# On the control of balance during quiet standing

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## Abstract

**A computer-interfaced balance board, with facilities for data capture and analysis, and with provision for various forms of biofeedback, was built primarily as a balance retraining aid for stroke and head injury victims and for amputees. The opportunity was taken to do a modelling study of the human balance control system as it presents itself during quiet standing; to apply principles of optimum stability; and to try to identify patterns among those recorded which might be indicative of predominant visual/somatosensory control on the one hand and predominant vestibular control on the other.**

## Introduction

The ability to maintain an upright stance at rest is very well developed in healthy human beings, but its apparent ease belies the complicated underlying biological control mechanisms [1]. Some or all of these may be impaired to a greater or less extent under pathological conditions such as brain damage due to stroke or head injury, or necessary adjustment to prostheses following leg amputation. As part of our continuing contribution to the rehabilitation of disabled people, we designed and built a computer-interfaced balance board for use by the Physiotherapy Department at Ireland's National Rehabilitation Hospital. Brief details of its features and use are given below. We availed of the opportunity to study the literature on human balance during quiet standing and to synthesise the works of others, notably Nashner [2,3,4], Hemani *et al.*[5,6] and Pal'tsev *et al.*[7,8] into a reasonably comprehensive model. This contains four dynamic feedback control paths, involving visual and somatosensory effects and two vestibular paths, involving the *otoliths* and the *semicircular canals*. For the purpose of stability analysis, we divided these into two groups, visual/somatosensory and vestibular, and explored various approaches to optimum stability design. The tools which proved most useful were parameter plane, root locus and Nyquist, such as are treated in hundreds of undergraduate textbooks on automatic control ( e.g. Dorf and Bishop [9] ) and have been developed by de Paor [10,11]. Root locus and Nyquist analysis were accomplished using Program CC [12]. We proposed optimum stability designs for each of these two subsystems and then combined them into an overall scheme, parametrised by a single coupling constant which has a range from 0 ( purely visual/somatosensory) to 1 ( purely vestibular). We injected Gaussian random noise into a state variable model set up under SIMNON [13], computed autocorrelation functions of the model's output ( angle of misalignment from the vertical in the saggital plane).and compared these with autocorrelations of stabilograms recorded from our clients. We feel that we have had some success in thereby classifying the recorded patterns.

## Experimental Methods

In order that it rest stably on all floor surfaces, we designed our balance board as an equilateral triangle--made of wood, with a metal substructure--63 cm on the side. It is supported by three metal legs at the apices. Each of these, terminated in a hemisphere, is fitted with a pair of strain gauges, responsive to axial compression. Adjacent to each leg is a shorter pillar, carrying two unstressed or *dummy* gauges. The four gauges at each apex are connected in a Wheatstone bridge configuration, to give a dc output voltage proportional to the force borne by each leg. Each dc signal voltage is amplified on site by a high quality instrumentation amplifier, INA102, and then routed to the computer via an Analogue Devices Real Time Interface Card, RTI 800.The sampling frequency used is 50Hz. The software developed has many features, some of which are summarized here. The Centre of Force, computed from the three pillar voltages, can be displayed in real time, superimposed on a vertical view of the plate. A dc offset routine allows it to be set to the centroid of the triangle, so that subsequent motion can be displayed relative to that point. Crosshairs can be brought up on the screen, to be rubbed out by bringing the centre of force over them. A moving circular target can be made to spiral out from the centroid, to be tracked by the centre of force. A tone can be activated, whose frequency increases with distance of the centre of force from the centroid or from the moving target. The display can be divided into a number of squares, with colour determined by dwell time of the centre of pressure. A thick arrow can be called up, pointing in the direction in which the subject must move their centre of force to attain the centroid. A three-column display can be placed adjacent to the image of the plate, with dynamically varying heights indicating the forces borne by the three pillars. Autocorrelograms and Power Spectra of saggital and lateral displacements of the centre of force from the centroid can be computed and displayed. Diffusion Coefficients and Scaling exponents of a Random Walk model, as discussed by Collins and De Luca [14], can be graphed.

## Analysis and Results

The model which has guided our thoughts is shown in transfer function form on Figure 1.

