/feedback[14, 11], linear (P/PD/ PID) control[2] [5] [6], optimal control [8, 15], and predictive control [10]. In the previous research of human postural control system, many researchers have considered the impact of delay to balance ability [5, 8]. Qu Xingda established a human body mathematical model with the approximation time delay in the method of Taylor series expansion [8], as the time delay constant from body sense organs. In analyzing human delay model, John Milton, Juan Luis Cabrera, and Toru Ohira et al attempted to set the controller delay in paper [11]. However, their human body model was oversimplified about the important delays. And they neither analyzed the potential larger delay from patients, nor considered the effect delay from multiple organs human on human balance ability. Even many studies ignored the effects of time delays in biomechanical applications of the inverted pendulum to human balance control.

Based on the inverted pendulum with ankle joint model, we derivate the kinetic equation of human musculoskeletal model, and proposed a robust controller as the central nervous system (CNS) for the human balance controller mathematical model. Then the controller parameters K were calculated by using Matlab LMI ToolBox. Finally, applying simulation software, we obtained the balance regulation kinematics responses to anterior and posterior (A/P) surface translations, and discussed the effect on the dynamic response of the human body to different kinds of the time-delay.

2. Model formulations

The balance maintaining control system can be assumed as a continuous time feedback control system [5]. The neural controller with an upright reference position can sense the error when body sway from it, and then sends commands to various muscles to keep the body upright [7].

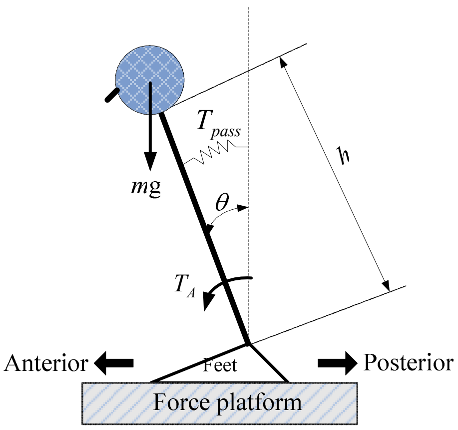

Fig. 1. A inverted pendulum model. The model consists of links with ankle joint. *m* represents the total mass of the inverted pendulum, *h* the distance from ankle joint to the total center of mass (CoM) of the pendulum. T_{pass} is the viscous damping coefficient.

The dynamical equation for the inverted pendulum model of the body musculoskeletal was given by:

$$J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} = mgh\sin(\theta) + T_{\mathrm{A}} + T_{pass} + T_d$$
$$T_{pass} = k_e\theta + k_v\dot{\theta} \tag{1}$$

where, θ the was the sway angle; the input T_A was the total ankle torque, which was produced by CNS; m was mass of the musculoskeletal segment; g was the acceleration of gravity; h is the distance from the ankle joint to COM; J was the moment of inertia of the musculoskeletal segment; T_{pass} was the passive torque from joint viscous and elastic; viscous and elastic coefficient were k_v and k_e respectively; and T_d was the disturbance torque. Without loss of generality, we set $\sin\theta \approx \theta$ to simplify the human body system, for the angular scope is less than $\pm 5^\circ$ during stable posture regulation [6].

The dynamical equation (1) did not consider any delay. Actually, the time delay is one of the most significant factors which would affect the standing stability of the human body [8,9,11]. The main delays include: the sensory delay, the controller delay and the musculoskeletal movement delay [8, 9]. In order to study how the effect of the various delays affect the human balance ability, we represented the musculoskeletal movement delay as τ_1 , and controller delay as τ_2 . Especially, the sensory delay can be regarded as a part of controller delay here, but we did not ignore it.

