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Balance-Keeping Control of Upright Standing in Biped Human Beings and its Application for Stability Assessment

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1. Abstract

One of the most important tasks in biped robot is the balance-keeping control. A question arisen as how do our human beings make the balance-keeping possible in upright standing as human beings are the only biped-walking primates, which takes several million years of evolution period to achieve this ability. Studies on humans' balance-keeping mechanism are not only the work of physiologists but also a task of robot engineers since bio-mimetic approach is a shortcut for developing humanoid robot. This chapter will introduce some research progresses on balance-keeping control in upright standing. We will introduce the physical characteristics of human body at first, modeling the physical system of body, establishing a balance-keeping control model, and at last applying the balance-keeping ability assessment for falls risk prediction. We wish those studies make contributions to robotics.

2. Introduction

Scientist's interest and fascination in balance control and movement has a long history. Leonardo da Vinci emphasized the importance of mechanics in the understanding of movement and balance, wrote that "Mechanical science is the noblest and above all the most useful, seeing that by means of it all animated bodies which have movement perform all their actions[1]". In 1685, by using a balance board, Italian mathematician Johannes Alphonsus Borelli, in his "De motu animalium", determined the position of the center of gravity as being 57% of the height of the body taken from the feet in the erect position. Those early studies on human body mechanics determining the inertial properties of different body segments serve an important and necessary role in modern biomechanics.

Not like static upright stance in biped robot, upright standing in human is a high-skill task needed a precise control. In 1862 Vierordtand later Mosso (1884) demonstrated that normal standing was not a static posture but rather a continuous movement. Kelso and Hellebrandt in 1937 introduced a balance platform to obtain graphic recording of the involuntary postural sway of man in the upright stance and to locate the centre of weight with respect to the feet as a function of time. Using a force analysis platform and an accelerometer,

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Whitney[2] (1958) concluded that the movement of the center of foot pressure must exaggerate the accompanying movement of the center of gravity of the body mass. Based on those studies, postural sway is regarded as presenting at the hip level suggests that the trunk rotates relative to the limbs during standing.

In other hand, clinical significance of postural sway was first observed by Babinski in 1899. He noted that a patient with the disorder termed "asynerhie cerebelleuse" could not extent his trunk from a standing position without falling backwards. He concluded that the ankle must perform a compensatory movement to prevent the subject from falling backwards. Thus, Babinski was one of the first to recognize the presence of an active postural control of muscular tone and its importance in balance control and in voluntary movements.

Modern theory on postural control was established on the work of Magnus[3] and De Kleijn[4]; they proposed that each animal species have a reference posture or stance, which is genetically determined. According to this view, postural control and its adaptation to the environment is based on the background postural tone and on the postural reflexes or reactions, which are considered to originate from inputs from the visual[5], vestibular[6] and proprioceptive[7] system. The gravity vector is considered to serve as a reference frame. The center nervous system needs to accomplish two tasks related to the force of gravity. First, it must activate extensor muscles to act against the gravity vector, creating postural tone. Second, it must stabilize the body's centre of gravity with respect to the ground.

Many studies[8-10] on balance-keeping control have been published in recent two decades. A lot of theoretical control models have been proposed for elucidating the body sway phenomenon during upright standing. Among them, Inverted pendulum is the most popular model for body sway analysis. However, those studies are seldom considered individual's physical conditions, and one-link inverted pendulum is dominated. However, a practicable control model for humans' balance-keeping ability assessment is still unavailable. For this reason, we proposed a PID model of upright standing, and a reality-like body sway was simulated. This chapter presents some recent research results in our laboratory in balance-keeping control and emphasizes its application for fall risk prediction in fall-prone subjects.

3. Upright Standing and Body Sway

Force-plate is a popular device for postural sway measurement[11]. A force-plate usually installs three or four force sensors for ground reaction force measurement. The center of ground reaction pressure (COP) can be calculated automatically by a computer program. However, COP is not equal to body sway because body's inertia is an important factor which influences the deviation of COP[12]. We developed an optical measuring system, which can directly record the trunk sway.

The body sway-measuring system was designed to record multi-channel video signal simultaneously (Fig.1). This device included three high-resolution CCD video cameras and one personal computer that were used for video signal recording and image processing. Three markers (white ball, 3.0cm in diameter) were used for imaging recognizing with one being put on subjects' back and two being put on legs 10cm above about the knee joint, and on the floor, a force-plate was installed for COP deviation assessment. During the measuring, subjects were told to stand on the force-plate and glance at a marker put on the front wall in the same level of their eyes.

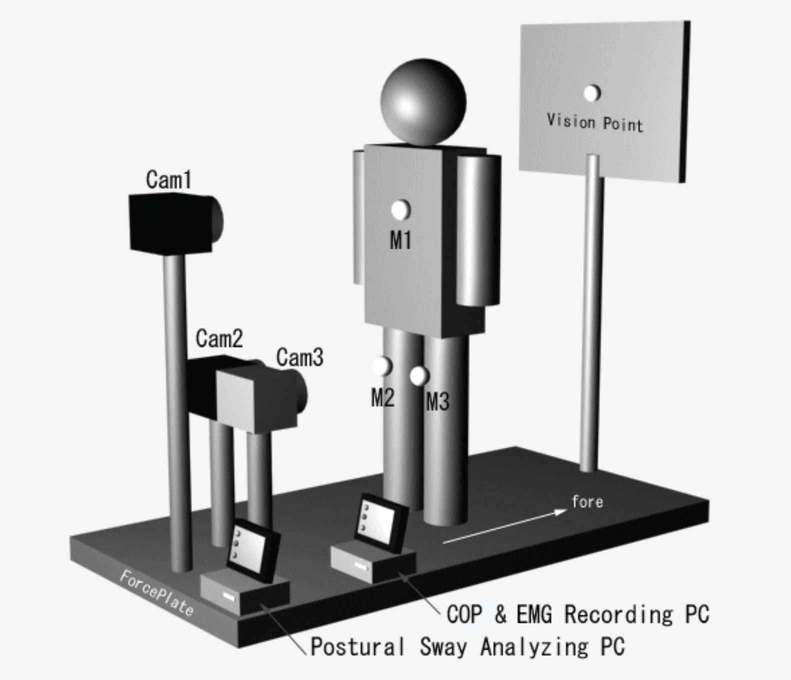

Fig.1. The scheme shows of the body sway-measuring device. The device consists of three high-resolution CCD cameras (Cam1, Cam2 and Cam3) and a whiteboard. A white ball with diameter of 1.0cm was put on the whiteboard in subject's eye level. During the measurement, subjects were asked to fix their eyes on the ball. Postural sway analyzing was executed on one desktop PC, and an EMG recording PC was also installed too.

