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Comparison of three methods to estimate the center of mass during balance assessment

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Abstract

Evaluation of postural control is generally based on the interpretation of the center of pressure (COP) and the center of mass (COM) time series. The purpose of this study is to compare three methods to estimate the COM which are based on different biomechanical considerations. These methods are: (1) the kinematic method; (2) the zero-point-to-zero-point double integration technique (GLP) and (3) the COP low-pass filter method (LPF). The COP and COM time series have been determined using an experimental setup with a force plate and a 3D kinematic system on six healthy young adult subjects during four different 30 s standing tasks: (a) quiet standing; (b) one leg standing; (c) voluntary oscillation about the ankles and (d) voluntary oscillation about the ankles and hips. To test the difference between the COM trajectories, the root mean square (RMS) differences between each method (three comparisons) were calculated. The RMS differences between kinematic–LPF and GLP–LPF are significantly larger than kinematic–GLP. Our results show that the GLP method is comparable to the kinematic method. Both agree with the unified theory of balance during upright stance. The GLP method is attractive in the clinical perspective because it requires only a force plate to determine the COP–COM variable, which has been demonstrated to have a high reliability.

1. Introduction

The most common model used to characterise the postural control during quiet standing is the inverted pendulum. In this model, the postural control is defined by the relation between the center of pressure (COP) and the center of mass (COM). The COP oscillates on either side of the COM where the COP displacement always exceeds the COM. The COP is the integrated control variable whereas the COM is the controlled variable (Winter, 1995). The variable COP–COM, which is defined as the time course arithmetic difference of the COP and COM position, is highly correlated to the horizontal acceleration of the COM (Winter et al., 1996). The variable COP–COM is reported as the 'error' of the postural control system and provides important insight into the postural control mechanism. It was recently shown that the root mean square (RMS) error of the COP–COM is greater in elderly with neurological impairments compared with healthy elderly (Corriveau et al., 2000a). Metrological studies also demonstrated that the COP–COM variable has a high reliability in elderly subjects (Corriveau et al., 2000b; 2001).

The COP is defined as the point of application of the ground reaction forces under the feet measured by one or two force platforms. It is the outcome of the inertial forces of the body and the restoring equilibrium forces of the postural control system. The COM is an imaginary point at which the total body mass can be assumed to be concentrated. The position of the COM is hypothesised to be subject to body postural control. For convenience of certain calculations, it can be computed as the weighted average position of the segments. Several methods have been suggested to estimate the COM. The kinematic method (also known as 'segmental method') is based on the definition of the COM and has been frequently used in quiet standing (Hasan et al., 1996a, b; Winter et al., 1998; Corriveau et al., 2000a, b, 2001). Recently, the mechanical relationships between COM and COP during quiet standing allowed researchers

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to define the COM based on Newtonian mechanics (King and Zatsiorsky, 1997; Levin and Mizrahi, 1996; Morasso et al., 1999; Shimba, 1984; Zatsiorky and King, 1998). Since the frequency content of the COP is higher than the COM, other estimation methods have been proposed using a low-pass filter (LPF) on the COP time series (Benda et al., 1994; Caron et al., 1997).

The COM estimation methods based on Newtonian mechanics are attractive in the clinical perspective because they require only a force platform to calculate the COP–COM. The purpose of this study is to compare three different methods to estimate the COM displacement during different standing tasks. Although earlier comparisons have been reported (Eng and Winter, 1993), to our knowledge this is the first time that techniques from three different methods to estimate the COM location are directly compared under different standing conditions. This comparison may help potential users to choose a method for estimating the COM location.

2. Methods

2.1. Protocol and data collection

Six young male adult subjects participated in this study. Informed consent was obtained from each subject before the experimentation. Subjects were instructed to stand barefoot in a side-by-side position on a force platform (model OR5-6, Advance Mechanical Technology Inc, Watertown, USA). They were asked to perform four different standing tasks with eyes open: (a) 30 s of quiet standing; (b) 30 s of one leg standing; (c) 30 s of voluntary oscillation about the ankles and (d) 30 s of voluntary oscillation about the ankles and hips. During the data collection in quiet and one leg standing (tasks 'a' and 'b'), the participants were also instructed to keep their arms hanging at their sides and place their head in a normal forward-looking position and focusing on a fixed target located at eye height approximately 2 m away. For the voluntary oscillation trials, they were requested to oscillate only around the ankle like an inverted pendulum for one trial (task 'c') and using both ankle and hip joints for the second trial (task 'd'). They were also instructed to oscillate without moving their feet or make a step over the force platforms. Before data collection, the subjects were allowed to practice few trials of voluntary oscillations.

