XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

RECONSTRUCTING THE OSCILLATIONS OF THE CENTER OF MASS OF THE HUMAN BODY IN UPRIGHT STANDING

P.G. Morasso[1], G. Spada[2] and R. Capra[2]
[1]University of Genova, DIST, I-16145, Genova, Italy
[2]Hospital La Colletta, Center of Bioengineering, I-16011 Arenzano, Italy

Abstract: *The stability of upright posture is usually analyzed by means of force platform measurements. The outcome is the trajectory of the Center of Pressure* (COP) *of the ground reaction. This point is not coincident with the projection of the Center of Mass* (COM) *on the support surface and the evolution of the* COM-COP *difference is a physiologically significant variable. In the paper an algorithm is described for recovering the* COM *from the* COP: *it is based on a dynamic model (the postural inverted pendulum) and the integration of the corresponding ordinary differential equation by means of a variational approach based on spline functions.*
Keywords: IMEKO, World Congress, Human Functions Measurement.

1 INTRODUCTION

Sway is the persistent oscillation of the COM (Center Of Mass); this variable is not measurable in a direct way, although is frequently confused with the COP (Center Of Pressure) that is typically measured by means of a force platform. The difference between the two trajectories is small but is physiologically and clinically significant [1]. An empirical approach for reconstructing the COM from the COP is based upon the fact that the two trajectories have similar shapes but the COP trajectory appears to be more "noisy"; thus, the computation can be seen as a type of "filtering" [2]. More formal approaches [3,4] take into account that the acceleration of the COM is proportional to the horizontal component of the ground reaction: this force is measured by means of a fully equipped platform and integrated twice, with a technique for recovering the unknown initial conditions. Here we propose a new method that is based on a biomechanical model but does not require to measure the horizontal component of the ground reaction force and thus can operate with a much cheaper force platform.

2 METHOD

Body sway is usually approximated with the oscillations of an inverted pendulum (Fig. 1) in which we can single out the ground reaction force (f_H, f_V), the force of gravity *mg*, and the ankle torque t_{ankle} due to the muscles.

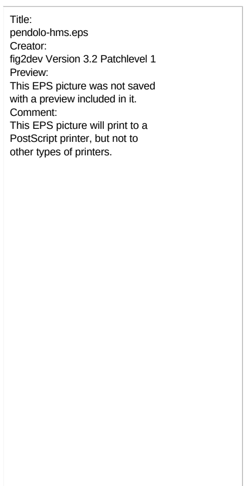

Figure 1. Mechanics of upright standing.

For the foot we can write an equilibrium equation:

$$f_H d + f_V u + t_{ankle} = 0 \tag{1}$$

For the sway movements of the rest of the body the following equations apply:

$$\begin{aligned} & f_V - mg = m\ddot{z} \approx 0 \\ & f_H = m\ddot{y} \\ & t_{ankle} + mgy = \frac{d}{dt}(I\dot{q}) \approx I\ddot{q} \approx mh^2 k_s \frac{\ddot{y}}{h} = mhk_s \ddot{y} \end{aligned} \tag{2}$$

where m is the mass of the body excluding the feet, h is the distance of the COM from the ankle, I is its moment of inertia with respect to the ankle joint, and k_s is a shape factor that depends on the distribution of mass in the body. (For the human body $k_s \approx 1.2$.) There are three approximations in the model, that are well satisfied for sway in quiet standing: (*i*) the vertical acceleration of the COM is negligible, (*ii*) the moment of inertia is constant, and (*iii*) the angular acceleration is proportional to the horizontal acceleration of the COM. We can now combine the four relations, obtaining the following sway equation:

$$\ddot{y} = \frac{g}{h_e}(y - u) \tag{3}$$

where $h_e = hk_s + d$ .The computational task is to integrate Eq. 3 with u as the driving input signal. The problem is that we do not know the initial state. However we know that the solution must be a smooth function of time and we can seek it within a suitable class of functions by means of a variational method. This requires to define a functional to be minimized, using the equation as a constraint. We chose a piece-wise polynomial representation of $y(t)$ in terms of B-spline functions [5] because it is linear_in_the_parameters and thus the solution is known in closed form, by using a LSE method. Moreover, in order to have an algorithm whose performance is independent of the duration of the experiment, we adopted a moving-window paradigm. This means that LSE is iterated on shifted strings of data of duration $\pm T_w$.

The LSE estimation step.

Let m be the number of B-splines, n the number of samples in the window, $\{p_i; i = 1, m\}$ the set of unknown B-spline coefficients. We write the B-spline approximations of $y(t)$ and $\ddot{y}(t)$:

$$\begin{aligned} & y(t) = \Sigma_i \, B_i(t) \cdot p_i \\ & \ddot{y}(t) = \Sigma_i \, \ddot{B}_i(t) \cdot p_i \, . \end{aligned} \tag{4}$$

We apply them to Eq.1 for each instant in the window and thus obtain a linear algebraic system in the unknown parameter vector $\underline{p}$:

$$[A] \cdot \underline{p} + g / h_e \, \underline{u} = \underline{e} \tag{5}$$

where $[A]$ is a matrix of samples of the B-spline functions, $\underline{u}$ is the input vector of platform measurements in the given time window and $\underline{e}$ is the approximation error vector whose norm must be minimized. The solution is obtained by means of the Moore-Penrose pseudo-inverse matrix that minimizes the norm of the error vector $\underline{e}$:

$$\hat{\underline{p}} = -g / h_e \left([A]^T \cdot [A]\right)^{-1} \cdot [A]^T \cdot \underline{u} \tag{6}$$

With this value of the parameter value it is then possible to estimate the position of the COM at the time t_k in the center of the time window:

$$y(t_k) = S_i \, B_i(t_k) \cdot \hat{p}_i \tag{7}$$

The iteration procedure.