In this study, body sway in lateral direction was recorded and the body was regarded as two-link inversed pendulum. The motion of the first link was on ankle and the second link was on lumbosacral. The angular sway of the first link was measured as the averaged value of the two legs and the angular sway of the second link was calculated indirectly as shown in Fig.2, where point O is the ankle joint and point A is the lumbosacral joint. P1 represents the marker of legs and P2 represents the marker of subject's back. There have

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

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

Because the angular deviation scope is relatively small (usually < 2.0 degree), then we set $\sin\theta_1 = \theta_1, \sin(\theta_1 + \theta_2) = \theta_1 + \theta_2$ approximately, and θ_2 can be calculated as equation (3),

$$\theta_2 = (\frac{x_2}{L_1 + l_2} - \frac{x_1}{l_1})(1 + \frac{L_1}{l_2}). \qquad (3)$$

Here, we defined the height of lumbosacral as L_1, which is the distance from floor to 5th lumbar spine. The entire calculations can carried out online. Subjects kept a static upright stance on the force-plate with eyes open or eyes closed. For minimizing psychological influence, subjects were asked to numerate on mind while doing standing task.

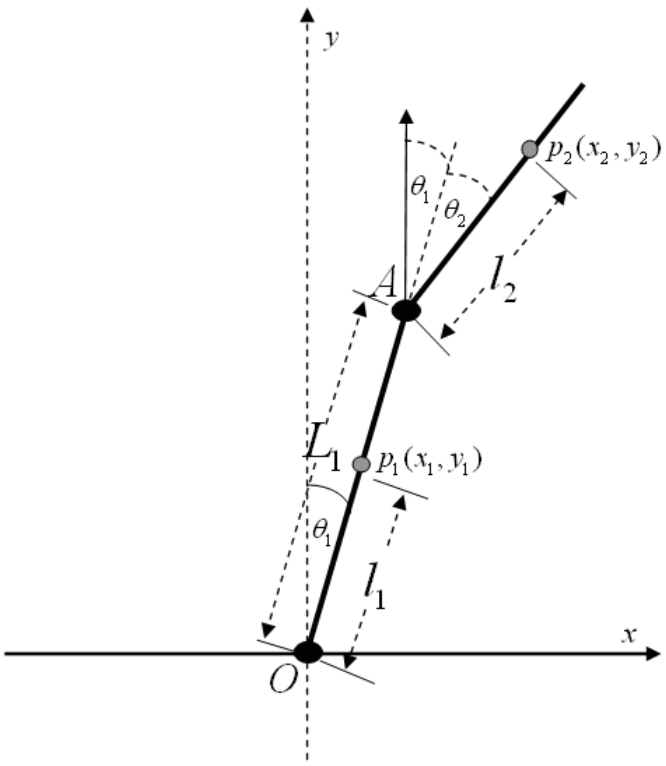

Fig.2. Relation of the sway angles during static upright stance. Points P1 and P2 are the positions of the markers, their coordinates can be calculated by the CCD video camera measuring system. Points O and A represent are the ankle joint and lumbosacral joint respectively. θ_1 is the angular sway of the ankle joint, and θ_2 is the angular sway of the lumbosacral joint. The postural sway is considered only in coronal direction.

A study from eight healthy young subjects[13] shown that the body sways scope of ankle and lumbosacral were 0.94±0.36degree (eye-open), 1.35±0.52degree (eye-closed) and 0.99±0.41degree (eye-open), 1.27±0.72degree (eye-closed), respectively. No significant difference existed between the ankle and lumbosacral. The ankle and lumbosacral sway approximately in the same degree during the static upright stance. Further more, Fourier transform of the sway time series showed that the phase differences between ankle and lumbosacral were approximately equal to π, i.e. i,e, ankle sways in opposite direction to the lumbosacral. The results help for establishing a structural inverted pendulum model.

We also analyzed the relationship between trunk sway and deviation of COP[12]. By setting $y(t)$ as the deviation of COP, $u(t)$ as the trunk sway, an approximate equation can be acquired, $y(t) \approx k\ddot{u}(t) + hu(t)$, where, k, h are constants. The result proven that COP deviation is different with trunk sway, and body's inertia effect does added on the effect of COP deviation as Whitney pointed out[5].

4. Musculoskeletal System of Human Body

From the viewpoint of structural specificity of the human body, pelvis and ankle are two major structures that play a pivotal role in balance control, the pelvic strategy and ankle strategy as hereby defined.

Human 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 (Fig.3a). Muscles associated with lumbosacral are mainly ascribed to two pairs: posas major (PM) and glutaeus medius (GM), and in addition, also the erectors. In fact, many muscles surround hip joint are involved in the joint movement, and because the synergic effect[14, 15] of muscles' activity, it is difficult to deal each individual muscle separately. For model's simplicity, two pairs of muscles are selected for representing the total muscles' effects in the lateral direction movement (Fig.3a), i.e. PM and GM. It is regarded that the movement of lumbosacral is controlled by PMs and GM. This assumption can well explain the relationship between GM contraction and COP deviation in coronal direction.

The characteristic structures of femur are its head, greater trochanter and lesser trochanter. The greater trochanter is a large, irregular, quadrilateral eminence, situated at the junction of the neck with the upper part of the body, serves as the insertion of the tendon of the GM. The Lesser Trochanter is a conical eminence, projects from the lower and back part of the base of the neck, gives insertion to the tendon of the PM. The shape of femur looks like a letter of "Y" (Fig.3b). Based on the structural characteristics of pelvis, lumbosacral, hip and femurs an upright body model was constructed (Fig.3c). 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, form a closed multi-link system. In order to make the dynamics analysis concisely, the distance between two feet was supposed equal to the distance between two hip joints. Thus, the aim of central nerve system is to keep the angles θ_1 and θ_2 to be zero, i.e. to keep the body upright (Fig.3c).

From the structural model of body the position of vertical projection of center-of-mass (COM) defined as V_{cop} which can be calculated as equation (4).

$$V_{com} = \frac{\sum_i m_i g V_{m_i}}{\sum_i m_i g} \tag{4}$$

When $|V_{com}| > d$, upright standing is impossible and falls may happen. In other words, upright stance is possible only when

$$|V_{com}| \le d. \tag{5}$$

Because the angular sway scope in ankle is approximately equal to the sway scope in lumbosacral, and their phase difference is π, the relationship of sway angles between ankle and lumbosacral can be considered as (Fig.3c)

$$\theta_1 = -\theta_2. \tag{6}$$

Equation (6) also indicates that the trunk of body is always keeping perpendicular to the horizon. Based on this fact the structure model of body can be simplified as be shown in Fig.4.

