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ESTIMATION OF THE CENTER OF MASS DISPLACEMENT IN QUIET STANDING BY MEANS OF A 3D BIOMECHANICAL MODEL

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1. Introduction

Body sway has been used as an indicator of balance in quiet standing. In most cases, this has been done using force plate information and particularly the center of pressure (COP). However the center of pressure reflects the response of the neuro-muscular system to the center of mass (COM) excursion (Winter, 1987). Consequently, the measures of the COP are different from those of the COM.

Methods developed to estimate the COM excursion are based on anthropometric data or biomechanical models. Though video-based systems have been shown to be highly accurate, anthropometric measurements are still far from error free. Biomechanical models use force plate information since the position of the COP is related to that of the COM. They can be classified into three methods, namely double integration of the acceleration (Zatsiorsky and King, 1998) low-pass filters (Brenière et al., 1996) and equations of motion (Levin and Mirrahi, 1996).

Three-dimensional (3D) Newtonian mechanics should have the advantage of estimating both the horizontal and vertical displacements of the center of mass and be free of simplifications related to a) the constant height of the COM during body sway, b) the methods for obtaining the constants of integration of the acceleration and c) the similar COM and COP time histories. The objectives of this study were to i) calculate the displacement of the center of mass during quiet standing from a 3D dynamic model of a particle and ii) compare the performance of this model with the results

obtained from a low-pass filter method (Caron et al., 1997) and a 3D videographic technique.

2. Three-dimensional dynamic model of the center of mass

The human body is represented as an inverted pendulum which oscillates about an origin C located at a point lying midway between the ankles (Fig. 1). The x axis is positive in the postero-anterior direction; the y axis is directed towards the left and the z axis is upwardly oriented. The center of mass, G_{b-f} (body less feet) is modeled as a particle of body weight \vec{W}_{b-f} having an acceleration \vec{a}_{b-f} . Body weight is measured by the force plate while its position relative to the origin, C is determined from anthropometric tables (Winter, 1990) and by the reaction board method. The weight of the feet, \vec{W}_f is located at the midpoint, G_f of a line joining the center of mass of the right (G_{rf}) and left feet (G_{lf}). Anthropometric tables are also used to estimate the weight of the feet. The ground reaction force, $\vec{F}_{g/f}$ is acting at point P_a which lies on the force plate. It is assumed that the joint reaction force, $\vec{F}_{f/b-f}$ and moment, $\vec{C}_{f/b-f}$ act at the origin, C.

For the feet, the second equation of motion about the origin, C is

$$\vec{C}_{b-f/f} + \vec{M}_{\vec{F}_{g/f},C} + \vec{M}_{\vec{W}_f,C} + \vec{M}_{\vec{F}_{b-f/f},C} = \vec{\delta}_{f,C} \quad (1)$$

where $\vec{\delta}_{f,C}$, the product of the moment of inertia by the angular acceleration, is zero since the feet are fixed and $\vec{M}_{\vec{F}_{b-f/f},C}$ is also zero because it has no moment arm. Equation 1 becomes

$$\vec{C}_{f/b-f} = \vec{M}_{\vec{F}_{g/b-f,C}} + \vec{M}_{\vec{W}_f,C} \quad (2)$$

For the whole body less the feet, the second equation of motion about the origin, C is

$$\vec{C}_{f/b-f} + \vec{M}_{\vec{F}_{f/b,C}} + \vec{M}_{\vec{W}_{b-f,C}} = \vec{\delta}_{b-f,C} \quad (3)$$

Again $\vec{M}_{\vec{F}_{f/b,C}}$ is zero.

Since $\vec{\delta}_{b-f/C} = \vec{CG}_{b-f} \wedge \mathbf{m}_{b-f} \cdot \vec{a}_{b-f}$ about C, equation 3 becomes

$$\vec{C}_{f/b-f} + \vec{M}_{\vec{W}_{b-f,C}} = C\vec{G}_{b-f} \Lambda \mathbf{m}_{b-f} \cdot \vec{a}_{b-f} \quad (4)$$