Considering the effect of multi-source delay, the human body model dynamical equation should be expressed as:

$$J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} = mgh\theta(t-\tau_1) + u(t-\tau_2) + T_{pass} + T_d$$
$$T_{pass} = k_e\theta + k_v\dot{\theta}$$
$$0 \le \tau_i \le d_0, i = 1,2 \tag{2}$$

In view of the dynamical function (2) and the delay conditions derive from the above, we considered the human body as a contnuous time linear system with time delays:

$$\dot{\mathrm{x}}(t) = \mathbf{A}\mathrm{x}(t) + \mathbf{A}_{\mathrm{d}}\mathrm{x}(t-d_0) + \mathbf{B}u(t-d_0))$$
$$z(t) = \mathbf{C}\mathrm{x}(t)$$
$$\mathrm{x}(0) = 0, t \in [-d_0, 0] \tag{3}$$

where, $\theta = x_1, \dot{\theta} = x_2$, $\mathbf{x}(t) = [x_1(t) \quad x_2(t)]$ was the state vector; T_d was a non-determined partial, and it could be omitted in order to facilitate the analysis; $z(t)$ is the system output, which was given by test data; and the matrix C was obtained by regulation;

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$$\mathbf{A}=\begin{bmatrix}0 & 1\\ \frac{k_e}{J} & \frac{k_v}{J}\end{bmatrix}\ \mathbf{A_d}=\begin{bmatrix}0 & 0\\ \frac{mgh}{J} & 0\end{bmatrix},\ \mathbf{B}=\begin{bmatrix}0\\ \frac{1}{J}\end{bmatrix}$$

3. CNS Controller design

The sense organs of the human body can be considered a state observer, and it provided state information to CNS for motion control. We proposed a continuous time controller with an observer as human CNS:

$$\begin{aligned}\dot{\hat{\mathbf{x}}}(t) &= \mathbf{A}\hat{\mathrm{x}}(t)+\mathbf{A}_{\mathrm{d}}\hat{\mathrm{x}}(t-d_0)+\mathbf{B}\,\mathrm{u}(t-d_0))\\ &\quad +L(z(t)-\hat{z}(t))\\ \hat{z}(t) &= \mathbf{C}\hat{\mathrm{x}}(t)\\ \mathrm{u} &= \text{-K}\hat{\mathrm{x}}(t)\end{aligned}\tag{2}$$

where, L was the observer gain, K is the constant gain matrix. and state error was defined by:

$$e(t)=x(t)-\hat{x}(t)\tag{3}$$

Substituting the observer system equation (2) to (3), we got:

$$e(t)=x(t)-\hat{x}(t)=(\mathbf{A}-LC)e(t)+\mathbf{A}_d E(t-d_0)\tag{4}$$

Substituting the control law $\mathrm{u}=\text{-K}\hat{\mathbf{x}}(t)$ into the time-delay system state error (3) and (4) yields

$$\begin{aligned}\dot{\hat{\mathrm{x}}}(t) &= \mathbf{A}\hat{\mathrm{x}}(t)+\mathbf{A}_d\hat{\mathrm{x}}(t-d_0)+\mathbf{B}K\hat{\mathrm{x}}(t-d_0))\\ &\quad +\mathbf{LC}e(t)\\ \dot{e}(t) &= \dot{x}(t)-\dot{\hat{x}}(t)=\mathbf{A}\mathrm{x}(t)+\mathbf{A}_d\mathrm{x}(t-d_0)\\ &\quad -\mathbf{A}\hat{\mathrm{x}}(t)+\mathbf{A}_d\hat{\mathrm{x}}(t-d_0)+\mathbf{LC}(x(t)-\hat{x}(t))\end{aligned}\tag{5}$$

The human body system (1) can be asymptotically stable by the controller (4) with observer, if the $\mathbf{A_L}=\mathbf{A}-\mathbf{LC}$ is stable, and there exist positive-definite matrices P, Q such that

$$\begin{bmatrix}\mathbf{H_1} & \mathbf{LC} & \mathbf{A_dP^{-1}} & \mathbf{0}\\ \mathbf{(LC)^T} & \mathbf{H_2} & \mathbf{0} & \mathbf{QA_d}\\ \mathbf{P^{-1}A_d} & \mathbf{0} & -\mathbf{P^{-1}} & \mathbf{0}\\ \mathbf{0} & \mathbf{A_dQ} & \mathbf{0} & -\mathbf{Q}\end{bmatrix}<0\tag{6}$$

where some terms are defined as follows:

$$\mathbf{H_1}=\mathbf{P^{-1}A^T}+\mathbf{AP^{-1}}+\mathbf{P^{-1}}$$

$$\mathbf{H_2}=\mathbf{(A-LC)^TQ}+\mathbf{Q(A-LC)}+\mathbf{Q},$$

the state feedback gain $\mathbf{K}=\mathbf{B^TP}$.

