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# Two-Dimensional Automatic Control Modeling of a Posture Control System

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NOTES

# Two-Dimensional Automatic Control Modeling of a Posture Control System

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A posture control model has been developed on the basis of the 2-dimensional feedback control theory. Human postural characteristics were investigated in 5 healthy participants. Tests were performed with eyes open and eyes closed. After 5 s of quiet standing, each participant was unexpectedly pulled forward by 30 mm at his pelvis height and then released. Postural sway was measured over 20 s at a rate of 100 per second. Transfer functions to represent the posture control characteristic were identified by the least squares' method. These showed good results of the model's fitness, predictability, and stability. The response of the eyes-closed condition to perturbation is more oscillatory than that of the eyes-open condition. It seems that the model identified could be applicable to ergonomics, sports, or clinical situations.

posture control model   posturography   perturbation
parameter identification   model fitness   stability   predictability

## 1. INTRODUCTION

Human body balance is stabilized by the constant regulation of the complex neuromuscular system. That is, the maintenance of balance is a dynamic motor skill requiring reception and transmission of signals of proprioceptive sensors in the central nervous system, interacting with visual and vetibular responses. Thus, the human body sways continuously to maintain balance while a person is standing upright.

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For centuries investigators have attempted to gain an understanding of the dynamics of human standing balance. Since Romberg's test in 1853, postural sway and the factors affecting it have been the subject of much study and experimenting. The analysis of postural sway during upright stance has been widely used as a tool in evaluating man's ability to balance and the disorders of the nervous system. In addition to neurologic and muscular defects, vision, malfunction of the inner ear, foot position, leg length discrepancy, alcohol and other drugs, and aging are factors presently known to affect standing balance. The study of the postural control system has important implications for sports, rehabilitation medicine, and ergonomics.

As Maki (1986) summarized, postural sway has been characterized by the motion of body segments or joints, joint moments, EMG activity, and displacement of the center-of-pressure (COP) at the feet. The most common measures of postural sway use a force platform to quantify the displacement of the COP. The COP is the location of the vertical reaction vector on the force platform (Winter, 1990). An area, length, and power spectrum analysis of postural sway has been proposed for equilibrium function (Dichgans, Mauritz, Allum, & Brandt, 1976; Kapteyn & Wit, 1972; Murray, Seireg, & Sepic, 1975; Seidel, Bräuer, Bastek, & Issel, 1978; Thomas & Whitney, 1959). However, such data seem to be insufficient for understanding the internal mechanism of the posture control system, because they merely represent a resultant sum of the internal noises in the system (Ishida & Miyazaki, 1987).

To gain an understanding of the internal mechanism of the posture control system, researchers have considered a human posture control system as a feedback system of which an upright body is the controlled object. Thus, postural control is often discussed in terms of the control systems theory (Johansson & Magnusson, 1991; Lee, 1989; Woollacott & Shumway-Cook, 1990). To characterize the postural control system as an input-output model, destabilizing perturbations are used as input into the system, and the postural sway response is the output (Maki, 1986). Postural stability, also referred to as dynamic posturography, is the postural response to an external or volitional perturbation of the postural control system (Johansson & Magnusson, 1991). The postural response to the perturbation (Diener, Bootz, Dichgans, & Bruzek, 1983; Diener & Dichgans, 1988; Diener, Dichgans, Bootz, & Bacher, 1984; Diener, Dichgans, Bruzek, & Selinka, 1982; Dietz, Horstmann, & Berger, 1989; Keshner, Woollacott, & Debu, 1988; Moore, Rushmer, Windus, & Nashner, 1988; Nashner, 1977; Nashner, Shupert, & Horak, 1988; Nashner, Woollacott, & Tuma, 1979) reflects one of several movement strategies for correcting deviations from equilibrium (Nashner et al., 1979; Wolfson, Whipple, Amerman, & Klenberg, 1986).

Nashner (1971, 1972, 1973); Maki, Holliday, and Fernie (1987); Ishida and Miyazaki (1987); Peeters, Caberg, and Mol (1985); Johansson, Magnusson, and Akesson (1988); and others have developed control system models that characterize the transfer function of an input-output system with sensory feedback. Typically, these models predict the ankle joint torque, body sway angle, or both in response to an external postural perturbation. Virtually all of the postural control models are based on movements, torques, and perturbations in the AP (Anterior-Posterior) direction only due to the restrictive dynamics of the models.

We approach the problem of characterizing COP trajectories from a different perspective, namely, that of the two-dimensional automatic control theory. This is a new natural approach in being two-dimensional and there is no loss of information from dynamic posturography. In particular, we hypothesize that the input of the human postural control system under unexpected displacements of the body is the referencing position of postural balance and the output is the resultant COP trajectory. The proposed model is a two-dimensional interconnected system, which consists of PID (proportional, integration, and derivative) feedback controllers and dynamics with time constant. The scope of this study is to identify the feedback parameters of the model by the least squares' methods, to test model fitness and predictability by comparing model output with real output, and to gain useful information for explaining the human strategies to maintain posture in the eyes-open and eyes-closed conditions.