In this model, PM and GM are the actuators keeping the inverted pendulum to be balanced. By intuition, right GM and left PM should activate simultaneously, which is an agonist against left GM and right PM. Its dynamics can be deduced by Lagrangian equation as equation (7).

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

(τ : The torque generated from activities of GM and PM)

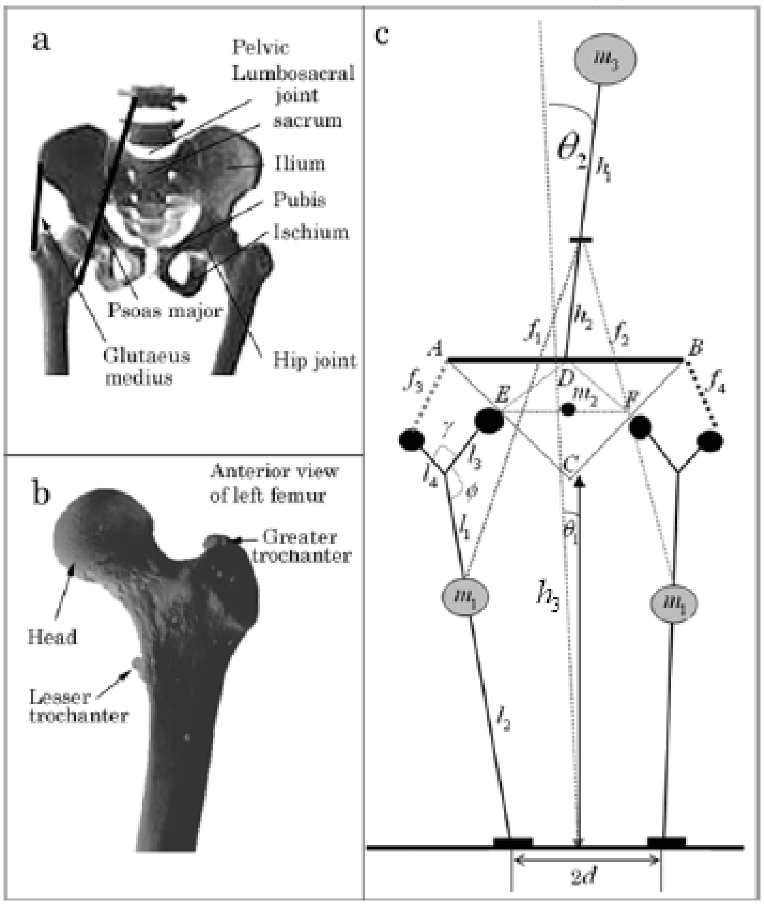

Fig.3. The pelvic anatomical structure and its responding structure model during static upright stance. The pelvic is fused by four bones, the sacrum, ilium, pubis and ischium, which linked with 5th lumbar spine and femur through lumbosacral and hip joint (a). The femur includes a head that is articulated with ilium and a greater trochanter and lesser trochanter where the GM and PM terminated (b). The structural model of pelvic is schemed (c). f_1, f_2 are the forces produced by PM, and f_3, f_4 are produced by GM. m_1, m_2 and m_3 represented the mass of lower leg, pelvic and upper body respectively. θ_1 is the sway angle of leg and θ_2 is the sway angle of upper trunk.

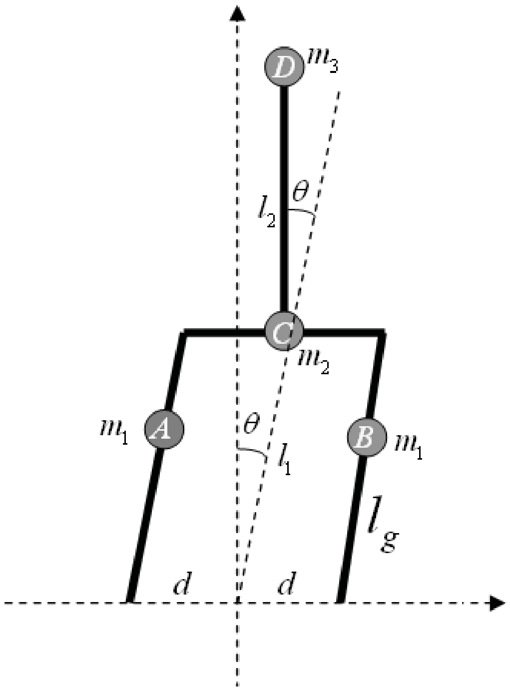

Fig.4. A simplified pelvic structural model during static upright stance. A, B are the masses of leg, C is the mass of pelvic and D is the mass of upper trunk. Because the lumbosacral always sways in inverse direction of the ankle joint with the same value of θ, the upper trunk is kept perpendicular to the horizon.

5. The Roles of Foot in Balance Control

Feet are special structure that evolved fit for standing and locomotion. The anatomy structure of human feet is quite complex which make up of a doze of muscles and near thirty bones. When subject stand on one foot, brisk EMG activities can be recorded on the surface of muscles around the ankle joint[16], by contrast, nearly no EMG activities can be recorded while standing on two feet. Using a force sheet to measure COP deviation, we recorded the surface EMG activities of m. tibialis anterior (TA), m. peroneus longus (PL) and Caput mediale m. gastrocnemii (MG) when asked subjects standing on one foot. The relationship between COP deviation and muscular activities was identified[13] (Fig.5). Based on the experimental data we established a model of muscular control of the COP deviation (Fig.6). Briefly, the ground reaction under the foot can be concentrated to three points; one is situated on the heel the other two are situated on the root of thumb and little figure respectively, which making up a triangle. The ground reaction forces acting on the vertex of the triangle are controlled by TA, PL and MG respectively as shown in the figure 6, which keeping the COP located in the scope of the triangle to make the inverted body balanced.