The estimation step is performed for each value t_k that identifies the position of the time window, yielding a sequence of COM position values. There are border effects and the simplest way to deal with them is to cut the initial and the final T_w seconds of recorded data. The value of T_w must be chosen according to two contradictory requirements: (*i*) it must be long enough to allow the estimate to be stable, (*ii*) it must be short enough to yield good fit with the cubic polynomials implemented by the B-splines. In practice we found that with the sway signals a window of ± 1 s is appropriate.

All the computations were performed using the spline package of Matlab©. Figure 2 shows an example of application of the algorithm. The COP trajectory was sampled at 50 Hz and then low-pass filtered with a 5 Hz cutoff frequency. The reconstructed COM trajectory is very weakly dependent on the value of h_e.

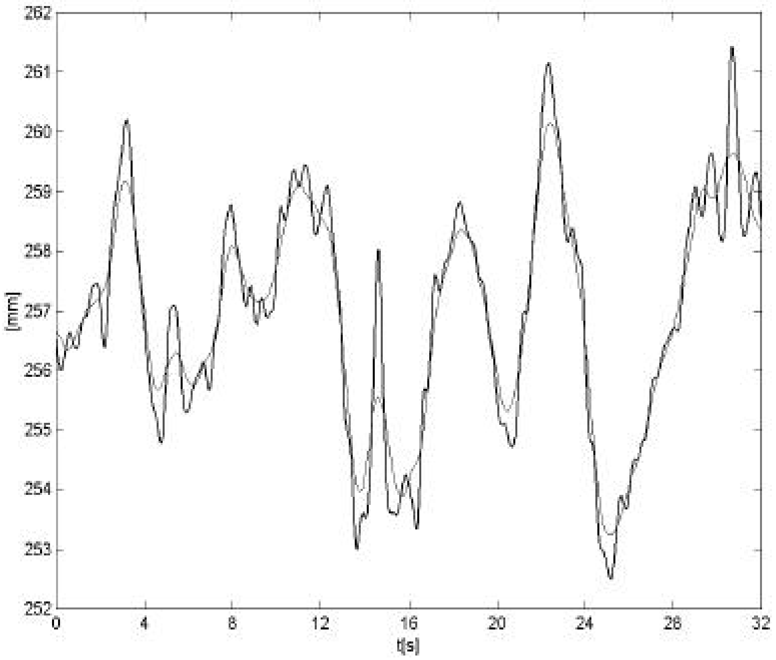

Figure 2. Reconstruction of the COM trajectory. Thick line: COP curve; thin line: reconstructed COM curve.

The validation of the method was carried out by means of an inverted pendulum of known geometry, stabilized by means of springs. The trajectory of the COP was measured by means of the same force platform and the corresponding COM trajectory was measured by means of an optical stereophotogrammetric system (Mac Reflex© by Qualisys) with a reflective marker placed as close as possible to the COM. The COP data were then processed according to the described algorithm, yielding the estimated COM trajectory. The discrepancy among the two values was very low. In particular, the phase error was undetectable at the sampling rate of 50 Hz. Thus it seems that the proposed method of extracting COM data from a basic force platform is reliable and simple enough to be applied in a clinical environment.

3 DISCUSSION

The proposed method exploits the fact that the horizontal acceleration of the COM is approximately proportional to the COP-COM difference. The estimate of this difference may have clinical significance because it has been argued [1] that the brain might estimate it in order to stabilize body sway movements that are associated with an unstable motor system (the body "inverted pendulum").

REFERENCES

[1] P. Morasso, M. Schieppati, Can muscle stiffness alone stabilize upright standing? *J. Neurophysiol.*, 82, 1622-1626, 1999.
[2] B.J., Benda, P.O., Riley, D.E. Krebs, Biomechanical relationship between the center of gravity and center of pressure during standing. *IEEE Trans. on Rehabil. Engineering* **2** (1994) 3-10.
[3] T. Shimba, An estimation of center of gravity from force platform data. *J. Biomech.* **17** (1984) 53-60.
[4] V.M., Zatsiorsky, D.L. King, An algorithm for determining gravity line location from posturographic recordings. *J. Biomech.* **31** (1998) 161-164.
[5] C. De Boor, *A practical guide to splines*, Springer Verlag, New York, 1978.

AUTHORS University Professor Pietro G. Morasso, DIST (Dept. of Informatics, Systems, Telecommunication) University of Genova, Via Opera Pia 13, 16045 Genova, Italy; Fax: +39 010 3532154; Email: morasso@dist.unige.it; W: http://www.laboratorium.dist.unige.it/~piero.
Roberto Capra and Gino Spada, bioengineers, responsible of the Center of Bioengineering, Hospital La Colletta, Via Giappone 3, 16011 Arenzano, Genova, Italy. Fax: +39 010 9134122; Email: colletta@csita.unige.it; W: http://www.laboratorium.dist.unige.it/~gino/CBC.htm.