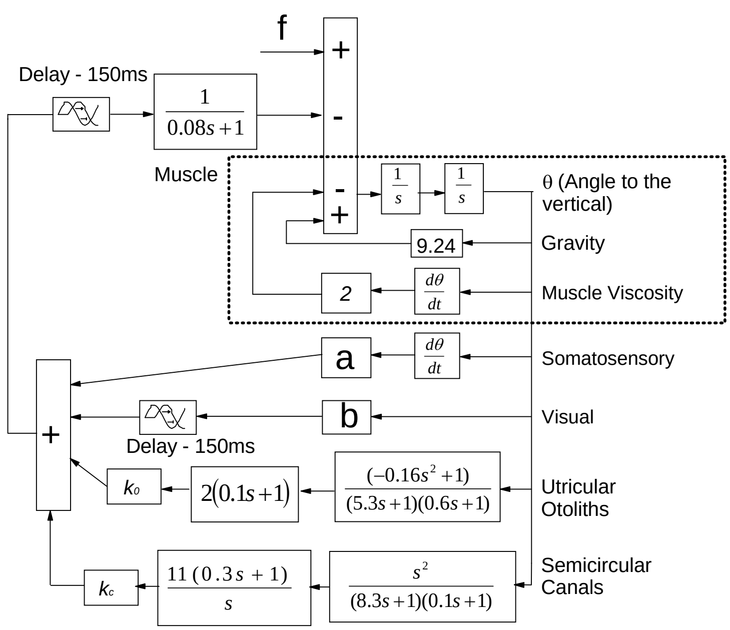


**Figure 1 Block diagram representation of the system**

This model has been inferred from the sources mentioned in the Introduction. The portion in the dashed box in the upper right hand corner represents an inverted pendulum. The figure 9.24 comes from Hemani *et al.* [6], and is based on an average human being with mass 74.2 kg, height of centre of gravity 0.93 m, and moment of inertia for saggital sway 73.27 kg $m^2$. The figure 2, representing viscous damping at the ankles, comes from Pal'tsev and Aggashyan [7]. We have simulated this model in state variable form using SIMNON and in transfer function form using

Program CC--with the time delays approximated by simple first order Padé approximations. ( It is noteworthy that the stability boundaries obtained by experimenting on the SIMNON model, which incorporates true time delays, are practically indistinguishable from those obtained using Routh, Root Locus and Nyquist routines on the simplified Program CC model).
Setting $k_o = 0$ and $k_c = 0$, we have computed the (*a*,*b*) parameter plane boundary shown on Figure 2, using the Routh routine in Program CC, backed up by experimentation on the SIMNON model.

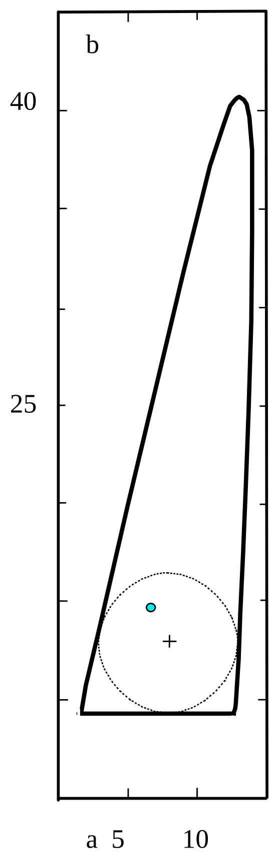


**Figure 2 Stability boundary (a,b)**

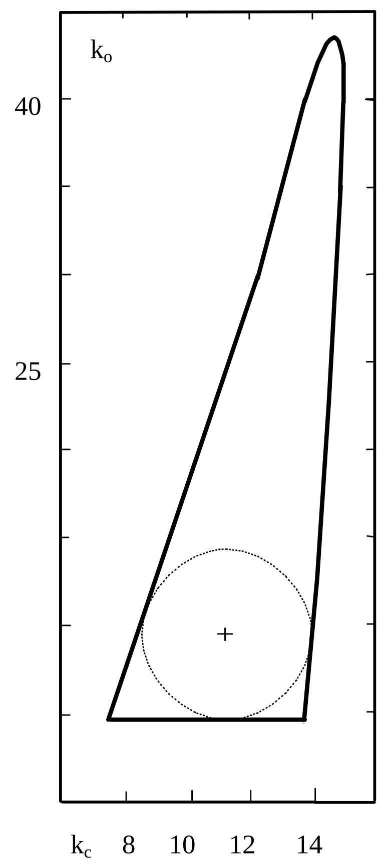


**Figure 4 Stability boundary ($k_c$,$k_o$)**

This suggests that one possible optimum stability design--for stability is the paramount consideration here--might be based on the generalised Vector Margin, which is the minimum perpendicular distance of the design point from the boundary. To optimise this measure, we place the largest possible circle within the domain of asymptotic stability and take the design point as its centre, resulting in $a = 8.3$, $b = 14$.This gives a very well damped impulse response to the SIMNON model, with a slight undershoot of the equilibrium condition, $\theta = 0$.However, we have been able to eliminate the undershoot by doing a root locus study on the CC model and invoking another optimum stability criterion--that the rightmost eigenvalue should lie as deep in the left half plane as possible. This criterion has been especially explored by de Paor [10, 11]. It is illustrated by the following analysis.
For $k_o = 0$, $k_c = 0$, the characteristic polynomial of the CC model is

$$P(s) = r_1 + a r_2 + b r_3 \qquad (1),$$

with

$r_1 = (s - 2.2)(s + 4.2)(s + 12.5)(s + 1/.075)^2$

$r_2 = -12.5s(s - 1/.075)(s + 1/.075)$

$r_3 = 12.5(s - 1/.075)^2$ (2).