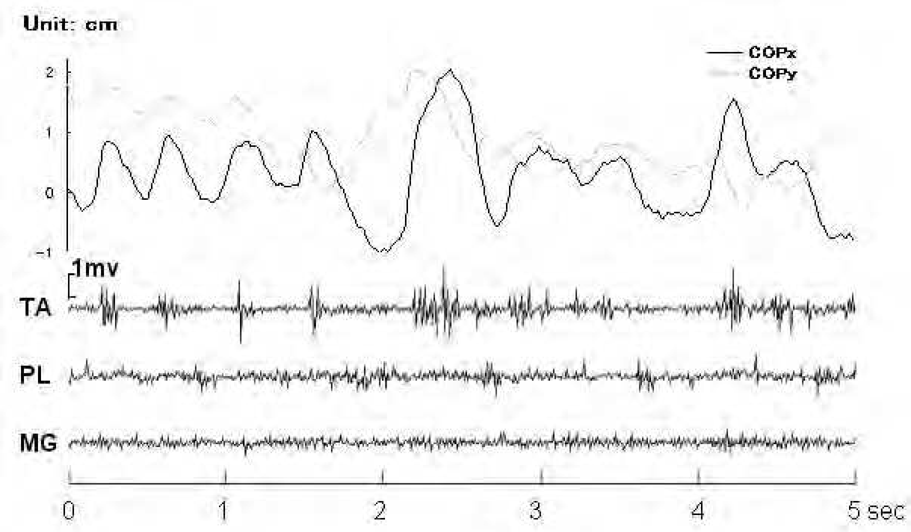

Fig.5. Showing COP deviation and surface EMG recordings from TA, PN and TS when standing on one foot. The COPx (coronal section) is closely related to TA and PN contraction.

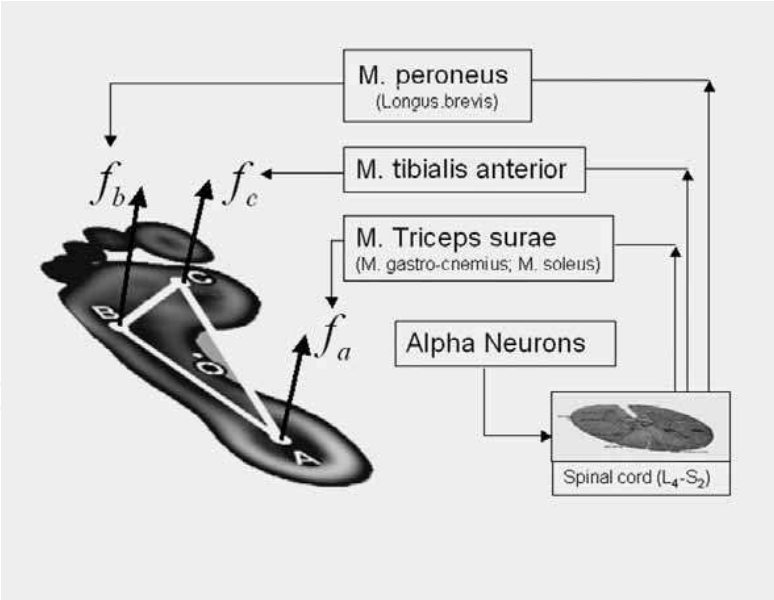

Fig.6. The model of COP control when standing on one foot. The scheme shows how the force under the three points is controlled by muscular contraction. Supposing the forces act on the three points as f_a, f_b and f_c, then the muscles bear the responsibility should be PN, TA, and TC respectively. The three muscles are innerved by neurons located at the L4-S2 level.

Nervous commands come from cerebral cortex reached to alpha motor neurons of the spinal anterior column to control the muscles around ankle joint to keep the body balanced. This kind of balance-keeping control is ankle strategy of balance control. In contract, nervous commands come from cerebrum to control the muscles around pelvis joints to keep the body balanced, hereby defined as pelvis strategy. It seems that the balance-keeping strategy is transformed from ankle to pelvis when the standing posture changes from one foot to two feet of upright standing.

Generally, the contact areas of the feet and ground play a key role in the static upright standing, with the more contact areas the feet have, the more stable of the posture[17] Will be. The contact surface is a polygon. Their vertexes are the contact points receive ground reaction force, and the area of the polygon was defined as effective contact area (Fig.7). What important is the physical stability of the inverted body, which determined by the height of the COM and the effective contact area of polygon. By defining the effective contact areas as s , the body mass as m and the height of COM as h, then $C = mgh/\sqrt{s}$ is an constrained value of the upright standing ability. In human beings, when standing on one foot, s value is approximately equal to 3000 cm^2, thus the C value reaches up to 10,000 Newton, which is far larger than the biped robot in the world in current time.

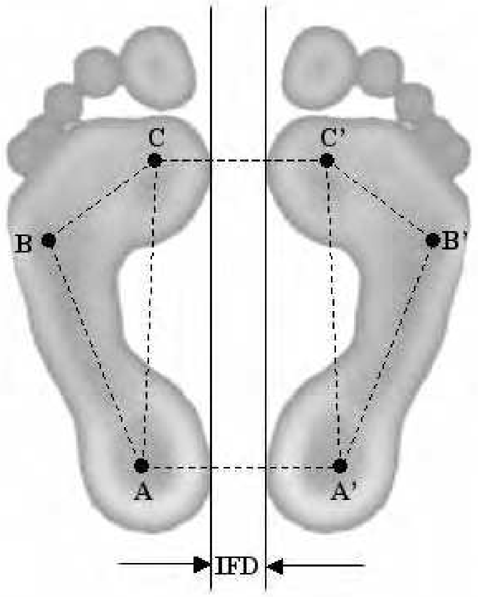

Fig.7. Scheme shows the effective contact area of support when standing in a static upright stance. The area is changed with different inter-foot-distance (IFD).

6. PID Model of Balance Control

As upright standing often modeled as an inverted pendulum, a feedback balance control is speculated to stabilize the pendulum system[18, 19]. Similar to control systems of any artifacts, balance-keeping control of human body is composed of sensors, actuators and a controller.

Physiologically, at least three sensory organs are contributed to balance-keeping, i.e. the vestibular organ[5], eyes[6] and proprioceptors[7] of muscles. Those sensors detect the gravity vector or body kinetic state and send information to the central nervous system (CNS). Actuators are muscles which affiliated to various body parts to produce torques. As mentioned ahead two pairs of muscle in pelvis, GM and PM are especially important in balance-keeping control (Figure 3a). The CNS works as a controller which controls muscles of whole body to produce torque needed for balance-keeping. Up now, the mechanism of body balance control is not clear clarified.