Considering that the feet are fixed, then

$$\vec{a}_{b-f} = \vec{a}_b \text{ and}$$

$$\mathbf{m}_{b-f} = (1-K) \cdot \mathbf{m}_b \quad (5)$$

with K is equal to m_f / m_b . Furthermore,

$$\mathbf{m}_b \cdot \vec{a}_b = \vec{F}_{g/f} + \vec{W}_b \quad (6)$$

Combining equations 4 to 6 yields

$$\vec{C}_{f/b-f} + C\vec{G}_{b-f} \Lambda (1-K) \cdot \vec{W}_b - C\vec{G}_{b-f} \Lambda (1-K) \cdot (\vec{F}_{g/f} + \vec{W}_b) = \vec{0} \quad (7)$$

This becomes

$$\left\{ \begin{array}{l} C'_x - F_z \cdot y + F_y \cdot z = 0 \\ C'_y + F_z \cdot x - F_x \cdot z = 0 \\ C'_z - F_y \cdot x + F_x \cdot y = 0 \end{array} \right\} \quad (8)$$

and where x, y and z are the coordinates of the center of mass of the body less the feet with respect to C and

$$\vec{C}'_{f/b-f} = \begin{bmatrix} C'_x \\ C'_y \\ C'_z \end{bmatrix} = \frac{1}{1-K} \cdot \vec{C}_{f/b-f},$$

$$\vec{F}_{g/f} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}, C\vec{G}_{b-f} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Equation 8 can be solved by adding the following constraint. The distance, r between the center of mass less the feet and C, is constant.

$$x^2 + y^2 + z^2 - r^2 = 0 \quad (9)$$

Substituting equation 8 into 9, three second order equations are obtained and solutions are

$$\begin{aligned} x_{1,2} &= \frac{C'_z \cdot F_y - C'_y \cdot F_z \pm \sqrt{\Delta_x}}{|\vec{F}_{g/f}|^2} \\ y_{1,2} &= \frac{C'_x \cdot F_z - C'_z \cdot F_x \pm \sqrt{\Delta_y}}{|\vec{F}_{g/f}|^2} \\ z_{1,2} &= \frac{C'_y \cdot F_x - C'_x \cdot F_y \pm \sqrt{\Delta_z}}{|\vec{F}_{g/f}|^2} \end{aligned} \quad (10)$$

with

$$\Delta_x = (C'_y \cdot F_z - C'_z \cdot F_y)^2 - |\vec{F}_{g/f}|^2 \cdot (C'_y{}^2 + C'_z{}^2 - F_x^2 \cdot r^2)$$

$$\Delta_y = (C'_z \cdot F_x - C'_x \cdot F_z)^2 - |\vec{F}_{g/f}|^2 \cdot (C'_z{}^2 + C'_x{}^2 - F_y^2 \cdot r^2)$$

$$\Delta_z = (C'_x \cdot F_y - C'_y \cdot F_x)^2 - |\vec{F}_{g/f}|^2 \cdot (C'_x{}^2 + C'_y{}^2 - F_z^2 \cdot r^2)$$

$$\vec{C}'_{f/1} = \begin{bmatrix} C'_x \\ C'_y \\ C'_z \end{bmatrix} = \frac{1}{1-K} \cdot \begin{bmatrix} y_a \cdot F_z - z_a \cdot F_y + y_f \cdot K \cdot W_b \\ z_a \cdot F_x - x_a \cdot F_z - x_f \cdot K \cdot W_b \\ x_a \cdot F_y - y_a \cdot F_x \end{bmatrix}$$

$$\text{with: } C\vec{P}_a = \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix}, C\vec{G}_f = \begin{bmatrix} x_f \\ y_f \\ z_f \end{bmatrix}$$

Finally, the position of the COM is given by

$$\vec{OG}_b = \frac{\mathbf{m}_f \cdot \vec{OG}_f + \mathbf{m}_{b-f} \cdot \vec{OG}_{b-f}}{\mathbf{m}_b} \quad (11)$$

Equation 10 enables the estimation of the center of mass displacement without requiring a method to determine the constants of integration on the accelerations or using low-pass filters.

3. Experimental procedures

Quiet standing posture was evaluated by means of video and force plate information obtained from a 24 year old subject whose height and weight were 1,85m and 69,7kg respectively. His center of mass determined from the reaction board method was located at 1,051m while the height of the ankle was measured at 0,078m.