## 2. METHODS

### 2.1. Modeling of the Posture Control System

When a participant loses balance by being exposed to an unexpected sagittal perturbation, his equilibrium regaining process can be modeled by the two-dimensional feedback control model, which consists of components as follows.

The correction command $\vec{u}(u_x(t),\ u_y(t))$ is made by PID (proportional, integration, and derivative) control of bi-directional error $\vec{e}(e_x(t) = r_x(t) - x(t),\ e_y(t) = r_y(t) - y(t))$ in the x (forward-backward) and y (left-right) direction as Equation 1.

$$\begin{cases} u_x(t) = K_{P1} \cdot e_x(t) + K_{D1} \cdot \dot{e}_x(t) + K_{I1} \int_0^t e_x(t)\,dt + d_x(t) \\ \qquad + K_{P3} \cdot e_y(t) + K_{D3} \cdot \dot{e}_y(t) + K_{I3} \int_0^t e_y(t)\,dt \\ u_y(t) = K_{P2} \cdot e_y(t) + K_{D2} \cdot \dot{e}_y(t) + K_{I1} \int_0^t e_y(t)\,dt \\ \qquad + K_{P4} \cdot e_x(t) + K_{D4} \cdot \dot{e}_x(t) + K_{I4} \int_0^t e_x(t)\,dt \end{cases} \tag{1}$$

where $K_{P1}$ is a proportional constant, $K_{D1}$ is a derivative constant, $K_{I1}$ is an integral constant, $r_x(t)$and $r_y(t)$ are referencing points, and $d_x(t)$ is an unexpected sagittal perturbation.

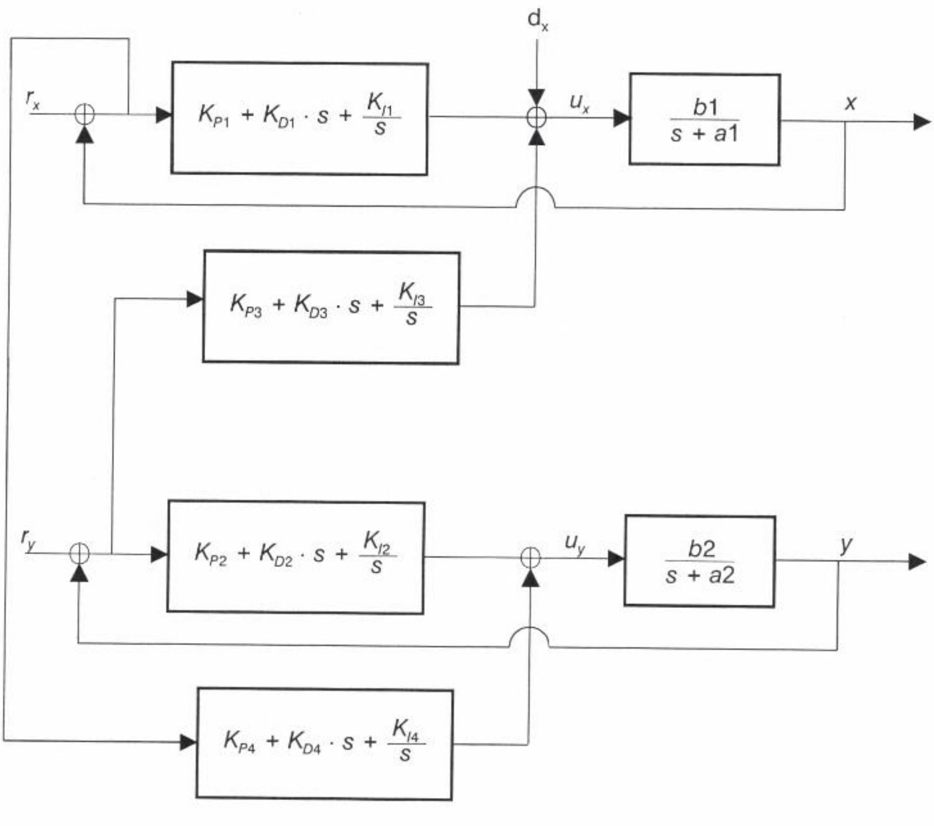


**Figure 1. A block diagram of the two-dimensional posture control model.**

The postural dynamics is such as Equation 2.

$$\begin{cases} x(t) = -a_1 \cdot x(t) + b_1 \cdot u_x(t) \\ y(t) = -a_2 \cdot y(t) + b_2 \cdot u_y(t) \end{cases} \tag{2}$$

PID control is chosen here because the proportional, derivative, and integral actions are fundamental modes of control. The PID concept is widely known (Åström & Wittenmark, 1984) and contains what is necessary for posture control. A block diagram of this system is shown in Figure 1.