The force platform was always allowed to temperature stabilize for at least 45 min before data collection in order to minimize any electronic drifts. One second data with the force platform unloaded was recorded at 20 Hz before each experimental session. The mean bias, which represents the mean shift of the transduced signals, calculated from these data was then removed from experimental data to ensure that force platform data have zero drift after amplification. Three orthogonal ground reaction forces and three moments were collected at a sampling frequency of 20 Hz, converted to a digital signal by a 16 bit A/D converter (model PCI-6033, National Instrument,) and stored in a personal computer. The raw data collected were thereafter filtered with a zero lag sixth-order Butterworth low-pass filter at 10 Hz and transformed (in N and N m) by multiplying the data array by the calibration matrix provided by the manufacturer. The displacement of the COP was calculated using the following equations:

$$\mathrm{COP}_x = \frac{-M_y + F_x \times Z_0}{F_z} + X_0$$

and

$$\mathrm{COP}_y = \frac{M_x + F_y \times Z_0}{F_z} + Y_0, \tag{1}$$

where M is the moment, F the reaction force, x, y and z are the mediolateral, anteroposterior and vertical direction, respectively, and X_0, Y_0, Z_0 are the offsets from the geometric center of the force platform.

2.2. Estimating the COM trajectory in quiet standing

Three methods were chosen in this study to estimate the COM: (1) the kinematic method which is frequently used in postural steadiness studies; (2) the "zero-point-to-zero-point double integration technique" (gravity line projection (GLP) method) and (3) the *"COP Filter method*" (LPF method). These methods are, respectively, based on different biomechanical considerations and will be described in the following sections. The COP and the three estimations of the COM were computed with MATLAB 5.1 software (Mathworks Inc., Natick, MA).

2.3. Kinematic method

The kinematic method is based directly on the definition of the COM. An accurate anthropometric model and full kinematics description of each marker attached on specific proximal and distal bony landmarks of several segments are required (Hasan et al., 1996a; Winter et al., 1998). In particular, the accuracy of the COM location is related to the validity of the mass inertia parameters (MIP) providing the COM position and mass fraction of each segment of the model. In the present study, the anthropometric model was composed of 13 segments (2 feet, 2 shanks, 2 thighs, pelvis, lower trunk, upper trunk and head, 2 total arms). The Zatsiorsky-Seluyanov's MIP were used to estimate the COM location (Lafond and Prince, 2003). Sixteen infrared light-emitting diodes were attached bilaterally to anatomic landmarks to define the anthropometric model of the COM (Fig. 1). Two OPTOTRAK position sensors (Northern Digital Inc, Waterloo, Ont, Canada) recorded markers displacement during the experiment at a sampling frequency of 20 Hz. The resolution of the OPTOTRAK position sensor is 0.01 mm and has a RMS error accuracy of 0.1 mm. Table 1 presents a complete description of the anthropometric model. The COM location in a given direction is calculated as follows:

$$\mathrm{COM} = \frac{1}{N}\sum_{i=1}^{n} \mathrm{COM}_i \times m_i, \qquad (2)$$

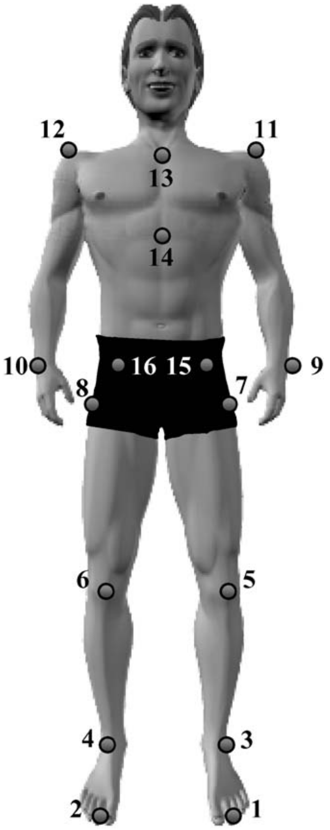

Fig. 1. Location of the 16 LEDs defining the 13-segment model to estimate body COM. See Table 1 for details of bony landmarks definition.

where M is the total body mass, m_i the mass of ith segment, COM_i the coordinate of ith segment and N the number of segments defining the body COM.