The body sway can be viewed as an output of body control process of humans' brain, which provides an interesting clue for investigating inner balance-keeping control mechanism. Using a classical control theoretical approach, a multi-link model of human body in coronal section as shown in Figure 3 has been constructed. The PID controller is modeled for the body's balance-keeping controller in upright standing. The dynamics of upright standing body is expressed as equation (7), the controller is

$$e(t) = r(t) - \theta(t) \qquad (r(t) = 0) \tag{8}$$

$$\tau(t) = K_P e(t - t_d) + K_D \frac{de(t - t_d)}{dt} + K_I \int_0^t e(t - t_d)dt, \tag{9}$$

where t_d is the time lag, K_P, K_D and K_I are unknown gains of the PID control. By combining the Eq. (7) and the Eq. (9), and set $\sin\theta(t) = \theta(t)$ yields

$$[2m_1 l_g^2 + (m_2 + m_3)l_1^2]\ddot{\theta}(t) - [2m_1 l_g + (m_2 + m_3)l_1]g\theta(t)$$
$$= K_P e(t - t_d) + K_D \frac{de(t - t_d)}{dt} + K_I \int_0^t e(t - t_d)dt. \tag{10}$$

The overall system is depicted in Figure 8.

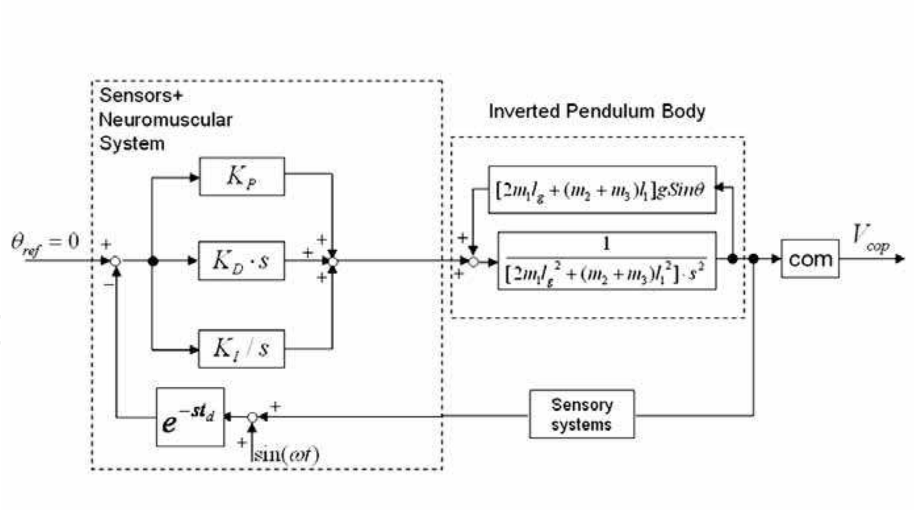

Fig.8. A block diagram of humans' static upright stance control. Because the aim of standing is to keep the body upright, the reference value of postural sway angle is set to zero. The central nervous system detects the error signal and sends output signal to muscles to keep the body upright, a state of equilibrium.

One task is to estimate its parameters of the PID model according to the measurement of body sway. This is a typical closed-loop identification problem to estimate controller parameters instead of plant parameters. Here, we take a modified lest square method for PID parameters estimation since a time lag parameter t_d is included in Eq. (10). The parameters of K_P, K_D, K_I and t_d can be identified based on the observation of θ. We use a linear regression scheme by rewriting the Eq. (10) as

$$
\begin{aligned}
&y(t) = K_P u_1(t-t_d) + K_D u_2(t-t_d) + K_I u_3(t-t_d), \qquad (11)\\
&(y = [2m_1 l_g^2 + (m_2+m_3) l_1^2]\ddot{\theta}(t) - [2m_1 l_g + (m_2+m_3) l_1]g\theta(t),\\
&u_1(t-t_d) = e(t-t_d),\\
&u_2(t-t_d) = \frac{de(t-t_d)}{dt},\\
&u_3(t-t_d) = \int_0^t e(t-t_d)dt).
\end{aligned}
$$

Here, the $y(t)$, $u_1(t-t_d)$, $u_2(t-t_d)$ and $u_3(t-t_d)$ are measurable. Rewriting Eq. (11) as:

$$\mathbf{y} = \Omega\mathbf{k} + \mathbf{e}, \qquad (12)$$

here, $\mathbf{y}, \mathbf{e}$ are $m \times 1$ vectors, $\mathbf{k} = [K_P \; K_D \; K_I]^t$ and Ω is a $m \times 3$ matrix ($m \geq 3$), then the parameters can be calculated as:

$$\begin{bmatrix} K_P \\ K_D \\ K_I \end{bmatrix} = A^{-1} \begin{bmatrix} (y(t), u_1(t-t_d)) \\ (y(t), u_2(t-t_d)) \\ (y(t), u_3(t-t_d)) \end{bmatrix}, \qquad (13)$$

where, $A = \Omega^t \Omega$. (,) is inner product. Lets $S = \mathbf{e}^T \mathbf{e} = \psi(t_d)$, t_d can be estimated because it satisfy

$$\frac{\partial S}{\partial t_d} = 0. \qquad (14)$$

While the parameters are identified, selecting an initial function such as $\theta(t) = 0.01 \times \sin(t)$, ($-t_d < t < 0$), the body sway can be simulated. Figure 9a shows one of the simulated body sway with parameters estimate from the experimental data of a 37 years old healthy male. When a white noise is added to the input in this simulation, the time series of the simulated body sway are similar with the actual recorded in its amplitude and frequency (Figure 9b). This proved that the plant/controller model captures an essential mechanism of body sway and balance-keeping control.

As considering the sensor noise is input as shown in Figure 8 of $\sin(\omega t)$, the total transfer function from sensor noise to output (Fig. 10) becomes

$$T(s) = \frac{G_1 G_2 e^{-st_d}}{G_1 G_2 e^{-st_d} + 1}, \qquad (15)$$

$$G_1(s) = \frac{K_D s^2 + K_P s + K_I}{s}, \qquad (16)$$

$$G_2(s) = \frac{1}{Is^2 + G}, \qquad (17)$$

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

Its frequency response can be calculated, the gain $|T(j\omega)|$ becomes a function of ω and t_d as show in Figure 11. The peaks of gain appeared in both eyes open and eyes closed are consistent with the experimental recorded. The results suggest that the PID model is reasonable and useful for balance-keeping control analysis.

