# On Mathematical Models to Control Three Upright Postures in the Elderly

Fumiya Kinoshita[1], Yuta Fukui[1], Masumi Takada[2], Masashi Furuta[3], Takayuki Hirata[1] and Hiroki Takada[1,2*]

[1]*Graduate School of Engineering, University of Fukui, Fukui 910-8507, Japan*
[2]*Graduate School of Medicine, Aichi University of Medicine, Nagakute 480-1195, Japan*
[3]*Department of School Health Sciences, Aichi University of Education, 1 Hirosawa, Kariya, Aichi 448-8542, Japan*
**E-mail address: takada@u-fukui.ac.jp*

(Received December 11, 2013; Accepted December 20, 2013)

Stabilometry, which is useful for quantitative evaluation of equilibrium function, is generally performed using Romberg's posture. However, there is a risk of falls in diagnosing diseases (Meniere disease, sudden deafness accompanied by vertigo, and vestibular neuronitis), measurement of body sway, and course observation of vertigo and balance dysfunction using stabilometry. The aim of this study was to compare the mathematical model in Romberg's posture with that in a posture in which the heels are together and feet are parallel. Stabilograms of the elderly were recorded with each posture. The distribution of stabilograms in the 2 postures did not also differ significantly. Therefore, we considered that there was no effect of the postural difference on their stability.
**Key words:** Body Sway, Stabilogram, Romberg's Posture, Stochastic Differential Equation (SDE), Temporally Averaged Potential Function

## 1. Stabilometry

In upright postures, the body continuously moves in a unique and complex rhythm; the amplitude and frequency of this rhythm depend on various sensory and motor system functions (Okawa *et al.*, 1995). The base supporting the body is an area surrounded by bilateral soles. To maintain a stable posture, it is necessary to control the spatial perpendicular line from the body's center of gravity within the narrow base (Winter *et al.*, 1998; Gatev *et al.*, 1999; Loram *et al.*, 2001). The bilateral legs provide the ground reaction force required to support the body; however, the center of gravity continuously sways. This is because of the location of the head-upper limbs-trunk, which accounts for two-third of the body weight, is located at a distance that is two-third of the height from the floor. The human mechanism for maintaining upright postures is termed the righting reflex. Physiologically, the righting reflex is a body equilibrium function controlled by the involuntary regulatory system (Kaga, 1992). Elucidating the body's equilibrium function is essential for diagnosing symptoms related to impairment of the balance function, such as those of progressive cerebellar degeneration, basal ganglia disorder, and Parkinson's disease (Okawa *et al.*, 1996).

Stabilometry, which is performed as an equilibrium test, is useful for investigating the overall equilibrium function. Stabilometry is a simple test involving a 60-sec recording that starts when body sway stabilizes. Stabilometric methods and indices of body sway analysis, such as the total locus length and locus length per unit area, are used to increase the diagnostic value of stabilometry. The locus length per unit area represents the microchanges in postural control and is considered as a scale for functional evaluation of spinal proprioceptive postural control (Suzuki *et al.*, 1996).



## 2. Mathematical Models of Body Sway

In stabilograms, variables $x$ (cross direction) and $y$ (longitudinal direction) are considered independent (Goldie *et al.*, 1986). The linear stochastic differential equation (Brownian motion process) have been proposed as a mathematical model to describe body sway (Emmerrik *et al.*, 1993; Collins and De Luca, 1997; Newell *et al.*, 1997). In order to describe the individual body sway, we especially show that it is necessary to extend the following nonlinear stochastic differential equations:

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x} U_x(x) + w_x(t), \qquad (1)$$

$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y} U_y(y) + w_y(t), \qquad (2)$$

where $w_x(t)$ and $w_y(t)$ are pseudorandom numbers produced by white noise. The following formula describes the relationship ($z = x, y$) between the distribution in each direction, $G_z(z)$, and the temporal averaged potential constituting the stochastic differential equations, $U_z(z)$ (Takada *et al.*, 2001).

$$U_z(z) = -\frac{1}{2} \ln G_z(z) + const. \qquad (3)$$

The variance of stabilograms generally depends on the temporal averaged potential function with several minimum values when it follows the Markov process without abnormal dispersion. Stochastic differential equations can represent movements within local stability with a high frequency component near the minimal potential surface, where a high density at the measurement point is expected.