For any chosen value of *a*, it is possible to plot the root locus of P(s) for *b* varying in the range $0 \le b < \infty$, by applying the Root Locus routine of Program CC to the transfer function

$mb = r_3/(r_1 + ar_2)$ (3).

Various topologies result. By experimentation, later refined by a numerical optimization routine, we have found that for *a* = 6.736 the plot shown on Figure 3 is obtained. This exhibits optimum stability for *b* = 14.76, since under that condition the negative real breakpoint is directly in line with the complex conjugate eigenvalues and the rightmost eigenvalue is therefore as deep in the left half plane as possible. The corresponding design point, (6.736, 14.76), is marked on Figure 2, just above and to the left of the optimum vector margin point. This gives a beautifully smooth single-signed impulse response to the SIMNON model.

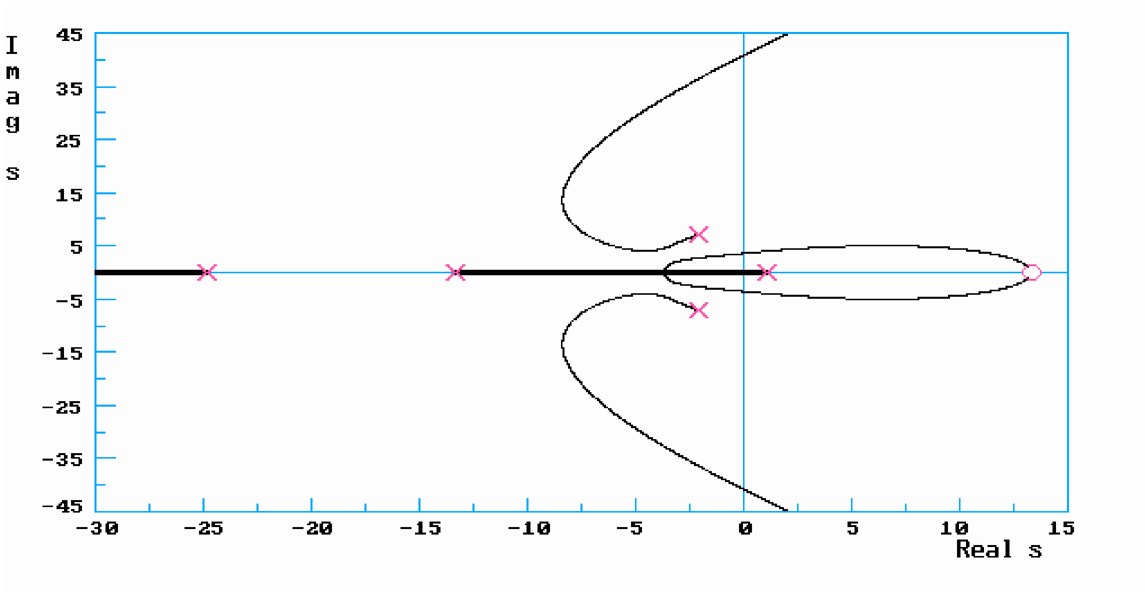


**Figure 3 Optimum stability root locus**

If in general we define a parameter vector

$\boldsymbol{P} = (a, b, k_c, k_o)$ (4),

This procedure gives our first value

$\boldsymbol{P(1)} = (6.736, 14.76, 0, 0)$ (5)

for use in subsequent analysis.

For *a* = 0, *b* = 0, the stability boundary in the ($k_c$, $k_o$) parameter plane is shown on Figure 4. The generalised vector margin design point is $k_c = 14$, $k_o = 7.3$ and root locus analysis gives nothing better in this case. The corresponding impulse response is quite underdamped, but this is in line with vestibular-dominated responses reported in the literature [7,8].