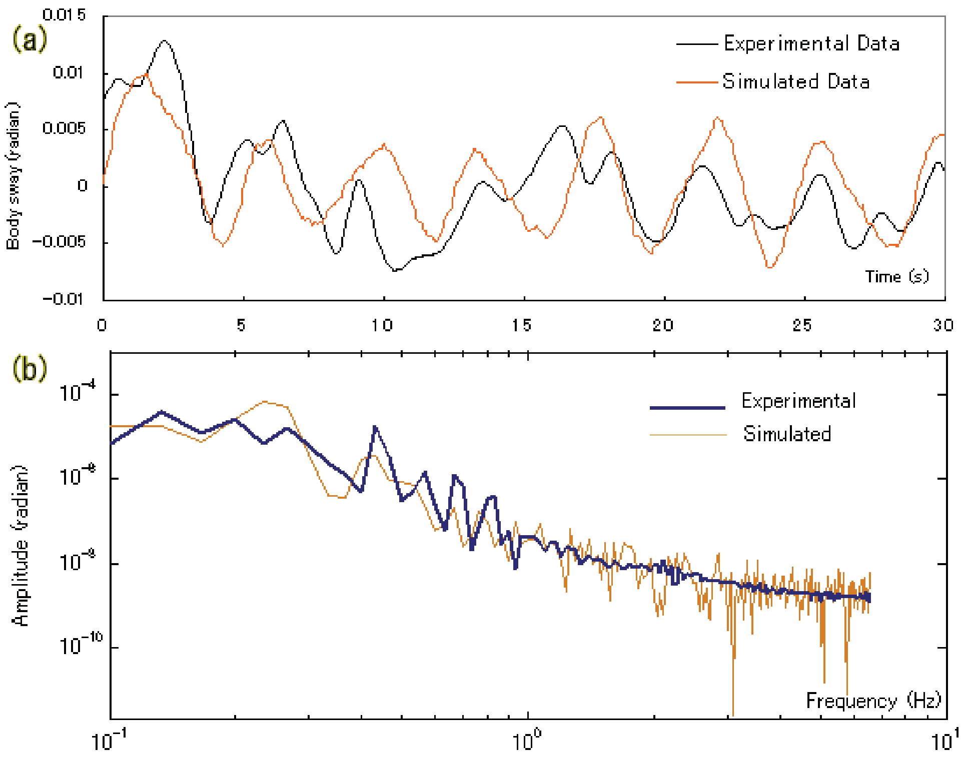

Fig. 9. Simulated and the Experimental recorded body sway in eyes open, time record (a) and frequency response (b). The subject is a 37-year old male. The body height is 1.65m, and body weight is 65Kg. K_P, K_D, K_I and t_d are estimated from the experimental data as 519.0Nm/rad., 72.3Nms/rad., 3.0 Nm/rad.s and 0.11s respectively. The frequency expression of simulated is similar to the experimental recorded.

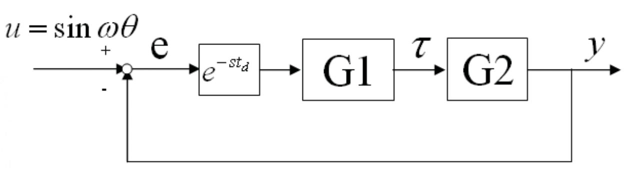

Fig. 10. While considering the sensory noise of $u = \sin \omega t$ as the input, the PID model can be simplified as three processes, i.e. a time-lag process, controller of G1 and dynamics of G2.

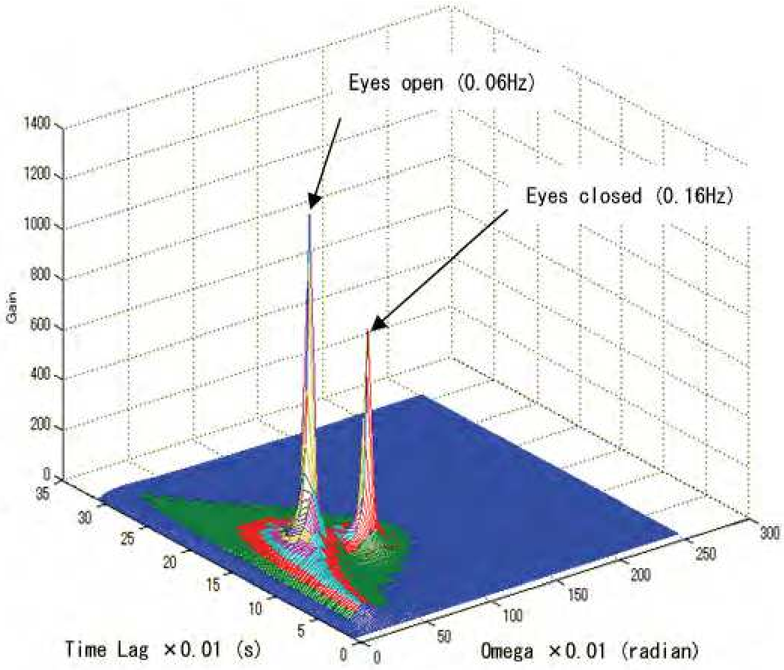

Fig. 11. The frequency response of the balance keeping control system simulated from the same subject. The gain is a function of ω and t_d. The peaks of gain in eyes open (0.06Hz) and eyes closed (0.16Hz) are different, which is roughly consistent with the experimental data as a peak of 0.02Hz in eyes open and a 0.12Hz in eyes closed.

7. Balance-Keeping Ability and fall prediction

Human beings' balance-keeping ability is developed in different age[20]. It is known that in age of 20 to 21 years, individual's balance-keeping ability get to his/her peak, and then decreased with aging[21]. One of main causing factors leads to falls happening in old subjects is the deterioration of the balance-keeping ability[22]. Because of this fact balance-keeping ability assessment becomes the first step for falls-happen prediction. Up to now, several versions of individual's balance-keeping procedures have been published[23], however satisfied and practicable method which can be used for falls-happen prediction is still unavailable. One reason of these failures attributed to the influence of individual's physical status on the balance-keeping ability assessment.

Previous works have shown that mean velocity of COP ($\dot{v}$ COP) is modified by a lot of factors including sex[24], aging, body weight[25], height[26], and also to subjects' grasping power[27]. These factors make the interpretation of the results uneasy when inter-individual comparisons are considered. An effort to adjust the results of COP examination by different age groups has been conducted and its results has been using for ordinary clinical practice[21]. However, subjects' physical characteristics, an important factor which affect the result of COP examination, are still not under specific consideration, even though a lot of models have been proposed[28, 29]. We introduced an index of averaged angular velocity (TSS) for stability estimation[30] and it was proven that TSS is a useful index. Based on a study on 68 subjects, we found that increased in body weight and height tended to decrease the body sway but aging increased body sway. The reciprocal of TSS, defined as trunk sway time (TST), kept a close correspondence with the $\dot{v}$ COP[30]. To reduce the influence of physical characteristics, especially the height on the measuring results, an empirical mathematic model had been introduced as

$$TST_s = k \times \frac{\sqrt{m} \times l^a}{\theta + B}, \qquad (18)$$

where m is body weight, l is height and k, θ are constants, B defined as $(\frac{y}{21} - 1)^2$, y is age (year). This model fit the recorded data quite well.