## 2.2. Parameter Estimation (Least Squares' Method)

By digital approximation of Equation 2, the resultant vector-matrix form of Equation 2 is acquired as Equation 3

$$\begin{cases} \vec{x} = A_x \cdot \vec{p}_x \\ \vec{y} = A_y \cdot \vec{p}_y \end{cases} \tag{3}$$

where $x(k)$ and $y(k)$ are the coordinates of each sample position with reference to the center of the plate, $k$ stands for the sample order, $q$ stands for the sample interval,

$$\vec{x} = \begin{pmatrix} x(3) \\ x(4) \\ \vdots \\ x(k+1) \\ \vdots \\ x(n) \end{pmatrix}, \vec{p}_x = \begin{pmatrix} 1 - qa_1 \\ b_1K_{P1} \\ b_1K_{D1} \\ b_1K_{I1} \\ b_1K_{P3} \\ b_1K_{D3} \\ b_1K_{I3} \end{pmatrix}, \vec{y} = \begin{pmatrix} y(3) \\ y(4) \\ \vdots \\ y(k+1) \\ \vdots \\ y(n) \end{pmatrix}, \vec{p}_y = \begin{pmatrix} 1 - qa_2 \\ b_2K_{P2} \\ b_2K_{D2} \\ b_2K_{I2} \\ b_2K_{P4} \\ b_2K_{D4} \\ b_2K_{I4} \end{pmatrix}$$

$$A_x = \begin{bmatrix} x(2) & q[r_x - x(1)] & x(1) - x(2) & q^2 \sum_{k=1}^{1} [r_x - x(k)] & q[r_y - y(1)] & y(1) - y(2) & q^2 \sum_{k=1}^{1} [r_y - y(k)] \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x(k) & q[r_x - x(k-1)] & x(k-1) - x(k) & q^2 \sum_{k=1}^{k-1} [r_x - x(k)] & q[r_y - y(k-1)] & y(k-1) - y(k) & q^2 \sum_{k=1}^{k-1} [r_y - y(k)] \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x(n-1) & q[r_x - x(n-2)] & x(n-2) - x(n-1) & q^2 \sum_{k=1}^{n-2} [r_x - x(k)] & q[r_y - y(n-2)] & y(n-2) - y(n-1) & q^2 \sum_{k=1}^{n-2} [r_y - y(k)] \end{bmatrix}$$

and

$$A_y = \begin{bmatrix} y(2) & q[r_y - y(1)] & y(1) - y(2) & q^2 \sum_{k=1}^{1} [r_y - y(k)] & q[r_x - x(1)] & x(1) - x(2) & q^2 \sum_{k=1}^{1} [r_x - x(k)] \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ y(k) & q[r_y - y(k-1)] & y(k-1) - y(k) & q^2 \sum_{k=1}^{k-1} [r_y - y(k)] & q[r_x - x(k-1)] & x(k-1) - x(k) & q^2 \sum_{k=1}^{k-1} [r_x - x(k)] \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ y(n-1) & q[r_y - y(n-2)] & y(n-2) - y(n-1) & q^2 \sum_{k=1}^{n-2} [r_y - y(k)] & q[r_x - x(n-2)] & x(n-2) - x(n-1) & q^2 \sum_{k=1}^{n-2} [r_x - x(k)] \end{bmatrix}$$

By minimizing the quantity J with respect to parameters, estimated parameters in the x direction are acquired as Equation 4. Estimated parameters in the y direction can be acquired by same procedure as that of the x direction.

$$\underset{\hat{\vec{p}}_x}{MIN}\ J = \sum_{k=3}^{n} (x(k) - x(\hat{k}))^2 = (\vec{x} - A_x \cdot \vec{p}_x)^T (\vec{x} - A_x \cdot \vec{p}_x)$$

$$\frac{\partial J}{\partial \vec{p}_x} = 0 \tag{4}$$

$$\hat{\vec{p}}_x = (A_x^T \cdot A_x)^{-1} A_x^T \cdot \vec{x}$$

## 2.3. Equivalent System

The two-dimensional posture control model shown in Figure 1 can be simplified by acquiring equivalent transfer functions after the parameter estimation. Equivalent transfer functions are obtained by simple algebra. The resultant equivalent system is shown in Figure 2.