Proof. A candidate Lyapunov functional is defined as:

$$\begin{aligned}V(t) &= V_1(t)+V_2(t)+V_3(t),\\ V_1(t) &= \hat{\mathrm{x}}^T(t)\mathbf{P}\hat{\mathrm{x}}(t),\\ V_2(t) &= e^T(t)\mathbf{Q}e(t),\\ V_3(t) &= \int_{t-d_0}^{t}\hat{\mathrm{x}}^T(s)P\hat{\mathrm{x}}(s)+e^T(s)\mathbf{Q}e(s))\,\mathrm{d}\,s.\end{aligned}\tag{7}$$

Taking the derivative of the Lyapunov functional (7) along the solution of Eq. (5) yields

$$\begin{aligned}\dot{V}_1(t) &= \dot{\hat{x}}^{\mathrm{T}}(t)\mathbf{P}\hat{x}(t)+\hat{x}^{\mathrm{T}}(t)\mathbf{P}\dot{\hat{x}}(t)\\ &= \hat{x}^{\mathrm{T}}(t)(\mathbf{A^TP}+\mathbf{PA})\hat{x}(t)+\hat{x}^{\mathrm{T}}(t)(\mathbf{PA_d}-\mathbf{PBK})\\ &\quad \hat{x}(t-d_0)+\hat{x}^{\mathrm{T}}(t-d_0)(\mathbf{A_d}^{\mathrm{T}}\mathbf{P}-\mathbf{B}^T\mathbf{K}^T\mathbf{P})\dot{\hat{x}}(t)\\ &\quad +e^{\mathrm{T}}(t)(\mathbf{LC})^{\mathrm{T}}\mathbf{P}\hat{x}(t)+\hat{x}^{\mathrm{T}}(t)\mathbf{PLC}e(t)\\ \dot{V}_2(t) &= \dot{e}^T(t)\mathbf{Q}e(t)+e^{\mathrm{T}}(t)\mathbf{P}\dot{e}(t)\\ &= e^{\mathrm{T}}(t)(\mathbf{A}-\mathbf{LC})^T\mathbf{Q}+\mathbf{Q}(\mathbf{A}-\mathbf{LC})e(t)+\\ &\quad e^{\mathrm{T}}(t)\mathbf{QA_d}e(t-d_0)+e^{\mathrm{T}}(t-d_0)\mathbf{A_d^T}\mathbf{Q}e(t)\\ \dot{V}_2(t) &= \hat{x}^T(t)\mathbf{P}\hat{x}(t)-\hat{x}^{\mathrm{T}}(t-d_0)\mathbf{P}\hat{x}(t-d_0)+\\ &\quad e^{\mathrm{T}}(t)\mathbf{Q}e(t)-e^{\mathrm{T}}(t-d_0)\mathbf{Q}e(t-d_0)\end{aligned}\tag{8}$$

$$\dot{V}(t)=\dot{V}_1(t)+\dot{V}_2(t)+\dot{V}_3(t)\tag{9}$$

Then, substituting the state feedback gain $K=\mathbf{B^TP}$ to equation (9),

$$\begin{aligned}\dot{V}(t) &\le \hat{x}^{\mathrm{T}}(t)(\mathbf{A^TP}+\mathbf{PA}+\mathbf{P})\hat{x}(t)+\\ &\quad \hat{x}^{\mathrm{T}}(t)\mathbf{PLC}e(t)+\hat{x}^{\mathrm{T}}(t)\mathbf{PA_d}\hat{x}^T(t-d_0)\\ &\quad +e^{\mathrm{T}}(t)(\mathbf{LC})^T P\hat{x}(t)+e^T(t)[(\mathbf{A}-\mathbf{LC})^T\mathbf{Q}\\ &\quad +\mathbf{Q}(\mathbf{A}-\mathbf{LC})+\mathbf{Q}]e(t)+e^{\mathrm{T}}(t)\mathbf{QA_d}e(t-d_0)\\ &\quad +\hat{x}^{\mathrm{T}}(t-d_0)\mathbf{A_d^T}\mathbf{P}\hat{x}(t)+\hat{x}^{\mathrm{T}}(t-d_0)(-\mathbf{P})\\ &\quad \hat{x}(t-d_0)+e^{\mathrm{T}}(t-d_0)\mathbf{A_d^T}\mathbf{Q}e(t)-\mathbf{Q}\end{aligned}\tag{10}$$