2.4. Zero-point-to-zero-point double integration technique

The zero-point-to-zero-point double integration technique was initially proposed by King and Zatsiorsky (1997) and described later in more details (Zatsiorsky and King, 1998). This method is based on the premise that when the horizontal ground reaction forces equal zero, the COP and the vertical projection of the COM, namely GLP, coincide. Therefore, the instantaneous GLP position can be determined by integrating the horizontal ground reaction forces. However, the initial constants of integration have to be determined. Since the COP and GLP coincide at $F_H = 0$, the location of the GLP at this instant can be estimated. Because of sampling of the analog signal from the force platform, it is almost impossible to obtain an exact value of zero of horizontal forces. Initially, Zatsiorsky and King (1998) suggested a preset threshold range of F_H around zero as an approximation of $\mathrm{COP}_H(t_0)|F_H = 0$. However, the threshold range is sampling frequency dependent. With a high sampling rate (200 Hz or more) a smaller threshold range can be used which provides a better estimation of $F_H = 0$ in quiet standing. In this study, the instant at which $F_H = 0$ was estimated by a modified version of the zero-point-to-zero-point double integration technique (Zarsiorsky and Duarte, 2000). A local linear interpolation of the horizontal forces time series was performed throughout the data where F_H changed its polarity. The COP positions at these instants were determined. These zero-force points have been named 'instant equilibrium points or IEP' (Zatsiorsky and Duarte, 1999, 2000). The limitation of other methods proposed to estimate the GLP by double integration of the horizontal forces is that the initial constants of integration, which are the initial position, $x(t_0)$ and the

Table 1
Segments and markers description of the anthropometric model used in the kinematic method

Segment	Endpoints (proximal to distal)	Markers definition of COM	Mass ratio
Upper trunk and head	SPRS/XYPH	1.116 × 15	0.2290
Lower trunk	XYPH/ASIS	0.674 × 16 + 0.326 × (9 + 10)/2	0.1633
Pelvis	ASIS/TRC	0.894 × ((9 + 10)/2) + 0.106 × ((7 + 8)/2)	0.1117
Total arm (2)	ACR/STYL	0.571 × 11 + 0.429 × 13 0.571 × 12 + 0 429 × 14	0.0494
Thigh (2)	KJC/TRC	0.405 × 5 + 0.595 × 7 0.405 × 6 + 0.595 × 8	0.1416
Shank (2)	KJC/LMAL	0.405 × 6 + 0.595 × 5 0.446 × 4 + 0.554 × 6	0.0433
Foot (2)	LMAL/TTOE	0.442 × 1 + 0.558 × 3 0.442 × 2 + 0.558 × 4	0.0137

ACR = acromion; ASIS = anterosuperior iliac spine; KJC = knee joint center; LMAL = lateral malleoli; SPRS = suprasternal; STYL = styloid process; TTOE = tip of 2nd toe; TRC = greater trochanter; XYPH = xyphiod.

initial velocity, $v(t_0)$, are set to zero. Consequently, a drift occurs in the GLP trajectory during the double integration technique and it should be corrected a posteriori. The actual method encompasses this limitation. The second constant, $V(t_0)$, was analytically found using the next COP position when F_H is zero by Eq. (3) given below. The GLP trajectory can be determined in the anteroposterior direction (A/P) and mediolateral direction (M/L) as follows:

1. the first integration constant $\mathrm{COP}(t_0)$ is known and coincides with the GLP at $F_H = 0$, which is estimated with a local linear interpolation as described above;
2. at each interval between $t_i|F_H = 0$ and $t_{i+1}|F_H = 0$, noted by $\mathit{\Delta}_t$, the initial velocity, $v(t_0)$, is determined by

$$v(t_0) = \frac{\mathrm{COP}(t_{i+1}) - \mathrm{COP}(t_i) - \sum_{t_i}^{t_{i+1}} \Delta_t \sum_{t_i}^{t_{i+1}} \frac{F_H(t)}{M}\Delta_t}{(t_{i+1} - t_i)}, \quad (3)$$

3. where $v(t_0)$ is the initial velocity, t_i and t_{i+1} are the successive instants when $F_H = 0$, M is the mass of the subject and Δ_t is the time interval.
4. The GLP time-history is then obtained by integrating twice the horizontal forces

$$\mathrm{GLP} = \mathrm{COP}(t_i) - v(t_i)(t_{i+1} - t_i) + \sum_{t_i}^{t_{i+1}} \Delta_t \sum_{t_i}^{t_{i+1}} \frac{F_H(t)}{M}\Delta_t. \quad (4)$$