Another interesting result acquired from a study on aging effect on the PID controller. Parameters identification showed that k_D is deceased with aging[31] (Fig.12). The result suggests a promising method for individual's balance-keeping ability assessment in the future.

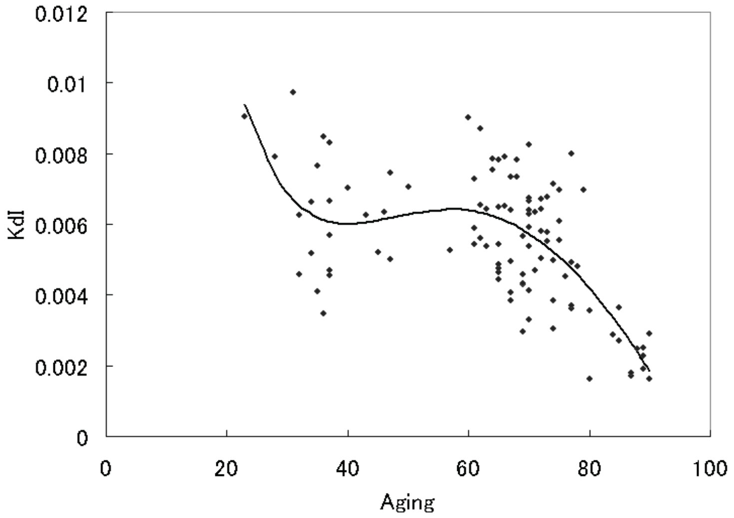

Fig.12. K_D values take from 102 healthy elderly subjects (averaged 64.1±16.3 years old). The K_D is normalized as $KdI = K_D / mgh$ (m: body weight, g: gravity acceleration, h: body height). The result shows the K_D decreased with aging just like the equilibrium ability.

A consequences of falls may be serious at any age, but to the elderly they have significant beyond that in younger people. These consequences can be direct physical effects such as injury or death, or less direct effects of increased dependency and impaired self-care, leading to demands on carers, or profound psychological effects. It is known that postural stability is related to the incidence of falls in elderly. Individuals with poor postural stability show high fall incidence. When defining the measured trunk-sway-time as TST_r, the value of $R_f = TST_r / TST_s$ represents individual's postural stability. From a study of 51 older health subjects[32], the relationship between individual's R_f value and the incidence of falls was investigated. Regressive analyses showed that the value of R_f and the incidence of falls have a reverse relationship, when $R_f \leq 1.12$ the falls incidence was significantly higher than $R_f > 1.12$. The results suggest that falls are predictable by R_f assessment, and this procedure appeared a useful means for fall-prevention especially in elder people.

8. Vision influences on Balance Control

Keeping upright stance is a basic task for other complex motions such as locomotion and running. The mechanisms of visual information benefit for motor control are still unknown. We investigated the visual influence on balance-keeping control in upright standing[33]. Ten healthy subjects (male 4, female 6, aged 37.7±7.21 years) take part in the study. Four kinds of visual stimulation patterns are designed (3 for central visual field stimulation, one is eyes closed, Fig.13).

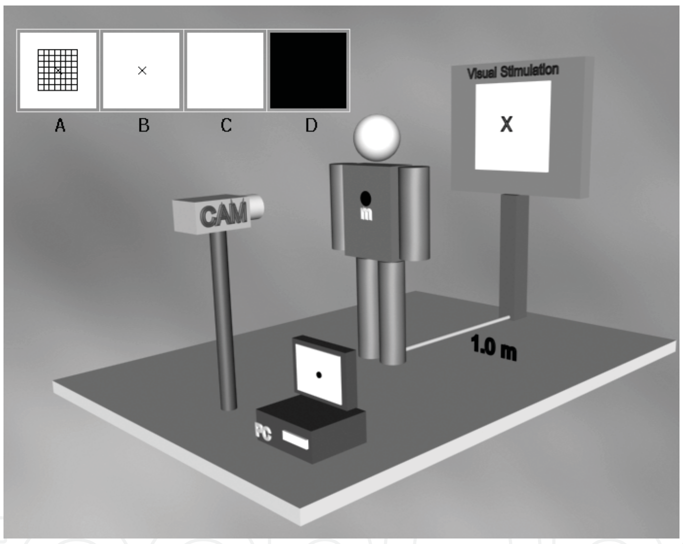

Fig.13. A shows a simplified body biomechanics structural model during static upright stance. Ⓐ, Ⓑ are the masses of leg, Ⓒ is the mass of pelvic and Ⓓ is the mass of upper trunk. Because the lumbosacral always sways in inverse direction of the ankle joint with the same value of θ, the upper trunk is kept perpendicular to the horizon. B is the block diagram of humans' static upright stance control. Because the aim of static upright standing is to keep the body upright, the reference value of postural sway angle is set to zero. The central nervous system detects the error signal and sends output signal to muscles to keep the body upright, a state of equilibrium. C shows a simplified block diagram of upright stance control. Here, the sense noise ($\sin(\omega t)$) is looked as an input, and the output is y,

the deviation of the body’s center-of-mass. G1 is the transfer function of PID controller, and G2 is the transfer function of inverted pendulum model.

The results showed that the gain of the PID parameter K_D is decreased significantly in eyes closed (131.5±37.6Nms/rad in eyes open and 90.4±26.0Nms/rad in eyes closed , p<0.001, Fig.14), however, K_P and K_I are unchanged. Simulation results also proved that when decreasing the gain of K_D locus of simulated is more like the measured spontaneous body sway in eyes closed. The results suggested environmental visual cue is important for balance-keeping control, and this effect is pattern-dependent. Of cause, angular velocity is also increased when eyes are closed (Fig.15).