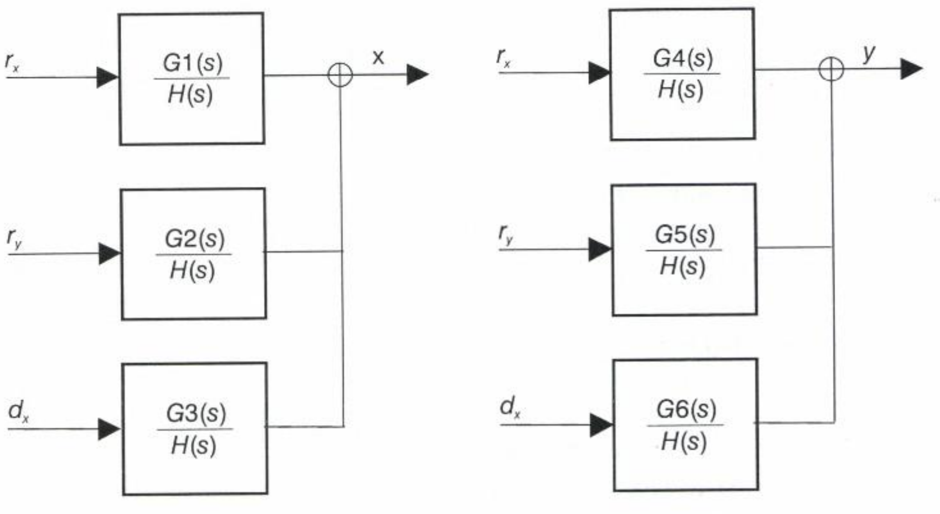


**Figure 2. An equivalent system of the two-dimensional posture control model.**

In Figure 2, $H(s)$ and $G_1(s)$ are given as follows:

$$
\begin{aligned}
H(s) = {} & (1 + b1K_{D1} + b2K_{D3} + b1K_{D1}b2K_{D3} - b1K_{D2}b2K_{D4})\,s^4 + (a1 + a2 + \\
& b1K_{P1} + b2K_{P3} + a1b2K_{D3} + b1K_{P1}b2K_{D3} + b1K_{D1}a2 + b2K_{D3}b2K_{P3} - \\
& b1K_{P2}b2K_{D4} - b1K_{D2}b2K_{P4})\,s^3 + (b1K_{I1} + b2K_{I3} + a1a2 + a1b2K_{P3} + \\
& b1K_{P1}a2 + b1K_{P1}b2K_{P3} + b1K_{D1}b2K_{I3} + b1K_{I1}b2K_{D3} - b1K_{P2}b2K_{P4} - \\
& b1K_{D2}b2K_{I4} - b1K_{I2}b2K_{D4})\,s^2 + (a1b2K_{I3} + b1K_{P1}b2K_{I3} + b1K_{I1}a2 + \\
& b1K_{I1}b2K_{P3} - b1K_{P2}b2K_{I4} - b1K_{I2}b2K_{P4})\,s + b1K_{I1}b2K_{I3} - b1K_{I2}b2K_{I4} \\
G1(s) = {} & (b1K_{D1} + b1K_{D1}b2K_{D3} - b1K_{D2}b2K_{D4})\,s^4 + (b1K_{P1} + b1K_{P1}b2K_{D3} + \\
& b1K_{D1}a2 + b1K_{D1}b2K_{P3} - b1K_{P2}b2K_{D4} - b1K_{D2}b2K_{P4})\,s^3 + (b1K_{I1} + \\
& b1K_{P1} + a2 + b1K_{P1}b2K_{P3} + b1K_{D1}b2K_{I3} + b1K_{I1}b2K_{D3} - b1K_{P2}b2K_{P4} - \\
& b1K_{D2}b2K_{I4} - b1K_{I2}b2K_{D4})\,s^2 + (b1K_{P1}b2K_{I3} + b1K_{I1}\mathrm{a}2 + b1K_{I1}b2K_{P3} - \\
& b1K_{P2}b2K_{I4} - b1K_{I2}b2K_{P4})\,s + b1K_{I1}b2K_{I3} - b1K_{I2}b2K_{I4} \\
G2(s) = {} & b1K_{D2}\,s^4 + (b1K_{P2} + b1K_{D2}a2)\,s^3 + (b1K_{I2} + b1K_{P2}a2)\,s^2 + (b1K_{I2}a2)\,s \\
G3(s) = {} & (1 + b2K_{D3})\,s^3 + (a2 + b2K_{P3})\,s^2 + b2K_{I3}\,s \\
G4(s) = {} & b2K_{D4}\,s^4 + (b2K_{P4} + b2K_{D4}a1)\,s^3 + (b2K_{I4} + b2K_{P4}a1)\,s^2 + b2K_{I4}a1\,s \\
G5(s) = {} & (b2K_{D3} + b2K_{D3}b1K_{D1} - b2K_{D4}b1K_{D2})\,s^4 + (b2K_{P3} + b2K_{P3}b1K_{D1} + \\
& b2K_{D3}a1 + b2K_{D3}b1K_{P1} - b2K_{P4}b1K_{D2} - b2K_{D4}b1K_{P2})\,s^3 + (b2K_{I3} + \\
& b2K_{P3}a1 + b2K_{P3}b1K_{P1} + \mathrm{b}2K_{D3}b1K_{I1} + b2K_{I3}b1K_{D1} - b2K_{P4}b1K_{P2} - \\
& b2K_{D4}b1K_{I2} - b2K_{I4}b1K_{D2})\,s^2 + (b2K_{P3}b1K_{I1} + b2K_{I3}a1 + b2K_{I3}b1K_{P1} - \\
& b2K_{P4}b1K_{I2} - b2K_{I4}b1K_{P2})\,s + b2K_{I3}b1K_{I1} - b2K_{I4}b1K_{I2} \\
G6(s) = {} & - b2K_{D4}\,s^3 - b2K_{P4}\,s^2 - b2K_{I4}\,s \qquad (5)
\end{aligned}
$$