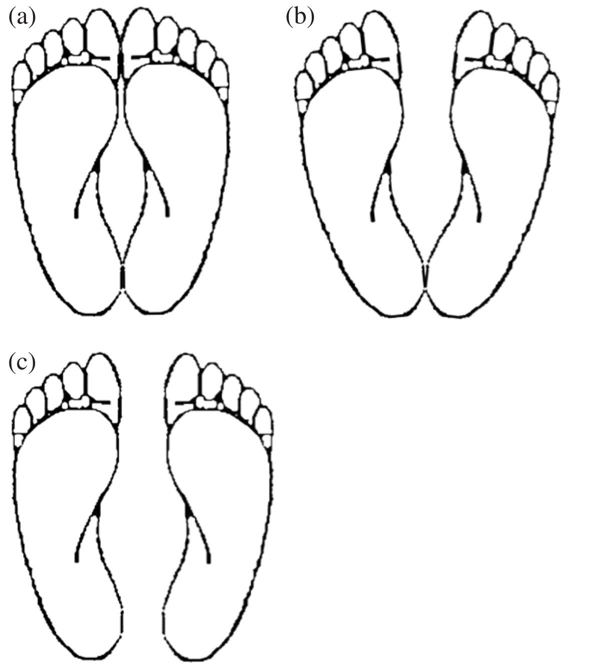


Fig. 1. Arrangements of soles in each posture: (a) the Romberg's posture, (b) a posture with open toes and heels together, and (c) a posture with parallel feet.

## 3. A Problem of the Clinical Stabilometry and Solution

Stabilometry is generally performed in Romberg's or Mann's posture. Romberg's posture is an upright posture with the bilateral toes and heels together. Body sway increases in inversely to the area of the supporting base because these are unstable upright postures with a small support area; therefore, stabilometry in upright postures is not appropriate in subjects having difficulty maintaining a standing position for a certain amount of time. Elderly persons and the patients in equilibrium e.g. Meniere disease may have difficulty sustaining this upright posture because their balance-retaining ability is impaired by aging and muscle weakness (Stevens and Patterson, 1995). Romberg's posture with a narrow support area may increase the risk of falling, and hence, preventive countermeasures are necessary. Excluding unstable upright postures with a small support area or proposing surrogate postures for the stabilometry, we can prevent subjects from falling down on the floor.

Accordingly, changes in the standing position control system resulting from disturbance or abnormal body equilibrium function are reflected with greater sensitivity of the abovementioned unstable postures with a narrow support area. Stabilometry can usually detect the deterioration in the equilibrium function. Because the control system to maintain these postures is unstable, it is important to introduce the abovementioned surrogate postures to the stabilometry

1. in which subjects are theoretically considered not to fall down;
2. which can detect the deterioration in the equilibrium function.

In addition, few studies have succeeded in findings of potential functions (3) to control upright postures except for the Romberg's posture. Thus, we herein introduce

I. a posture with open toes and heels together
II. a posture with parallel feet

to the stabilometry (Fig. 1).

We compared histograms that were composed of all subjects' stabilograms (Appendix A). The frequency of an $x$ coordinate near the origin was greater in the postures I and II than in the Romberg's posture. When the histograms for the Romberg's posture and the posture I were compared in the $x$ and $y$ directions, with open and closed eyes, using the chi-squared test, no significant differences were observed. However, there is a significant difference between histograms for the Romberg's posture and the posture II in the $x$ direction. Thus, the system to control the upright posture I is regarded as the same system to maintain the Romberg's posture because potential functions to control upright postures (Fig. 2) can be obtained from the histograms in accordance with Eq. (3). However, the system to control the upright posture II is not regarded as the same system.

## 4. Future Research Directions

In previous studies on the body sway, stabilometry was generally performed in Romberg's posture. However, the balance-retaining ability decreases with aging, and the risk of falling is increased for elderly subjects in tests using Romberg's posture because it is an unstable upright posture. There is also an increased risk of falling when the technique is used for diagnosing diseases (e.g., Meniere disease, sudden deafness accompanied by vertigo, and vestibular neuronitis), measurement of body sway, and course observation of vertigo and impaired balance function. If the risk of falling during the test can be reduced by performing stabilometry in the posture with heels together, additional studies are needed to further develop and validate the technique for application in medical practice.

The indices calculated from the stabilograms indicated that the standing position in Romberg's posture was less stable in both young and elderly subjects (Yoshikawa *et al.*, 2013). However, no significant differences were also noted in the analytical parameters between Romberg's posture and the posture I in the elderly subjects, which is consistent with the result of this paper; therefore the posture I may be used in stabilometry as a substitute for Romberg's posture in elderly persons.