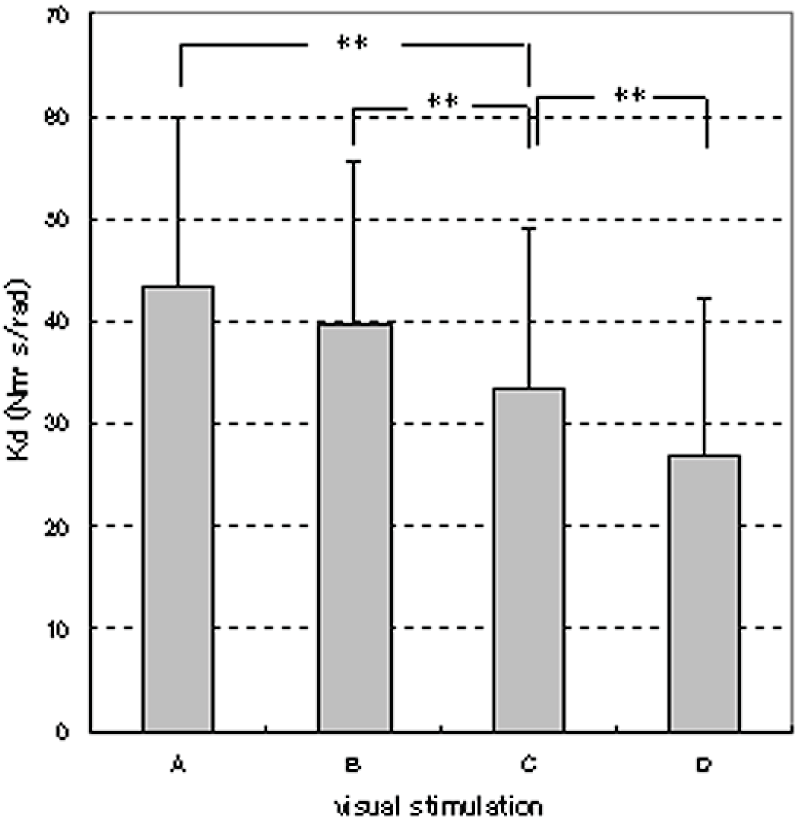

Fig.14. Averaged K_D values of the 10-subject decreased from A to D. No significant differences was found between A and B, however, others showed significant difference. **: p < 0.01.

There are two hypothesizes have been proposed about the mechanism of the visual effect on balance-keeping. One regards that information coming from proprioception of extra-ocular muscles is important for balance-keeping control[34]. The other theory is "retinal slip" insisted that images slip on the retinal is used as a cue for balance-keeping control[35]. Our present studies agreed with the retinal slip hypothesis.

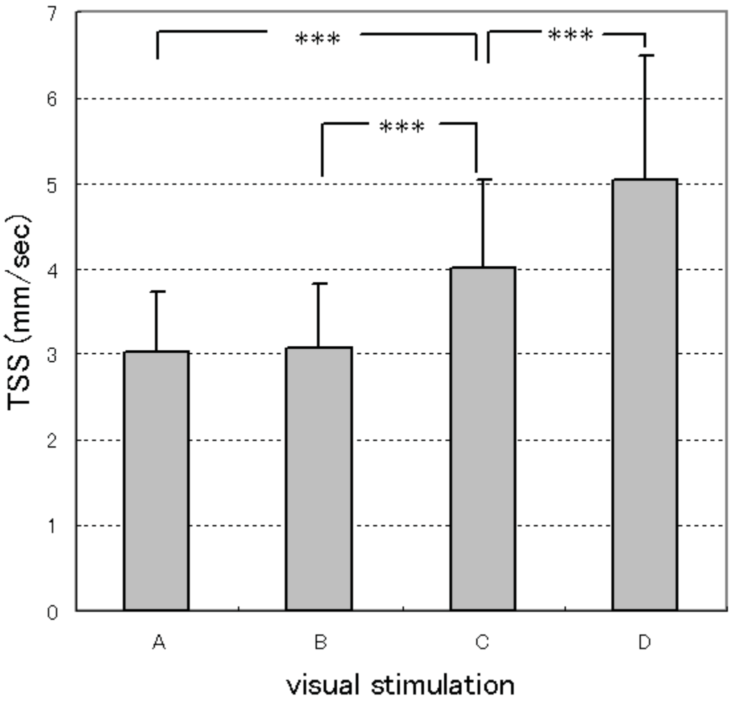

Fig.15. Averaged values of the TSS in different visual stimulations are increased from A to D. However, no significant difference between A and B. ***: $p < 0.001$.

9. Summary

Upright standing is a simple and basic posture of human beings. However, the relatively large mass of the upper body and its elevated position in relation to the area of support during standing accentuate the importance of an accurate control of trunk movements for the maintenance of equilibrium. The kinematics and control strategy of the central nervous system have been studied in recent decade, which brought a PID control algorithm to model the balance-keeping in upright standing and had successfully interpreted the phenomenon of spontaneously body sway. Modeling the human body as two-link inverted pendulum system, we successfully identified parameters of individual's PID parameters and make this model analyzable and practicable. The simulation results, both of the body sway and the spectral response, are quite consistent with experimental data. This proved that the PID model is a reasonable and a useful method as well as by measuring the averaged angular velocity. Both of the two methods help for falls prediction, and become a promising method for falls prevention.

Many authors have argued that complex architectures including feedforward/feedback is necessary for the maintenance of upright stance, however, our studies together with some other recent studies have shown that a model based primarily on a simple feedback mechanism with 120-ms to 150-ms time delay can account for postural control during a broad variety of disturbance[36]. Also, one interesting result is that k_D is a key parameter related to individual balance keeping ability. Since k_D is not just influenced by visual cue but also sensitive to aging. It seems that human balance keeping ability is mainly determined by the gains regulation of k_D, and still there have much works to be done in the future.

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Humanoid Robots: New Developments
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For many years, the human being has been trying, in all ways, to recreate the complex mechanisms that form the human body. Such task is extremely complicated and the results are not totally satisfactory. However, with increasing technological advances based on theoretical and experimental researches, man gets, in a way, to copy or to imitate some systems of the human body. These researches not only intended to create humanoid robots, great part of them constituting autonomous systems, but also, in some way, to offer a higher knowledge of the systems that form the human body, objectifying possible applications in the technology of rehabilitation of human beings, gathering in a whole studies related not only to Robotics, but also to Biomechanics, Biomimmetics, Cybernetics, among other areas. This book presents a series of researches inspired by this ideal, carried through by various researchers worldwide, looking for to analyze and to discuss diverse subjects related to humanoid robots. The presented contributions explore aspects about robotic hands, learning, language, vision and locomotion.

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