## 3. EXPERIMENT

### 3.1. Participants

Five healthy male students, aged 24 to 27 years and free of any back problems in a required medical examination, participated in the experiment. Their height ranged from 168 to 187 cm, and their weight ranged from 58 to 77 kg.

### 3.2. Instrumentation

The experimental apparatus used for the automatic measurement of the center-of-pressure location consisted of three parts: (a) a multicomponent measuring platform (Kistler, type 9281B); (b) an electronic charge amplifying unit (Kistler, type 9861A); and (c) recording equipment (IBM PC with a 12-bit A/D converter).

The measuring platform was connected by a special cable to an electronic amplifying unit, which converted the electric charges yielded by the force transducers of the platform into voltage. It was possible to feed the output signals from the charge amplifiers via a 12-bit A/D converter into a computer. The connected computer controlled the A/D converter, performed calculations on the converted digital values to obtain the positions of center-of-body pressure at a rate of 100 per second and stored them.

### 3.3. Experimental Procedure

Each experiment was performed under conditions of open and closed eyes. Each participant was placed on the platform, feet together with 0° splay and hands at the sides, and was asked to look straight ahead at a fixed point in a quiet room. After 5 s of quiet standing, each participant was unexpectedly pulled forward by 30 mm at his pelvis height and then released. All of the participants were familiarized with the experimental process before the experimental data were collected. All tests were done three times for each participant, each test lasting 20 s. A 5-min rest was allowed between tests.

## 4. RESULTS AND DISCUSSION

Center-of-pressure data from the force platform were sampled at a rate of 100 per second and stored on an IBM-compatible PC. Using these data of 2000 input-output pairs, we estimated parameters of the two-dimensional posture control model.

A typical example of the estimated parameters of one participant is shown in Table 1. Figures 3 and 4 show the comparison between the outputs and model outputs. This comparison yields good results of the model fitness and predictability in spite of the large number of parameters to be estimated.

**TABLE 1. Estimated Parameters**

| Parameter | $a1$ | $b1 \cdot K_{P1}$ | $b1 \cdot K_{D1}$ | $b1 \cdot K_{I1}$ | $b1 \cdot K_{P3}$ | $b1 \cdot K_{D3}$ | $b1 \cdot K_{I3}$ |
|---|---|---|---|---|---|---|---|
| Eyes Open | 0.03 | 0.47 | −0.82 | −0.01 | −0.17 | 0.00 | −0.01 |
| Eyes Closed | −0.23 | 0.64 | −0.86 | −0.04 | 0.17 | 0.03 | 0.00 |
| | $a2$ | $b2 \cdot K_{P2}$ | $b2 \cdot K_{D2}$ | $b2 \cdot K_{I2}$ | $b2 \cdot K_{P4}$ | $b2 \cdot K_{D4}$ | $b2 \cdot K_{I4}$ |
| Eyes Open | 0.44 | −0.14 | −0.65 | 0.09 | −0.09 | 0.03 | 0.01 |
| Eyes Closed | 1.71 | −1.51 | −0.71 | 0.19 | 0.01 | 0.00 | −0.05 |