The temporal averaged potentials in Romberg's posture were determined from the histograms using Eq. (3) in the elderly subjects (Fig. 2). The shapes of the potentials were more complex and tended to be nonlinear in the Romberg's posture and the lateral component $x$ because coefficients of the regression polynomials (Appendix A) were less than 0.9 in several cases (Tables 1 and 2). Multiple minimal points in the potential function have been obtained from each healthy young subject in accordance with the theory mentioned in Section 2 (Takada *et al.*, 2001). Especially in the posture II, two minimal points in the potential function might correspond to each center of the sole. In the next step, we will quantitatively examine whether distance between open toes changed the potential function in the posture I.

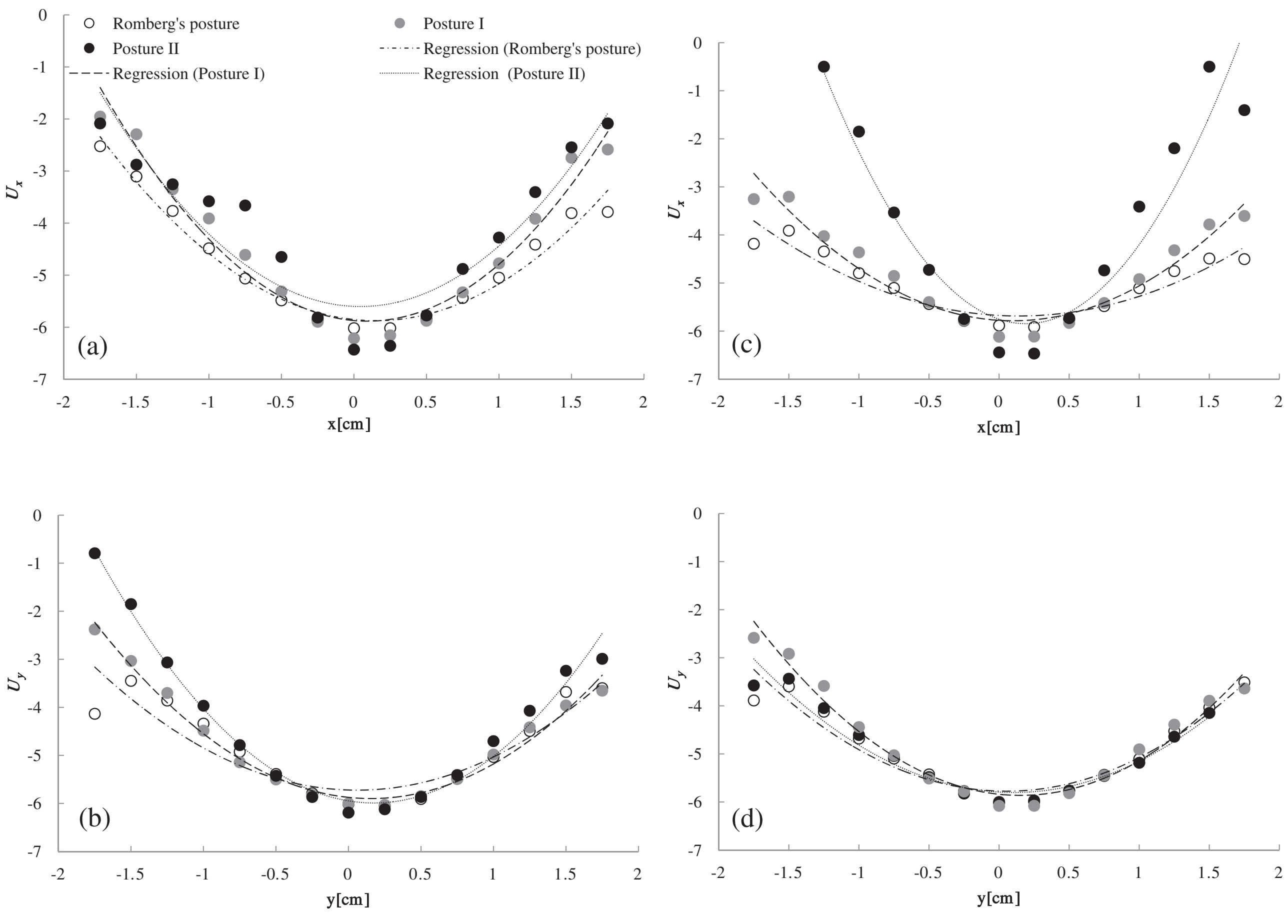


Fig. 2. Temporal averaged potential function derived from stabilograms of the elderly in each posture with their eyes open (a), (c) and with their eyes closed (b), (d).

