Balance Platform: Mathematical Modeling for Clinical Evaluation

Daniel Contarino,[1,2] Guillermo O. Bertora,[2] and Julia M. Bergmann[2]

[1]*Megasynergy S.A, and* [2]*Neurofisiologia Otooftalmologica, Buenos Aires, Argentina*

Abstract: This study describes from a technological and mathematical point of view a systematic method for daily patient equilibrium evaluation during clinical work. We present the hardware commonly used for center-of-gravity determination and the basic tasks of the software that runs in a personal computer, including an original procedure for rehabilitation measure. Using a simple approach, the method allows quantification of amelioration of the patient's condition and provides very useful (and, in practice, effective) distribution percentages for visual, somatosensory, and vestibular contributions to stability or sensory equilibrium organization.

Key Words: balance; equilibrium; platform; posturography; rehabilitation; stability

DATA CAPTURE

The most common (and widespread) technique for evaluating a patient's equilibrium in static condition is study of the center-of-gravity (COG) projection over the standing surface. To accomplish this, we used a static platform of 50 × 50 cm, which has four pressure sensors (one in each corner), each with a force range of 0–100 kg. Each sensor produces a small voltage proportional to the pressure supported. The platform holds the necessary electronic capability to amplify these signals, convert them to digital format, and transmit the information to a personal computer (PC), using the serial port. The computer receives the information from each pressure sensor with a resolution of 16 bits (a resolution of approximately 2 parts in 100,000, or 0.002%). The PC receives one complete set of measures each 20 msec (or 50 times per second). The special software running in the PC (under Windows) allows for complete COG calculation and further analysis.

COG DETERMINATION

Suppose we have a platform measuring L × L cm that stands on the floor and has four pressure sensors, numbered 1–4 (Fig. 1). With a patient standing on the platform, each sensor receives a pressure or force (F_1, F_2, F_3, and F_4). Figure 2 shows a lateral view: $P = F_1 + F_2 + F_3 + F_4$, the patient's weight. In Figure 2, $Fa = F_1 + F_4$ and $Fb = F_2 + F_3$.

The patient's weight (P), actually distributed along the feet, can be represented as concentrated in the COG's projection. The COG's position in one axis are determined by x_1 and x_2 (x axis). Similar considerations can be made for the y axis. As the platform is still,

$$Fa \cdot x_1 = Fb \cdot x_2 \quad \text{or} \quad x_1 = Fb \cdot x_2/Fa; \quad x_2 = L - x_1$$

so

$$x_1 = \frac{Fb(L - x_1)}{Fa} \quad \text{and} \quad x_1 = \frac{Fb \cdot L}{Fa + Fb}$$

but

$$Fa + Fb = P, \quad \text{so} \quad x_1 = Fb \cdot L/P$$

where L = platform width, $P = F_1 + F_2 + F_3 + F_4$, and $Fb = F_2 + F_3$, all data available to the PC. In a similar fashion, the program computes y_1, establishing the exact position of the COG's projection each 20 msec.

PRELIMINARY ANALYSIS

In the so-called test of balance (TOB), a 30-second test in four different patient conditions, based on the clinical test of sensory interaction on balance (CTSIB), or "foam and dome," proposed by Shumway-Cook and Horak

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Reprint requests: Guillermo O. Bertora, Dr. Med., Republica Dominicana 3388-6P, C1425GKB, Ciudad de Buenos Aires, Argentina. Phone: 005411 4823 8454; Fax: 005411 4215 2359; E-mail: otooftal@vertigo-dizziness.com

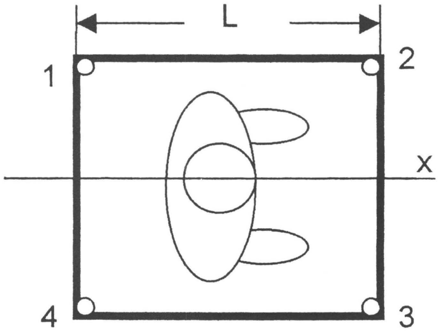

Figure 1. Upper view (sketch) of patient over the platform, with sensor's relative position.

[1], the software acquires a collection of 1,500 sets of *x-y* points for each test. These point sets describe a patient's COG position as a function of time. Performing a simple computational task and knowing a patient's height, the software calculates the COG's angular velocity (in degrees per second).

Five velocity parameters (averaged) are obtained: front, rear, left, and right direction and resultant average velocity (V; in degrees per second). During the test, the program shows the COG's position and the instant velocity in the front-rear and right-left directions. At the end of each test, the software also evaluates the predominant direction of the movement (angle in degrees), the area (A) of the COG's projection (in centimeters squared), and the total displacement (TD) or length (in centimeters) of the COG's projection path. Several relationships are calculated from these parameters.

The four patient conditions that define each 30-second test are:

- Test 1: eyes open, stable surface (EOS)—complete equilibrium information
- Test 2: eyes closed, stable surface (ECS)—somatosensory and vestibular information
- Test 3: eyes open, unstable surface (EOU)—visual and vestibular information
- Test 4: eyes closed, unstable surface (ECU)—vestibular information only

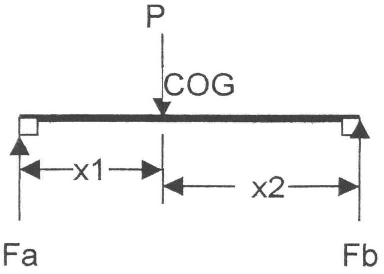

Figure 2. Loaded platform, front view.