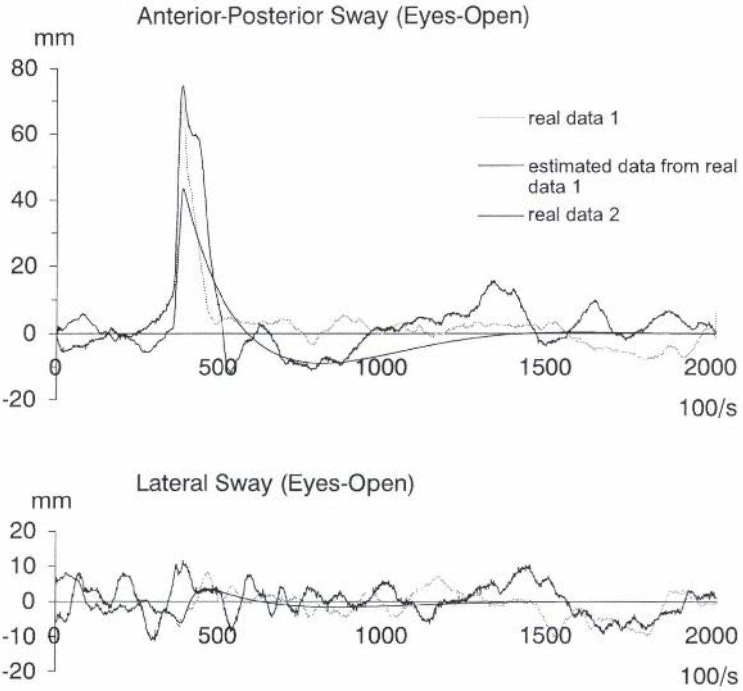


**Figure 3. Raw data and model outputs: Eyes open.**

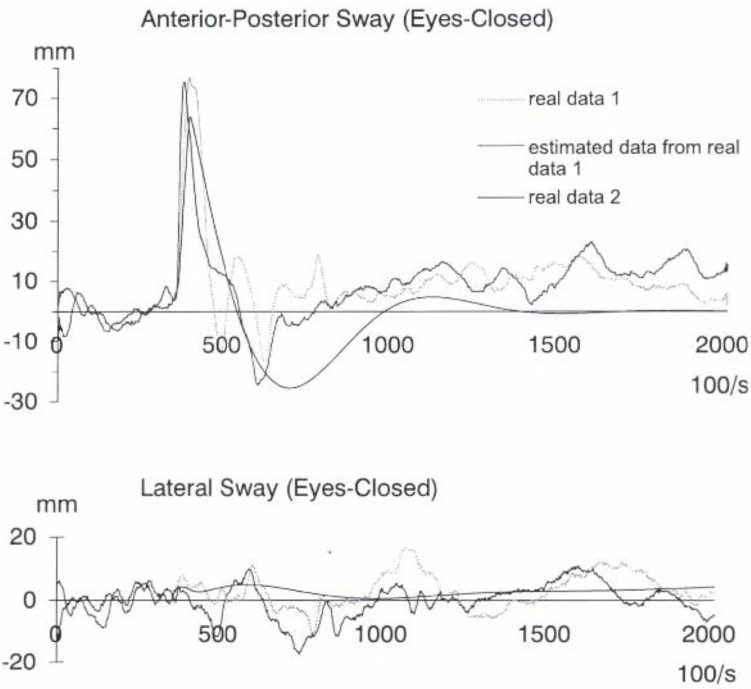


**Figure 4. Raw data and model outputs: Eyes closed.**

Transfer functions were derived from Equation 5. $G3(s)/H(s)$, which represents the response to external perturbation is given as follows.

$$\frac{G3(s)}{H(s)} = \frac{0.350s^3 + 0.294s^2 + 0.090s}{0.064s^4 + 0.207s^3 + 0.143s^2 + 0.043s + 0.001} \text{ eyes open}$$

$$\frac{G3(s)}{H(s)} = \frac{0.292s^3 + 0.199s^2 + 0.185s}{0.042s^4 + 0.074s^3 + 0.097s^2 + 0.077s + 0.008} \text{ eyes closed} \quad (6)$$

Root loci diagrams of Equation 6 are shown in Figures 5 and 6.

