

A DYNAMIC MODEL OF BODY SWAY CONTROL DURING UPRIGHT STANCE IN HUMAN

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Abstract

The aim of this study is to establish a new dynamic model for balance keeping control in upright standing; and to deduce the underlying possible control mechanism of central neuronal system with a special concern on the roles of pelvis and its muscles. The dynamic model including five joints, i.e. two ankles, two hips and one lumbosacral making up a multi-link system being driven by two pairs of muscles, the psoas major (PM) and gluteus medius (GM). In coronal section, experimental data shows the ankle and lumbosacral sway in almost the same amplitude, whereas their phase difference is approximately equal to π . The results indicate that the trunk is keeping perpendicularly to horizon during the standing process. By defining the model's physical parameters, assuming that the corrective torque needed for balance keeping process is regulated by PID (stands for proportional, integral and derivative) control, the body sway can be simulated. The simulation result is quite consistent with the experimental data suggests that the pelvis is one of the most important structure in balance keeping, moreover, the dynamics of the present proposed balance keeping model is a quite useful model for analyzing the posture sway.

(Jpn. J. Phys. Fitness Sports Med. 2006, **55** Suppl : S231~S236)

key word : Body sway, PID control model, Pelvis, psoas major, gluteus medius

I. Introduction

Upright stance is inherently unstable. Small deviation from an upright body position results in a gravity-induced torque acting on the body, causing it to accelerate further sway from the upright position. The mechanism underlying spontaneous body sway has not yet been fully understood. A problem arises as how our nervous system controls muscles to produce corrective torque to keep the body balanced, which is an important issue for postural stability evaluation^{1,2)}.

Inverted pendulum models, from single-link to multi-link, are widely adopted for dynamics analysis of upright stance^{2,3)}. It is argued that the lumbosacral and ankle joints play crucial roles in balance control in upright standing. However, which muscles are involved and how those muscles are controlled, are still unknown.

In this study, we aim to use a high-resolution optical system to measure lumbosacral, and ankle motion in roll plane in order to establish a PID

(stand for proportional, integral, derivative) model ; and using the relevant data to elucidate the underlying mechanism of the spontaneous body sway.

II. Methods

A. Postural sway assessment

1) *Subjects* : Eight healthy subjects took part in the study. Subjects ranged in age from 19 to 38 years (averaged 25.0 ± 7.52 year) and had no known musculoskeletal injuries or neurological disorders that might affect their ability to maintain balance. Their averaged height was 166.3 ± 6.9 cm, and averaged weight was 60.1 ± 7.2 Kg.

2) *Measuring device and Procedure* : A body sway-measuring device was assembled, which can record and analyze multi-channel video signal online (Fig. 1). This device includes three high-resolution CCD video cameras (DSR-PD150, Sony Co. Tokyo Japan) and one personal computer that were used for video signal recording and image processing, respectively⁴⁾. Three markers (black ball, 3.0 cm in diameter) were used for imaging, with one on subjects' back

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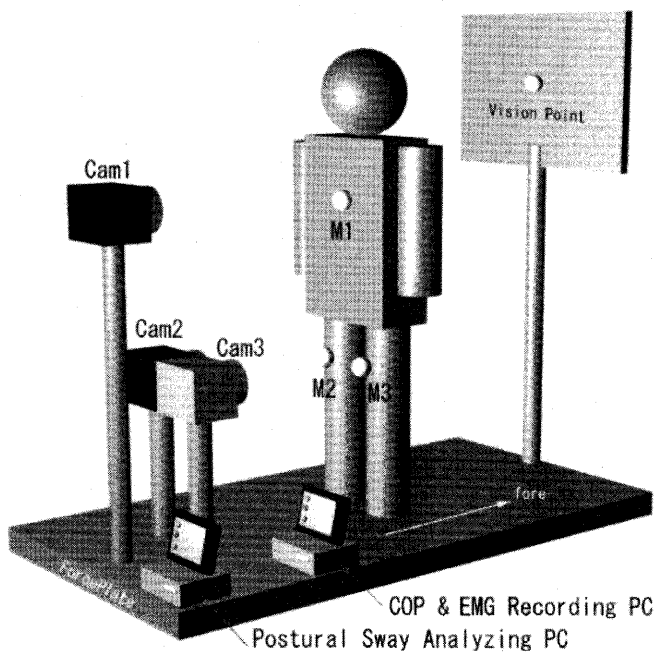


Fig. 1. The scheme of the postural sway analyzing device.

and two on the legs at the height of 10 cm above the knee joint. One piece of forceplate (9281C/CA, Kistler, Switzerland) was installed for center-of-pressure (COP) assessment. During the assessment, subjects were told to stand on the forceplate and glance at a marker that was put on the front wall at the same level of their eyes.