The unstable condition (tactile information suppressed or very attenuated) is performed using a thick foam cushion over the platform.

MATHEMATICAL ANALYSIS

Assume that TD, A, and V inversely describe a patient's ability to maintain an equilibrated or stable position over time. The patient's stability coefficients S_n are calculated as $S_n = 1/\sqrt[3]{TD_n \cdot A_n \cdot V_n}$ where *n* is the test number. The idea is to combine the three instability parameters (TO, A, and V), minimizing in the measurement process possible errors or artifacts usually seen in software that uses only one parameter for the calculations (Fig. 3).

Figure 3 shows a possible schematic of the idea of equilibrium. The subject or patient, who must remain still, receives perturbations or "noise" of several types: external (not generated by the test), such as floor vibrations, environmental changes, and wind, and internal (muscular involuntary movements, etc.). The result of these noises are the TD (COG's total movement), A (the area where the majority of the COG points reside), and V (the mean COG's velocity). However, there are mechanisms that try to keep the body still: visual, somatosensory, and vestibular feedback.

Let us assume that Kv, Ke, and Ks are the contributions of each mechanism (visual, vestibular, and somatosensory) to the patient's stability and that S*n* is the stability in test *n* (*n* being 1–4). Making some simplifications concerning the different frequency response of the equilibrium control systems, we can write:

1. $Ks + Kv + Ke = S_1$ condition in test 1 (all systems working)
2. $Ks + \_\_ + Ke = S_2$ condition in test 2 (no visual information)
3. $\_\_ + Kv + Ke = S_3$ condition in test 3 (no somato info)
4. $\_\_ + \_\_ + Ke = S_4$ condition in test 4 (only vestibular information)

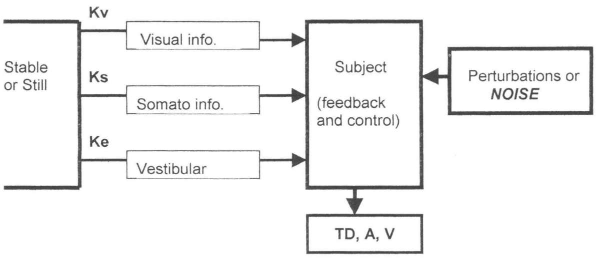

Figure 3. Simple equilibrium system block diagram.

Introducing Eq. 4 in Eqs. 1, 2, and 3, we get:

5. $Ks + Kv = S_1 - S_4$
6. $Ks = S_2 - S_4$
   $Kv = S_3 - S_4$

or introducing Eq. 6 in Eq. 5, we get:

7. $Kv \approx S_3 - S_4 \approx S_1 - S_2$

This double result for Kv is produced because we have four equations (tests) and only three variables. Different tests demonstrate that Eq. 7 is exact within less than 10%. We can assume Kv as the average between both solutions:

8. $Kv = (S_3 - S_4 + S_1 - S_2)/2$

We refer each contribution to the sum of Eqs. 8, 6, and 4, which is $(S_3 - S_4 + S_1 - S_2)/2$. As regards percentages:

$$Pv = \frac{S_3 - S_4 + S_1 - S_2}{S_3 - S_4 + S_1 + S_2} \cdot 100\%$$

visual contribution to stability

$$Ps = \frac{2 \cdot (S_2 - S_4)}{S_3 - S_4 + S_1 + S_2} \cdot 100\%$$

somatosensory contribution

$$Pe = \frac{2 \cdot S_4}{S_3 - S_4 + S_1 + S_2} \cdot 100\%$$

vestibular contribution

To minimize the possible effects of artifacts, we take three 10-second samples in each test, calculating the average of the P's in each case. The software shows in a histogram (with normalized limits) the three sensory percentages, allowing a speedy recognition of the pathology involved in a patient. The weighted total displacement (WTD) is obtained by giving to each TD_n (in each test) the weight related to the percentage of the mechanism involved:

$$\begin{aligned} WTD = {} & TD_1 \cdot (Pv + Ps + Pe)/100 \\ & + TD_2 \cdot (Ps + Pe)/100 + TD_3 \cdot (Pv + Pe)/100 \\ & + TD_4 \cdot Pe/100 \\ WTD = {} & TD_1 + TD_2 \cdot (Ps + Pe)/100 \\ & + TD_3 \cdot (Pv + Pe)/100 + TD_4 \cdot Pe/100 \end{aligned}$$

To allow us to compare successive TOBs in the same patient to demonstrate amelioration of his or her condition, we define an equilibrium score (ES) that compares the first weighted TDs with those obtained in successive tests. Naming WTD_1 as the value obtained in the first TOB performed (initial reference) for each posterior *n* visit, the ES is:

$$ES_n = WTD_1/WTD_n \cdot 100$$

According to this definition, ES = 100 for the first visit and will increase after successive rehabilitation.

PRELIMINARY RESULTS

According to our preliminary results in clinic practices, we observed that young and healthy people show that the three sensory contributions are very close to 33% each. This means that the three systems have similar effects. With increasing patient age, we observed a decrease of the somatosensory and vestibular contribution and an increase of the visual contribution (typically Kv = 50%, Ke = 25%, and Ks = 25%). In Alzheimer's disease, the visual contribution typically decreases to approximately 15%, and the somatosensory or vestibular element (or both) increases to make up the difference to 100%. In a patient with congenital high-frequency nystagmus, the software also calculates a low visual contribution.

REFERENCE

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