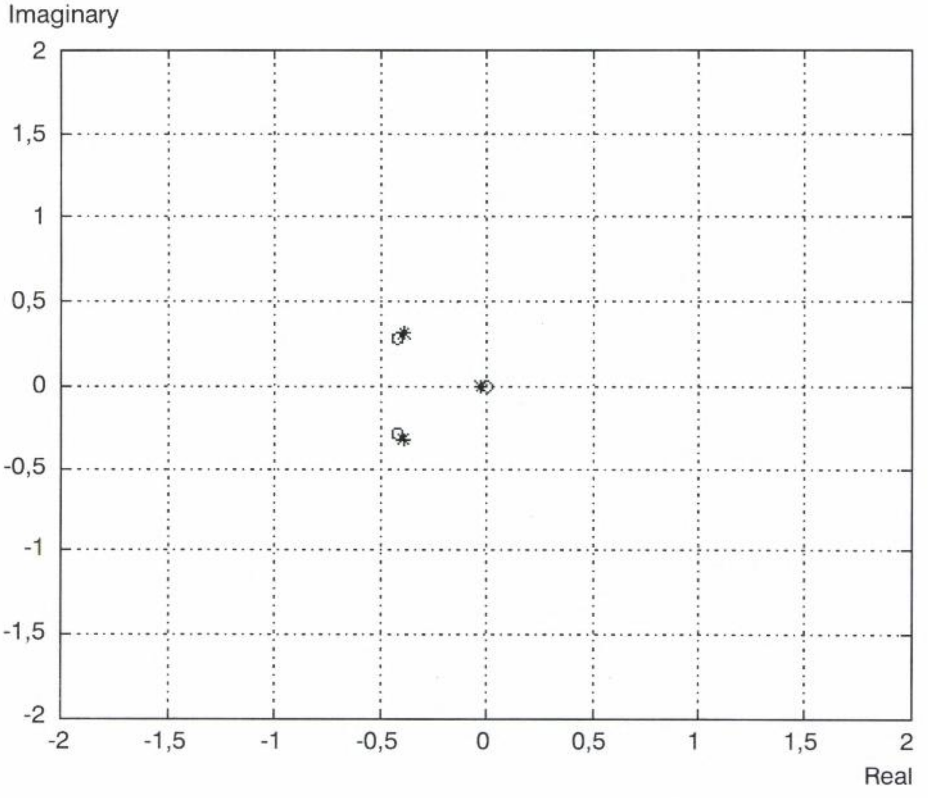


**Figure 5. A root loci diagram: Eyes open (O: zeros, *: poles).**

It should be noted that the transfer function $G3(s)/H(s)$ has no poles that lie in the right-half plane. Therefore, it is clear that the root loci in Figures 5 and 6 satisfy the stability criterion. It can also be seen that the response of the eyes-closed condition to perturbation is more oscillatory

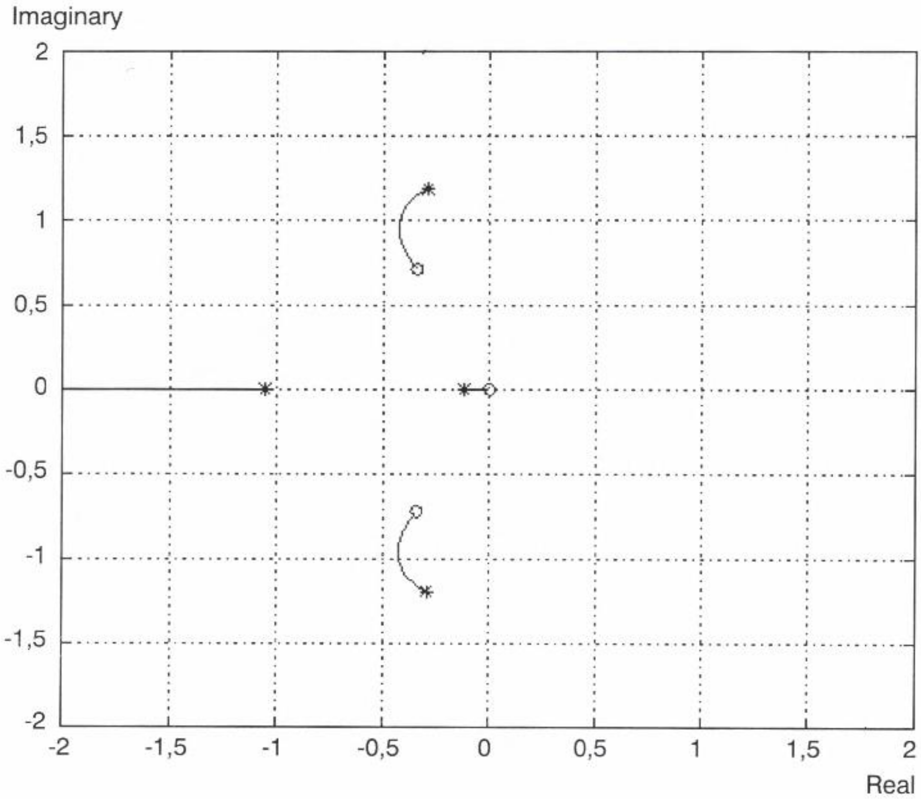


**Figure 6. A root loci diagram: Eyes closed (O: zeros, *: poles).**

than that of the eyes-open condition. This implies that different strategies are involved depending on whether visual information exists or not. Five participants showed similar results. It seems that an increase of gain of vestibular, proprioceptive, or both sensors occurs to compensate for the lack of visual information.

Consequently, the proposed model showed good results of model fitness, predictability, and stability. It is conjectured that the feedback parameters identified are suitable for explaining the characteristics of maintaining posture in the eyes-open and eyes-closed conditions. It seems that the model identified in this study could be applicable to ergonomics, sports, or clinical situations.

## REFERENCES


Åström, K.J., & Wittenmark, B. (1984). *Computer controlled systems*. Englewood Cliffs, NJ: Prentice-Hall.

Dichgans, J., Mauritz, K.H., Allum, J.H.J., & Brandt, T. (1976). Postural sway in normals and atactic patients: Analysis of the stabilizing and destabilizing effects of vision. *Agressologie*, *17-C*, 15–24.

Diener, H.C., Bootz, F., Dichgans, J., & Bruzek, W. (1983). Variability of postural "reflexes" in humans. *Experimental Brain Research, 52*, 423–428.