The body sway was analyzed automatically by a computer program. Body sway in lateral direction was preferred and modeled as a two-link inversed pendulum. The first link was ankle joint and the second was lumbosacral joint. The angular movement of the first link was calculated as the average of the two legs, and the movement of the second link was calculated simultaneously as follows (Fig. 2)

$$x_1 = l_1 \sin \theta_1 \quad (1)$$

$$x_2 = L_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) \quad (2)$$

Because the angular scope is small, we set $\sin \theta_1 = \theta_1$, $\sin(\theta_1 + \theta_2) = \theta_1 + \theta_2$ then

$$\theta_2 = \left(\frac{x_2}{L_1 + l_2} - \frac{x_1}{l_1} \right) \left(1 + \frac{L_1}{l_2} \right), \quad (3)$$

which gives the angular sway of lumbosacral joint.

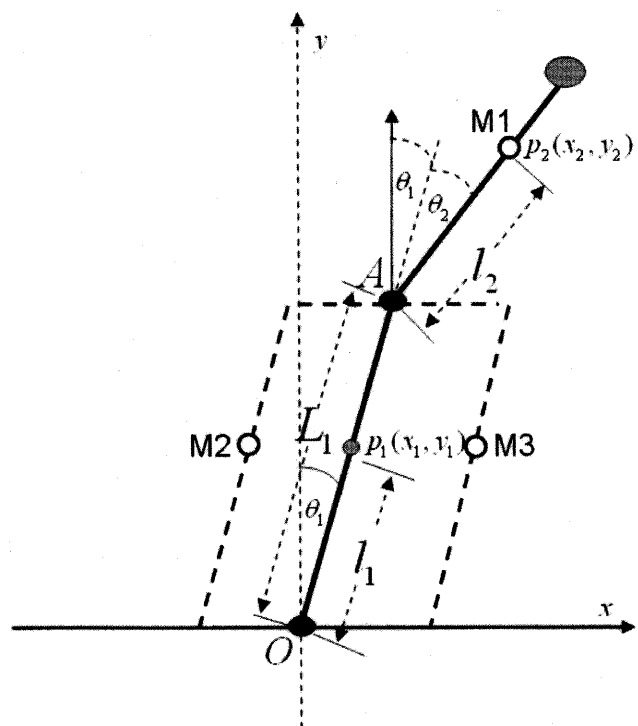


Fig. 2. Geometry of sway angles during static upright stance.

B. Surface electromyography (sEMG) recording

Gluteus medius (GM) activities were recorded by sEMG. When identifying the contraction of belly, the electrodes (Vitrode F-150M: Nihon kohden Co. Tokyo) were put on the center of the belly (separating about 2.6 cm). Skin was cleared until the impedance between the two electrodes was below 10 K. sEMG signal was amplified (frequency band set to 50-1000 Hz, MEG-6180, Nihon kohden Co. Tokyo) and A/D converted (Sampling 400 Hz, AD-12/8PM, Contec Co. Osaka Japan). The recorded data were stored on a hard disk for offline analysis.

III. Results

A. Body sway during upright stance

The angular movement scope of ankle and lumbosacral were $0.94 \pm 0.36^\circ$ (eye-open), $1.35 \pm 0.52^\circ$ (eye-closed) and $0.99 \pm 0.41^\circ$ (eye-open), $1.27 \pm 0.72^\circ$ (eye-closed), respectively. No significant difference existed between the ankle and lumbosacral. The results suggest that ankle and lumbosacral sway in almost the same degree. Further analysis of Fourier transform showed that the phase differences

between ankle and lumbosacral were approximately equal to π , i.e. ankle sway in opposite direction to the lumbosacral.

B. Positive muscular electricity activities were recorded from left and right GM.

The results showed that COP deviation was good related to GM contraction. When COP moves to the left, the left side of GM was activated, and vice versa. This indicated that left and right GM contracted alternately while COP deviated in the same side.

C. Pelvis structure and model in upright stance

Pelvis is composed of four irregular bones : two hip bones laterally and in front the sacrum and coccyx behind. Sacrum articulated with vertebral column formed lumbosacral joint, and also make joint with two femurs formed hip joints. Muscles associated with lumbosacral are mainly ascribed to two pairs : posas major and posas minor, and in addition, the erectors too. Indeed, since many other muscles surrounding hip joint are involved, it is difficult to deal with each individual muscle separately.

The characteristic structures of femur are formed by its head, greater trochanter and lesser trochanter. The greater trochanter serves as the insertion of the tendon of the GM. The lesser trochanter gives insertion to the tendon of the (psoas major) PM. The shape of femur looks like a letter "Y".