Let $\boldsymbol{\varphi}(t)=\begin{bmatrix}\mathbf{P}\hat{x}(t)\\ e^T(t)\\ \mathbf{P}\hat{x}^T(t-d_0)\\ e^T(t-d_0)\end{bmatrix}^{\mathrm{T}}$ we can obtained the function

$$\dot{V} \le \boldsymbol{\varphi}^T(t)\begin{bmatrix} \mathbf{H}_1 & \mathbf{LC} & \mathbf{A_d P^{-1}} & \mathbf{0} \\ (\mathbf{LC})^{\mathrm{T}} & \mathbf{H}_2 & \mathbf{0} & \mathbf{QA_d} \\ \mathbf{P^{-1}A_d} & \mathbf{0} & -\mathbf{P}^{-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{A_d Q} & \mathbf{0} & -\mathbf{Q} \end{bmatrix}\boldsymbol{\varphi}(t) \tag{11}$$

where, $\mathbf{H}_1 = \mathbf{P}^{-1}\mathbf{A}^{\mathrm{T}} + \mathbf{A}\mathbf{P}^{-1} + \mathbf{P}^{-1}$, $\mathbf{H}_2 = (\mathbf{A}-\mathbf{LC})^{\mathrm{T}}\mathbf{Q} + \mathbf{Q}(\mathbf{A}-\mathbf{LC}) + \mathbf{Q}$. The matrix inequality (6) can make the $\dot{V} \le 0$, so the system could be stable by the controller, proof completed.

Anthropometric parameters were calculated according a student in Yanshan University ($m = 72\mathrm{kg}$, $h = 0.9\mathrm{m}$, $J = 77.8\mathrm{kg}\cdot\mathrm{m}^2$), $k_e = 0.8$, $k_v = 4.0$[18], the state parameters are:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 \\ 0.01 & 0.052 \end{bmatrix}$$

$$\mathbf{A}_d = \begin{bmatrix} 0 & 0 \\ 8.2 & 0 \end{bmatrix}$$

$$\mathbf{B}_1 = \mathbf{B}_2 = \begin{bmatrix} 0 \\ 0.013 \end{bmatrix}$$

Then, applying Matlab LMI Toolbox[19], the solution of Eq.(16) can be solved. We got the result of

$$K = \begin{bmatrix} -1372.5 \\ -319.1 \end{bmatrix}.$$

4. Model simulation and result analysis

The modeling and simulations were performed in matlab/simulink(the MathWork inc., Natick, MA, USA). Anthropometric parameters were calculated according to the same student in Yanshan University, whose parameters were used to design the controller gains *K*.

4.1 Kinematics responses to surface translations

A sigmoid signal was used to translate the platform 1cm in 100 ms at a peak velocity of 35 cm/s in posterior direction at the 10th second after the simulation starting [20]. This stimulus was regarded as a pulse signal to the soles of the feet as fig.2.

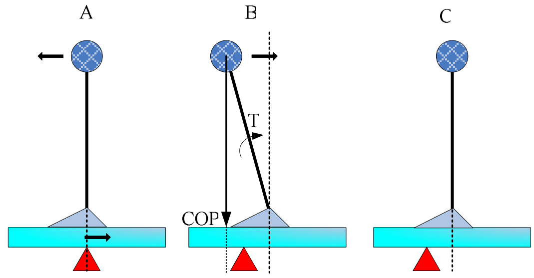

Fig.2. Kinematics response to posterior surface translation. The red triangle represents a ground reference. The blue rectangle represents the motion platform. Short black arrow indicates the direction of movement. A) The platform backward translations, so that the body center of gravity comes forward. B) Platform stopped movement in 100 ms, and the human body started to restore the balanced posture. C) The body returns to a balance posture.