Diener, H.C., & Dichgans, J. (1988). On the role of vestibular, visual and somatosensory information for dynamic postural control in humans. In O. Pompeiano & J.H.J. Allum (Eds.), *Progress in brain research, 76*, 253–262.

Diener, H.C., Dichgans, J., Bootz, F., & Bacher, M. (1984). Early stabilization of human posture after a sudden disturbance: Influence of rate and amplitude of displacement. *Experimental Brain Research, 56*, 126–134.

Diener, H.C., Dichgans, J., Bruzek, W., & Selinka, H. (1982). Stabilization of human posture during induced oscillations of the body. *Experimental Brain Research, 45*, 126–132.

Dietz, V., Horstmann, G.A., & Berger, W. (1989). Interlimb coordination of leg-muscle activation during perturbation of stance in humans. *Journal of Neurophysiology, 62*, 680–693.

Ishida, A., & Miyazaki, S. (1987). Maximum likelihood identification of a posture control system. *IEEE Transactions on Biomedical Engineering, BME-34*, 1–5.

Johansson, R., & Magnusson, M. (1991). Human postural dynamics. *CRC Critical Reviews in Biomedical Engineering, 18*, 413–437.

Johansson, R., Magnusson, M., & Akesson, M. (1988). Identification of human postural dynamics. *IEEE Transactions on Biomedical Engineering, 35*, 858–869.

Kapteyn, T.S., & Wit, G. (1972). Posturography as an auxiliary in vestibular investigation. *Acta Otolaryngologica, 73*, 104–111.

Keshner, E.A., Woollacott, M.H., & Debu, B. (1988). Neck, trunk and limb muscle reponses during postural perturbations in humans. *Experimental Brain Research, 71*, 455–466.

Lee, W.A. (1989). A control systems framework for understanding normal and abnormal posture. *American Journal of Occupational Therapy, 43*, 291–301.

Maki, B.E. (1986). Selection of perturbation parameters for identification of the posture-control system. *Medical Biological Engineering & Computing, 24*, 561–568.

Maki, B.E., Holliday, P.J., & Fernie, G.R. (1987). A posture control model and balance test for the prediction of relative postural stability. *IEEE Transactions on Biomedical Engineering, BME-34*, 797–810.

Moore, S.P., Rushmer, D.S., Windus, S.L., & Nashner, L.M. (1988). Human automatic postural response: Responses to horizontal perturbations of stance in multiple directions. *Experimental Brain Research, 73*, 648–658.

Murray, M.P., Seireg, A.A., & Sepic, S.B. (1975). Normal postural stability and steadiness: Quantitative assessment. *Journal of Bone and Joint Surgery, 57(a)*, 510–515.

Nashner, L.M. (1971). A model describing vestibular detection of body sway motion. *Acta Otolaryngologica, 72*, 429–436.

Nashner, L.M. (1972). Vestibular postural control model. *Kybernetik, 10*, 106–110.

Nashner, L.M. (1973). Vestibular and reflex control of normal standing. In R.B. Stein, K.B. Pearson, R.S. Smith, & J.B. Redford (Eds.), *Control of posture and locomotion* (pp. 291–308). New York: Plenum.

Nashner, L.M. (1977). Fixed patterns of rapid postural responses among leg muscles during stance. *Experimental Brain Research, 30*, 13–24.

Nashner, L.M., Shupert, C.L., & Horak, F.B. (1988). Head-trunk movement coordination in the standing posture. In O. Pompeiano & J.H. Allum (Eds.), *Progress in brain research* (Vol. 76, pp. 243–251). Amsterdam: Elsevier.

Nashner, L.M., Woollacott, M., & Tuma, G. (1979). Organization of rapid responses to postural and locomotor-like perturbations of standing man. *Experimental Brain Research, 36*, 463–476.

Peeters, H.P.M., Caberg, H.B., & Mol, J.M.F. (1985). Evaluation of biomechanical models in posturography. *Medical Biological Engineering & Computing, 23*, 469–473.

Seidel, H., Bräuer, D., Bastek, R., & Issel, I. (1978). On the quantitative characterization of human body sway in experiments with long-term performance. *Acta Biologica et Medical Germanica, 37*, 1551–1561.

Thomas, D.P., & Whitney, R.J. (1959). Postural movements during normal standing in man. *Journal of Anatomy, 93*, 524–539.

Winter, D.A. (1990). *Biomechanics of motor control and human movement* (2nd ed.). New York: Wiley-Interscience.

Wolfson, L.I., Whipple, R., Amerman, P., & Klenberg, A. (1986). Stressing the postural response: A quantitative method for testing balance. *Journal of American Geriatrics Society, 34*, 845–850.

Woollacott, M.H., & Shumway-Cook, A. (1990). Changes in posture control across the life span-A systems approach. *Physical Therapy, 70*, 799–807.