Based on the structural characteristics of pelvis, lumbosacral, hip and femurs, an upright body model was constructed. In this model, pelvis is expressed as a triangle connecting vertebral column and femurs with lumbosacral joint and hip joint, respectively and driven by two symmetrical pairs of actuators, the PM and GM which form a closed multi-link system. In order to make the dynamics analysis concise, the distance between two feet was supposed equal to the distance between the two hip joints. Thus, the aim of central nerve system is to keep the angles of θ_1 and θ_2 to be zero, i.e. to keep the body upright.

From the structural model of body (Fig. 3), the position of vertical projection of COM (V_{cop}) can be calculated as equation (4)

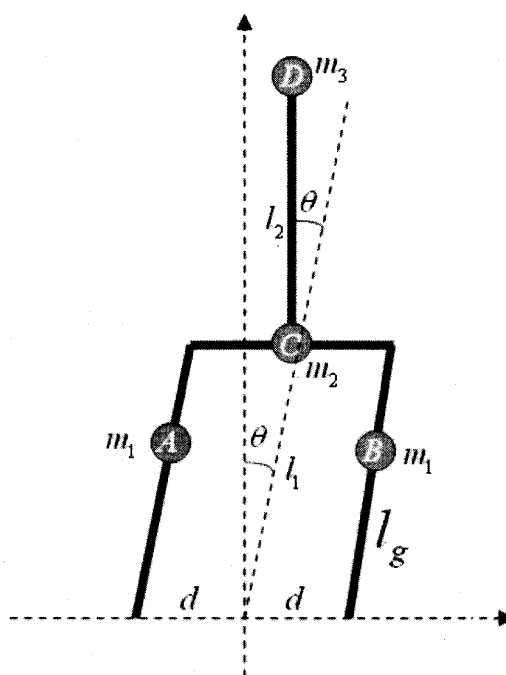


Fig. 3. Simplified pelvic structural model.

$$V_{cop} = \frac{1}{M} [m_3(h_1 + h_2) + (m_1 + m_2)h_3 + 2m_1l_2] \begin{bmatrix} \theta_2 \\ \theta_1 \end{bmatrix} \quad (4)$$

($M = m_1 + m_2 + m_3$, h_3 : height of pelvis), where the inertia is neglected.

Balance cannot be maintained if $|V_{cop}| > d$, or fall may happen. In other words, upright stance is only possible under the condition

$$|V_{cop}| \leq d. \quad (5)$$

D. Dynamics

Because the angular movement scope in ankle is approximately equal to the sway scope in lumbosacral, and their phase difference is nearly π , the relationship of sway angles between ankle and lumbosacral can be simplified as (Fig. 2)

$$\theta_1 = -\theta_2 \quad (6)$$

Equation (6) indicates that the trunk of body is always keeping vertical to the horizon. Based on this fact the structure model of body can be constructed as a multi-link inverted pendulum (Fig. 3).

In this model, PM and GM are actuators. Right GM and left PM activate simultaneously, which is an agonist against left GM and right PM. The dynamics

can be derived from Lagrangian equation. The result is given as follows

$$\tau = [2m_1 l_g^2 + (m_2 + m_3) l_1^2] \ddot{\theta} - [2m_1 l_g + (m_2 + m_3) l_1] g \sin \theta \quad (7)$$

(τ : torque generated by GM and PM)

E. PID control and simulation

Static balanced stance is controlled by central nervous system. It is widely accepted that corrective torque is generated by feedback; input sources include visual, proprioceptive and vestibular system. Fig. 4 shows the block diagram of the postural sway feedback control.

Central nervous system calculates the error (the reference should be the upright stance, where $\theta = 0$), sets the output strength, then activates the PM and GM to generate the corrective torque to minimize the error. If the relation (6) holds consideration, upright stance is maintained. Based on physiological view, we proposed a PID feedback control mechanism for the corrective torque generating process (equation 9).

$$e(t) = r(t) - \theta(t); \quad (r(t) = 0) \quad (8)$$

$$\tau(t) = \begin{cases} K_p e(t - t_d) + K_I \int_0^t e(t - t_d) dt + K_D \frac{de(t - t_d)}{dt}; & (|e(t - t_d)| > \zeta) \\ 0; & (|e(t - t_d)| \leq \zeta) \end{cases} \quad (9)$$