A Saga 3D system equipped with 6 cameras was used to film the subject and synchronized to a force plate (Logabex). Prior to the experiment, the subject was fitted with 2,5cm reflective markers over anatomical landmarks (Winter,1990) to determine the COM displacements.

With the subject standing barefooted on the force plate, the heels were aligned and spaced by 23 cm with the midline of the feet pointing externally by 15°. Then, he was asked to stand quietly for a four second period, with the arms on the sides of the body and to focus on a target placed at eye level. Video and force plate data were collected at 50Hz and filtered by a fourth order zero-phase lag Butterworth filter having a cut-off frequency of 4Hz to reduce the noise.

The displacements of the center mass were calculated a) from video data combined with anthropometric information, b) using equation 11 and c) the low-pass filter described by Brenière (1996) and Caron et al. (1997). A discrete FFT was computed to transform the entire COP time history into the frequency domain. The COM angular oscillations were assumed to correspond to the COM positions which were considered as simple periodic functions.

The position of the COM was then estimated by applying an inverse FFT to the filtered COP frequency response. This low-pass-filter was defined by the relative magnitude of the COM with respect to that of the COP as a function of the frequency of the oscillations. This relationship was calculated from the angular momentum equation applied to the body with respect to the COM using an inverse dynamic approach and force plate information.

Since there is no standard of COM displacements, the RMS values of the horizontal trajectory of COM were calculated between the results estimated from the video method and the proposed method based on the Newton-Euler equations of motion and between the video technique and the low-pass filter method.

Results and discussion

Fig. 2 illustrates the displacements of the COM in the antero-posterior direction obtained from video data (VID) and by the inverse dynamic (ID) and filtering (LPF) techniques. The low-pass filter method followed a relatively smooth path. However, there was a lack concordance with the peak values of the COM obtained from the video system. This strong attenuation could be the effect of the filter. Nonetheless, the low-pass filter method provided data which were nearer to those of the video-based system. The trajectory of the COM using the inverse dynamic approach was more irregular but followed the general shape of the COM (VID). Generally, the COM(ID) was relatively near to the COM (VID).

Fig. 3 presents the displacements of the COM in the medio-lateral direction obtained from the

three techniques. Again, the COM(LP) exhibited a very smooth trajectory compared to both the COM(VID) and COM(ID). The COM(ID) oscillated more though its amplitude was relatively low (0,4mm). These irregularities in the COM(ID) which were more pronounced in the medio-lateral direction could be due to sensibility of model to the noise in the force plate data. Nonetheless these variations were of small amplitudes.

Generally, the RMS were low. In the antero-posterior and medio-lateral directions, both the inverse dynamic and low-pass filter methods behaved similarly with an average value of about 0,6mm. It is important to note that the video results were subject to errors in the anthropometric data. Nonetheless the COM(VID) provided useful information since they are essentially the only values which can be used as reference between laboratories. For example, Zatsiorsky and King (1998) reported an average RMS value of 9,0 mm between the results obtained by their technique and a video-based system.

Conclusion

A method based on the Newton-Euler equations of motion was developed to estimate the displacement of the center of mass. This was achieved without fixing the height of the center of mass or by using methods to estimate constants of integration. The horizontal displacements of the center of mass obtained by this method compared favorably to the data obtained by a video-based system and to a method which filters the center of pressure time-history data.

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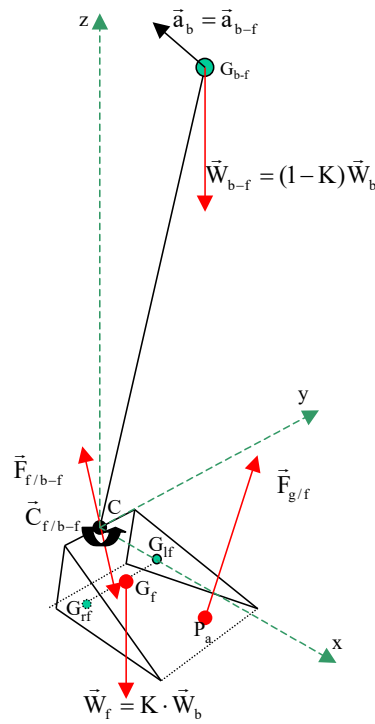


Fig. 1. Biomechanical model.