Accepting generalised vector margin design of the vestibular system we obtain the second parameter vector for subsequent analysis

***P(2) =*** (0, 0, 14, 7.3) (6).

We now explore the possibility that in general, human balance is governed by a compromise between optimum stability visual/somatosensory and optimum stability vestibular designs, as given by the parameter vector

$$\boldsymbol{P} = \boldsymbol{P(1)} + g\{\boldsymbol{P(2)} - \boldsymbol{P(1)}\}, \qquad 0 \le g \le 1, \qquad (7).$$

At the outset of this exploration, we assume that in quiet standing, without breathing, the human balance control system is excited by Gaussian Random noise, injected as is f on Figure 1. We applied such an input, using the facilities incorporated in SIMNON, and computed autocorrelation functions of the resulting outputs. We then compared these with patterns recorded from our subjects. Some results are shown on Figure 5.

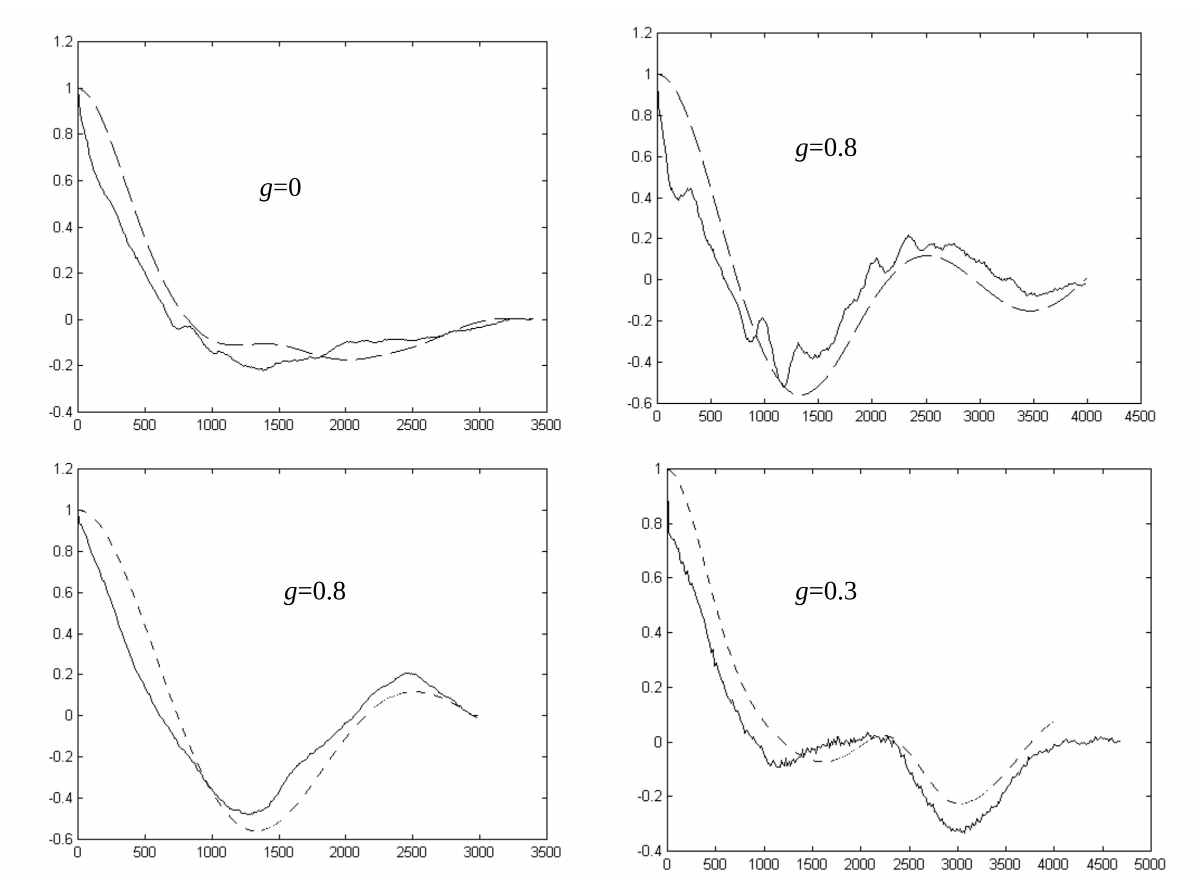


**Figure 5 Subject (solid line) and model (dashed line) autocorrelograms. Abscissae are in milliseconds and ordinates normalised.**

## Discussion

We are quite encouraged in our approach by the way in which the model matches the general features of autocorrelograms computed from real client data. By refining the model in various ways, such as tuning the parameters 9.24 and 2 from the inverted pendulum subsystem and including some mild non-linearities suggested by Nashner [2,3,4], we expect that matters could be further improved. For readers interested in the theory of automatic control, it is hoped that the brief discussions of approaches to optimum stability may be of interest.

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