Here, t_d is the time lag, and ζ represents the threshold. When $t_d = 0$, $\zeta = 0$, insertion of (9) in (7) yields

$$-K_p \theta - K_I \int_0^t \theta(t) dt - K_D \dot{\theta} = [2m_1 l_g^2 + (m_2 + m_3) l_1^2] \ddot{\theta} - [2m_1 l_g + (m_2 + m_3) l_1] g \sin \theta \quad (10)$$

By Laplace transforms of equation (10) gives

$$\theta(s) = \frac{Is\dot{\theta}(0) + (Is^2 + K_D s)\theta(0)}{Is^3 + K_D s^2 + (G + K_P)s + K_I} \quad (11)$$

$$(I = 2m_1 l_g^2 + (m_2 + m_3) l_1^2; G = -[2m_1 l_g + (m_2 + m_3) l_1] g; \sin \theta = \theta)$$

The stability conditions are $K_D > 0$ and $K_P > G$.

When t_d , ζ are not zero, defining the initializing functions of $\theta(t)$, $\dot{\theta}(t)$, body sway can be simulated. The result showed a well agreement between simulated and measured. By including an internal random disturbance torque, this model generates sway patterns that more resembles spontaneous sway (details are not shown).

IV. Discussions

Details of central nervous system on our body's balance controls are still unknown⁵⁾. However, we can simplify and linearize its control procedure like PID^{6,7)}. Parameters of PID control seems physiologically correspond to three feedback sources of vestibular, visual and proprioceptive. K_D was decreased when eyes were closed while K_P was unchanged (unpublished data). It suggests that the function of visual feedback is similar to a damper that sensitive to velocity.

Anatomically, PM and GM are the main actuators being responsible in controlling the body sway in lateral direction. PM connected to vertebral column and lesser trochanter and GM connected to pelvis and greater trochanter, the coordination of the two

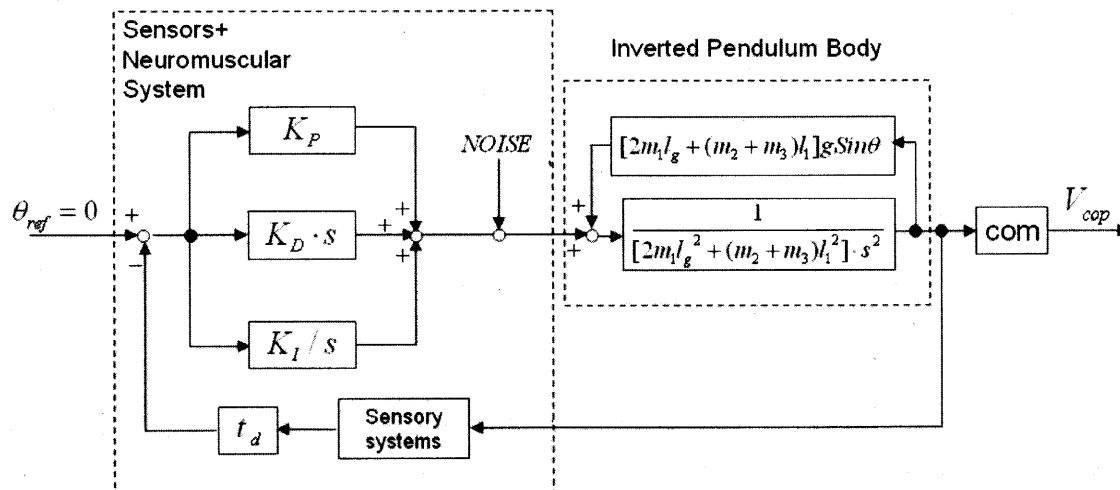


Fig. 4. A block diagram of humans' static upright stance control.

muscles controls the motion of ankle and lumbosacral joint. Because the trunk is kept perpendicular to the floor, it is observed that the right GM and the left PM contracted reciprocally with left GM and right PM. Due to technical difficulties, we only recorded the sEMG of GM in this study. Many muscles relate to the motion of pelvis. Because those muscles contract synergistically, here, we ascribed the total effect of those muscles to PM and GM for simplicity.

We proposed the model of human body as a two-link inverted pendulum. It is assumed that the balance is maintained by PID control in upright stance. The results showed that the ankle and lumbosacral joints sway in the reverse phase and in the same amplitude. This indicates that the trunk is always perpendicular to the floor during upright stance (Fig. 3).

Because the simulation results are quite consistent with experimental data, especially when we consider an internal random disturbance, the PID control seems to be a reasonable means for postural sway study. Many authors have suggested that complex architectures including feed forward/feedback is necessary for the maintenance of upright stance, but this study together with some other recent studies have shown that a model based primarily on a sim-

ple feedback mechanism with 120-ms to 150-ms time delay can account for postural control during a broad variety of disturbance.

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