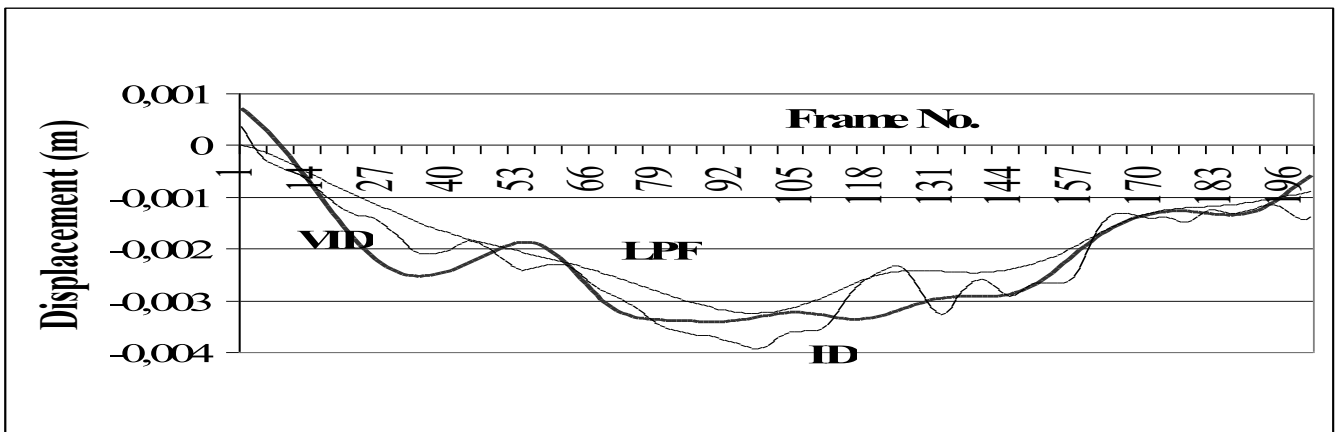


Fig. 2. Antero-posterior excursions of the center of mass calculated by the video (VID), low-pass filter (LPF) and inverse dynamic (ID) methods.

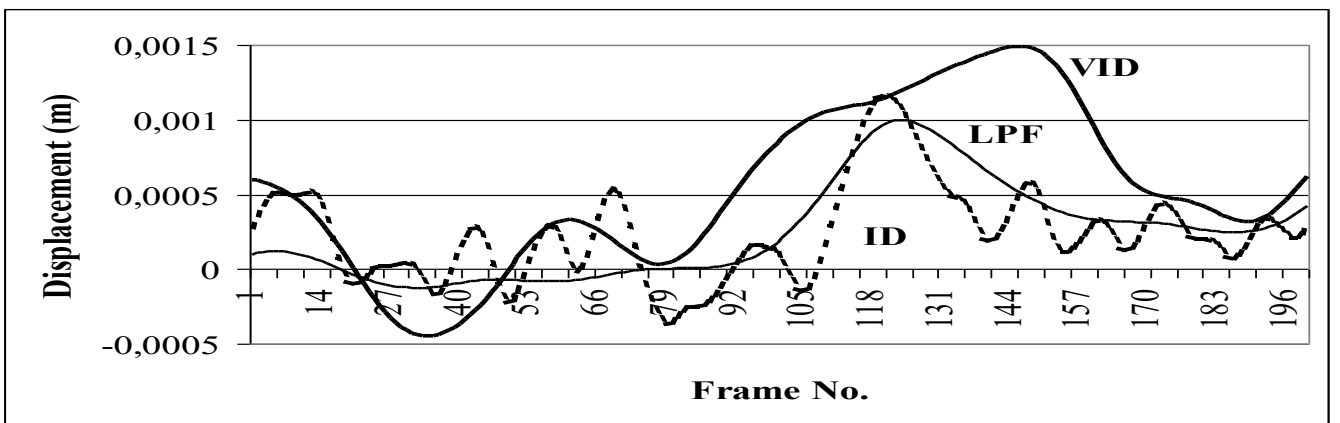


Fig. 3. Medio-lateral excursions of the COM calculated by the video (VID), low-pass filter (LPF) and inverse dynamic (ID) methods.