2.5. Cop low-pass filter method

This method uses a low-pass filter defined by the relation of the COP and COM in the frequency domain (Caron et al., 1997). According to Brenière (1996), the relative magnitude of the COM with respect to the COP is a function of the frequency of oscillation. The COM trajectory is determined by applying the low-pass filter, which is related to the inertial characteristics of the subject, to the COP frequency content. The following steps detail the procedure to estimate the COM:

1. The COP time series are transformed into the frequency domain by a discrete Fast Fourier Transform.
2. The complex spectrum of the COP time series is multiplied by the low-pass filter, $\phi_{\mathrm{COM}}/\phi_{\mathrm{COP}}$, which is defined as follows:

$$\phi_{\mathrm{COM}}/\phi_{\mathrm{COP}} = \left(mgh/I_{\mathrm{A}}\right)/\left(mgh/I_{\mathrm{A}} + (2\pi f)^2\right), \quad (5)$$

where I_{A} is the moment of inertia of the body around the ankle, f refers to the running frequency, h the height of the COM from the ankle, g the gravity and m the mass of the subject.

3. The moment of inertia of the body around the ankle was calculated using the following equations (Ledept and Brenière, 1994; Rougier et al., 2001):

$$I_{\mathrm{A/P}} = 0.0533 \times mH^2$$

and

$$I_{\mathrm{M/L}} = 0.0572 \times mH^2 \quad (6)$$

where H and m are, respectively, the height and the mass of the subject.

4. The filtered spectrum of the COP is, thereafter, considered to be equal to the spectrum of the COM time series. An inverse discrete Fast Fourier Transform (IFFT) is used to obtain the COM trajectory in the time domain.

2.6. Statistical analysis

To determine the difference between the COM trajectories, the RMS differences between each COM time series (3 comparisons: kinematic–GLP, kinematic–LPF and GLP–LPF) were calculated. An ANOVA was performed to assess the effect of the methods on the RMS differences.

3. Results

The COP trajectory and the COM trajectories estimated for each task of one representative subject are presented (Fig. 2). Our results show that the kinematic–GLP RMS difference is significantly smaller than the kinematic–LPF and GLP–LPF RMS differences in the A/P direction during quiet stance (Fig. 3). We obtained similar results during one-legged stance ($p < 0.001$) and during voluntary oscillation tasks ($p < 0.02$). However, there is no difference between all comparisons of kinematic–LPF and GLP–LPF RMS differences. These results indicate that the COM trajectories estimated by the kinematic and GLP methods are similar.

4. Discussion

The purpose of this study was to compare three different methods to estimate the COM during different standing tasks. The RMS difference between each COM trajectory has been used to determine the effects of these methods on the COM estimation. According to the unified theory of balance during quiet standing, the COP moves anteriorly and posteriorly with respect to the COM (Winter, 1995; Winter et al., 1996). It means the COM trajectory must be within the COP trajectory amplitude to maintain upright standing equilibrium. The COP trajectory always exceeds the COM trajectories