Table 1. Coefficients of the potential function in each component: (a) lateral direction $x$, and (b) anterior/posterior direction, while subject's eyes were open.

(a) component $x$

| | $a$ | $b$ | $c$ | $R^2$ |
|---|---|---|---|---|
| Romberg's posture | 0.98 | −0.29 | −5.85 | 0.97 |
| Posture I | 1.32 | −0.24 | −5.87 | 0.96 |
| Posture II | 1.28 | −0.11 | −5.60 | 0.86 |

(b) component $y$

| | $a$ | $b$ | $c$ | $R^2$ |
|---|---|---|---|---|
| Romberg's posture | 0.78 | −0.09 | −5.72 | 0.81 |
| Posture I | 1.01 | −0.31 | −5.87 | 0.98 |
| Posture II | 1.42 | −0.50 | −5.95 | 0.98 |

Table 2. Coefficients of the potential function in each component: (a) lateral direction $x$, and (b) anterior/posterior direction, while subject's eyes were closed.

(a) component $x$

| | $a$ | $b$ | $c$ | $R^2$ |
|---|---|---|---|---|
| Romberg's posture | 0.55 | −0.16 | −5.67 | 0.87 |
| Posture I | 0.90 | −0.18 | −5.78 | 0.92 |
| Posture II | 2.52 | −0.97 | −5.75 | 0.89 |

(b) component $y$

| | $a$ | $b$ | $c$ | $R^2$ |
|---|---|---|---|---|
| Romberg's posture | 0.78 | −0.08 | −5.77 | 0.92 |
| Posture I | 1.00 | −0.30 | −5.84 | 0.96 |
| Posture II | 0.81 | −0.17 | −5.79 | 0.93 |

## Appendix A. Appendix Material

The subjects used in the study included 32 elderly males and females (mean age ± standard deviation: 72.3 ± 4.99 years) with no prior medical history of ear or nervous system disorders. The experiment was explained to the subjects and written consent was obtained before testing.

Stabilometry was performed in three postures using a random order: Romberg's posture, posture I and posture II. The stabilometer used was a gravicorder (GS3000, ANIMA Corp.), with a sampling frequency of 20 Hz. The posture with heels together was an upright Romberg's posture with open tiptoes. After resting for 30 s, consecutive 1-min body sway measurements were completed, with both open and closed eyes. In the tests with open eyes, subjects were instructed to look at a gazing point placed 2 m in front of them, at the eye level.

The center of pressure (COP) is the point on the area of the supporting base where the total sum of a pressure field acts. The projection of a subject's center of gravity in the $x$ (right direction, designated as positive) and $y$ (posterior direction, designated as negative) directions onto a detection stand is expected to be measured as a COP, an average of the pressure of both soles. The COP is traced for each sampling time, and the time series data is traced onto an $x - y$ plane. By connecting the temporally vicinal points, a stabilogram is created.

Histograms of the stabilograms obtained from tests on all postures were prepared. Each stabilogram was processed by subtracting the series mean from each time-series to set the center of the stabilogram at the origin (0, 0). A comparison of the histograms showed that the stabilogram distribution near the origin in the $x$ direction increased in the postures I and II as compared to that in Romberg's posture, suggesting that stabilometry in the postures I and II reduces the body sway in the $x$ direction.

Using Eq. (3), potential functions to control upright postures (Fig. 2) can be obtained from the histograms of all subjects in this study. The potential function $U_z$ was herein regressed by a polynomial of degree 2:

$$\hat{U}_z = az^2 + bz + c \tag{A.1}$$

whose coefficient of determination was sufficiently greater than 0.8 (Tables 1 and 2). Coefficients of the regression polynomials were also shown in Tables 1 and 2. The coefficients in the Eq. (A.1) were estimated by the least square method. In the lateral component $x$, the coefficient of degree 2, $a$ was smaller in the Romberg's posture than that in the posture II. The lateral body sway in the posture II could be observed around the origin. Thus, the system to control upright posture II is regarded as a stable one.

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