More specifically, we added the interference value $\theta(10) = \delta \cdot s$ and $\dot{\theta}(10) = 0$ to current human musculoskeletal motion state $x(t)$ at the 10th second. Here, δ was defined by $\delta \approx h^{-1}$ according to the individual body. The sudden motion of platform will destroy the equilibrium state of human body, so the robust controller will dynamically regulate musculoskeletal to keep upright standing posture. We obtained the balance adjustment process data, and solved COP with the formula $COP = h \cdot \sin(\theta)$. $w(t)$ was the Gaussian noise, with zero mean and unity variance. Meanwhile, we tested the student in reality, and recorded the COP data.

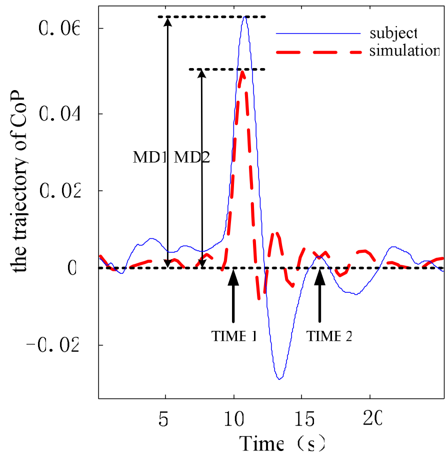

Fig.3 human balance recovery process. The horizontal axis indicates the simulation time; the vertical axis represents the trajectory of the COP in the anterior and posterior direction. Blue line shows the trajectory of the COP from the subject; the red dotted line is the trajectory of the COP from the human simulation model. At the moment of TIME1, platform started to move rearward. At the moment of TIME2, the body returned to balance state. The regulation time of the body is $\Delta\mathrm{T} = \mathrm{TIME2} - \mathrm{TIME1}$.

The simulation results and the experimental data were shown in Fig.3. It illustrates the model could be approximated to simulate the process of the transformation of the center of gravity of the human balance adjustment process, and there are some basic conclusions: (1) COP maximum distance MD2 is small, compared with the magnitude of the real human body data MD1. (2) The shock period of the results is larger, compared with the real data. (3) The damping of the oscillation process in the simulation is larger, and amplitude attenuation rapidly. (4) The time adjusted to the equilibrium state is consistent with real data.

4.2. Impacts of the different time-delay to the balance index

Furthermore, another task of the study was to analysis the affect of the different time delay to the human, and to investigate the relationship between the time delay and the balance ability performance. We simulated the system by varying the values of state delay or controller delay in the model, and let $w(t)=0$ to avoid the interference affect the results of the simulation.

Case 1

Simulation parameters: the level of motion platform backwards movement 10mm; controller delay τ_2 : 0.2s; the state delay changing the amount of 0.1-0.5s.

Case 2

Simulation parameters: the level of motion platform backwards movement: 10mm; state delay τ_1 : 0.2s; controller delay changing the amount of 0.1-0.5s.

The simulation results are list in Table 1 and Table 2. S-delay, C-delay, RT and MD mean state delay, controller delay, regulation time and maximum distance of COP respectively.

Table.1 Simulation Results about Case 1.

S-delay τ_1 (s)	**RT (s)**	**MD (cm)**
0.1	5.9	4.6
0.2	6.8	4.7
0.3	7.8	3.9
0.4	12.3	3.8
0.5	13.1	3.7
0.6	×	×

Table.2 Simulation Results about Case 2.

C-delay τ_2 (s)	**RT(s)**	**MD(cm)**
0.1	7.0	4.2
0.2	6.8	4.7
0.3	5.9	5.8
0.4	4.9	6.8
0.5	7.2	7.6
0.6	×	×

Nearly all the regulation time is within the ranges from 5.8s to 13.1s, and maximum distance of COP is within the ranges from 4cm to 7.6cm. In the simulation results, × means the system becomes unstable. In other words, the student may not withstand a delay more than 0.6s. The average changing rate of the simulation results obtained with the formula:

$$\varphi=\left(\sum_{2}^{N} a_i - a_{i-1}\right)\Big/(N-1) \tag{17}$$

where, φ average changing rate; a_i is the sample value, and N is the sample number. Fig. 4 shows the correlations between the simulation results and time-delay respectively.