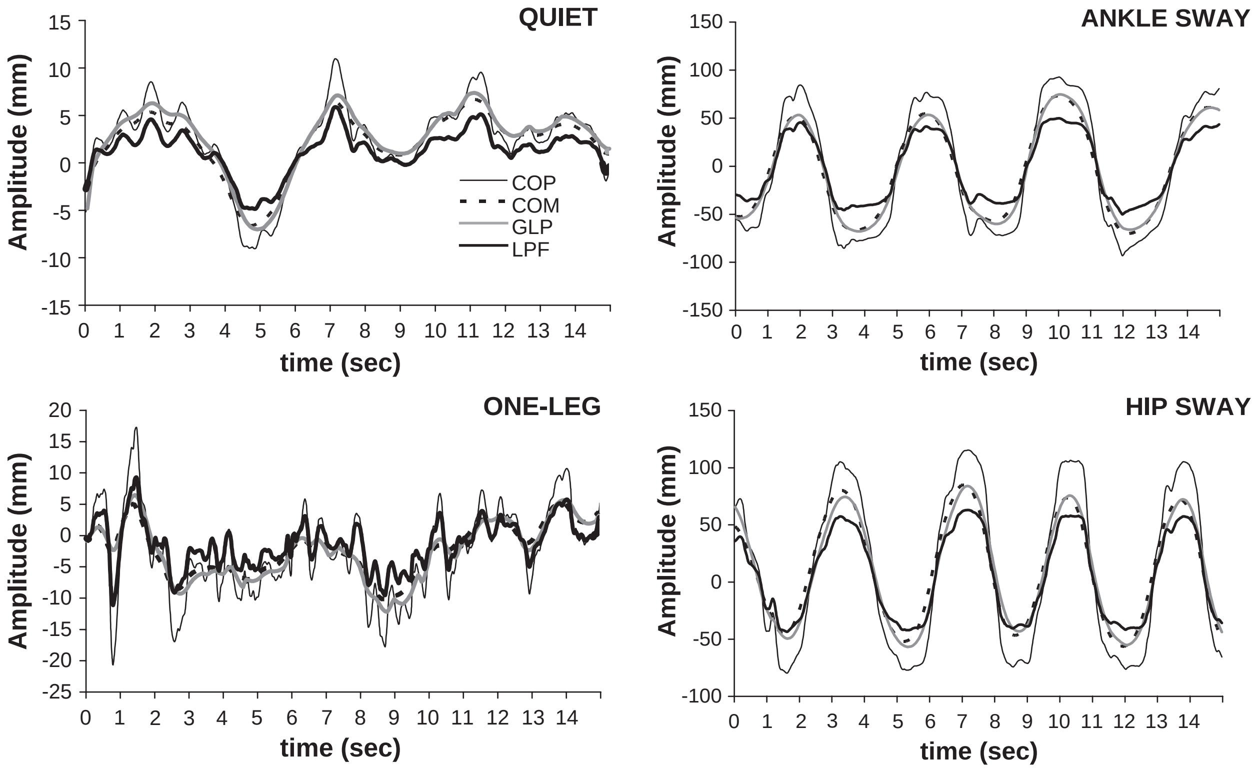

Fig. 2. Trajectories of the COP and COM estimated by the kinematic method (COM), the GLP method and the LPF method during quiet standing, one-legged stance, voluntary oscillation around the ankle and voluntary oscillation at hip and ankle. QUIET = quiet standing; ONE LEG = one legged stance; ANKLE SWAY = voluntary oscillation around ankles; HIP SWAY = voluntary oscillation around hip and ankles.

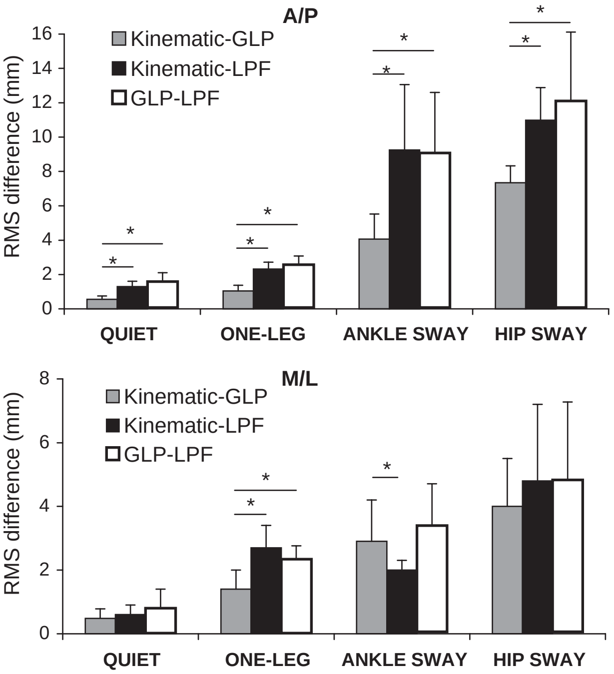

Fig. 3. Average RMS differences (mm) of COM time series between COM estimation methods in A/P and M/L directions. Kinematic–GLP = RMS difference between kinematic method and GLP method; Kinematic–LPF = RMS difference between kinematic method and LPF method; GLP–LPF = RMS difference between GLP method and LPF method. QUIET = quiet standing; ONE LEG = one-legged stance; ANKLE SWAY = voluntary oscillation around ankles; HIP SWAY = voluntary oscillation around hip and ankles.

estimated by the kinematic method and GLP method during all standing tasks (Fig. 2). However, the COM trajectory estimated by LPF method does not totally agree with the COP and COM relationship in quiet standing and one-legged stance. When the acceleration and the displacement of the COM are larger, the LPF method provides a better COM estimation as shown during voluntary oscillation tasks in respect to the COP–COM relationship. However, the amplitude of the COM displacement is underestimated with LPF method during voluntary oscillation tasks explaining a smaller RMS differences between the two other methods.

In conclusion, the GLP method gives similar COM trajectories compared to the kinematics method based on the definition of the COM. Moreover, the GLP and kinematics methods are independent of the standing conditions. The GLP method is very attractive for clinical settings because it only requires a force plate to estimate the COP–COM variable and to quantify the postural control under various somatosensory conditions.

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