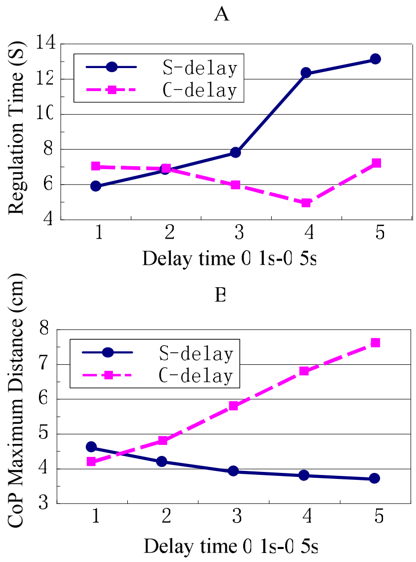

Fig.4 (A) the curve of regulation time about various delay. The horizontal axis indicates the S-delay and the C-delay, values were 0.1-0.5s; The vertical axis indicates the RT; Blue Line represents case1; red line represents case2. (B) The curve of the maximum distance COP about various delay. The horizontal axis indicates the S-delay and the C-delay, values were 0.1-0.5s; The vertical axis indicates the COP MD; Blue Line represents case1; red line represents case2.

From Fig. 4, we could conclude as following. The state delay τ_1 is proportional to regulation time, and the average change rate $\varphi=1.85$, however, controller delay τ_2 do not have the obvious effect to regulation time, whose average change rate $\varphi=0.1$. Fig.4.b shows the curves of the maximum COP distance affected by both different delays. Controller delay τ_2 has a significant positive relationship with COP maximum distance, and the average change rate is $\varphi = 0.85$. In addition, with the state delay increasing, the maximum distance COP is reduced, where the average changing rate is -0.225. The magnitude is small enough to be ignored.

5. Conclusions and Discussions

The purpose of the study was to develop a balance control model based on robust controller, which can reflect the human system with serious multi-source time delay in reality. The robust controller, which has a fixed gain vector K and a observer, can keep a system to stable with larger delay under strong interference. Of course, this is just a functional approximation, when the human body is assumed to be a black box. There are many deficiencies in the hypothesis model of human body, such as a larger gain K may result in ankle moment beyond the capability of the joints, but these deficiencies will be refined in our future studies. Anyway, the presented human balance control model indeed established a quantitative relationship between the changing trends of balance ability and multiple delays which exist in human body.

We designed the musculoskeletal model with muscle viscous force, which was related to the angular velocity of the ankle joint. The muscle viscous force is delay independent, but there are different time-varying delays within inertial force, gravity, and the controller inputs. By analyzing the above simulation results, we can visually see the controller time delay is proportional to maximum COP distance responding to the stimulation. According to the principle of human balance, The COP changing distance can not be out of the plantar stability region, otherwise the body will either fall down or step forward to maintain a balance posture. Therefore, we can conclude that: Human balance capacity is mainly affected by the impact of the amount of the controller delay. Larger controller delay can make the body lose standing balance, and the controller delay must be in a reasonable range. This conclusion also verified the conclusions in paper [7, 8].

Large state delay may be due to illness or disability, which is proportional to regulation time of human recovery stable posture. It means that human body need a large response time for the muscle activation. Some researchers [21, 22] used the hill model to study the relationship between bio-electrical signals and muscle forces, in which it assumed that the muscle activation characteristics satisfy an S-shaped curve. This derivative of the S function can be represented as the speed of human muscle activation. For athletes, the state delay determines the accuracy of posture in a short time. If one has a faster muscle activation speed, the state delay will decrease, which means he/she has a better performance in balance regulation. This performance could be improved through exercise.

References

[1] VDK Herman, J Ron, K Bart, G Henk, "A multisensory integration model of human stance control" Biological Cybernetics vol.80, No.5, 1999, pp.299-308.
[2] PA Fransson, M Magnusson, R Johansson, "Analysis of adaptation in anteroposterior dynamics of human postural control" Gait and Posture Vol. 7, No. 1, 1998, pp.64-74.
[3] Kuo, AD, "An optimal control model for analyzing human postural balance." IEEE Transactions on Biomedical Engineering, Vol. 42, No. 1, 1995, pp.87-101.
[4] Kuo, AD, "An optimal state estimation model of sensory integration in human postural balance" Journal of Neural Engineering, Vol. 2, No. 3, 2005, pp.S235-S249.
[5] K Masani, AH Vette, MR Popovic, "Controlling balance during quiet standing: Proportional and derivative controller generates preceding motor command to body sway position observed in experiments" Gait and Posture, Vol.23, 2004, pp.164-172.
[6] Y F Jiang and H Kimura, "A PID Model of Balance Keeping Control and Its Application to Stability Assessment in Proc. IROS", 2006, pp.5925-5930.
[7] Jo S, Massaquoi, SG, "A model of cerebellum stabilized and scheduled hybrid long-loop control of upright balance" Biological Cybernetics, Vol. 91, No.3, 2004, pp.188-202.
[8] Qu X, Nussbaum, MA, Madigan, ML, "A balance control model of quiet upright stance based on an optimal control strategy" Journal of Biomechanics, Vol.40, No.16, 2007, pp.3590-3597.
[9] Yoshiyuki A, Yuichi T, "Model of Postural Control in Quiet Standing: Robust Compensation of Delay-Induced Instability Using Intermittent Activation of Feedback Control" Plos One July 8, 2009.
[10] Peter G, Ian L, Martin L, "Predictive feedback in human simulated pendulum balancing" Biological Cybernetics, Vol.101, 2009, pp.131-146.
[11] John M, Juan LC, et al, "The time-delayed inverted pendulum: Implications for human balance control" CHAOS Vol.19, No.026110, 2009, pp.1-12.
[12] P. Gatev, S. Thomas, T. Kepple, M. Halett, "Feedforward ankle strategy of balance during quiet stance in adults" J. Physiol, Vol.514, No.3, 1999,pp.915–928.
[13] Robert J, Schilling S, Charles JR, "A Phase-Locked Loop Model of the Response of the Postural Control System to Periodic Platform Motion" IEEE Transactions on neural systems and rehabilitation engineering, Vol.18, 2010, pp.274-283.
[14] ID Loram, PJ Gawthrop, M Lakie, "The frequency of human, manual adjustments in balancing an inverted pendulum is constrained by intrinsic physiological factors " The Journal of Physiology, Vol.577,2006, pp.417-432.
[15] H C Diener, J Dichgans, et al, "On the role of vestibular, visual, and somatosensory information for dynamic postural

control in humans" Progress in Brain Res Vol.76, 1988, pp.253-262.
[16] Kreinder E, Jameson A "Conditions for nonnegativeness of partitioned matrices" IEEE ransactions on Automatic Control Vol.17, pp.147-148.
[17] Boyd SP, Ghaoui LE, et al, "Linear matrix inequalities in system and control theory" Philadelphia, PA:SIAM, 1994.
[18] Yasuyuki S, Taishin N, Maura C, Pietro M, "Intermittent control with ankle, hip, and mixed strategies during quiet standing: A theoretical proposal based on a double inverted pendulum model" Journal of Theoretical Biology, Vol.310,No.7, 2012, pp.55-79.
[19] Gahinet P, Nemirovski A, et al, "LMI control toolbox user's guide"The Mathworks, Inc, 1995, pp. 8.1-8.35.
[20] Sharon MH, Joyce F, Fay BH, "Control of Stance During Lateral and Anterior/Posterior Surface Translations" IEEE Transactions on rehabilitation engineering, Vol.6, No.1, 1998, pp.32-42.
[21] Rositsa TR, Boris IP, "Sensitivity of predicted muscle forces to parameters of the optimization-based human leg model revealed by analytical and numerical analyses" Journal of Biomechanics Vol.34, No.10, 2001, pp.1243–1255.
[22] Ahmet E, Scott M, Walter H, "Model-based estimation of muscle forces exerted during movements" Clinical Biomechanics Vol.22, 2007, pp.131-154.

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