A simplified marker set to define the center of mass for stability analysis in dynamic situations

Romain Tisserand, Thomas Robert, Raphaël Dumas, Laurence Cheze

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Author: R. Tisserand T. Robert R. Dumas L. Chèze

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Highlights

- We propose a simplified model based on 13 markers to estimate the whole body CoM.
- We tested it on quiet standing, gait and balance recovery tasks.
- We also tested a reference (38 markers) and a single-marker method.
- The proposed model is a good compromise between accuracy and simplicity.
- It appears particularly appropriate for balance analysis in dynamic situations.

Short Communication

Title: A simplified marker set to define the center of mass for stability analysis in dynamic situations

Author names: R. Tisserand[1], T. Robert[1], R. Dumas[1], L. Chèze[1]

Author affiliations:

[1]Univ Lyon, Université Claude Bernard Lyon 1, IFSTTAR, UMR_T9406, LBMC, F-69622, Lyon, France

Corresponding author: T. Robert

E-mail: thomas.robert@ifsttar.fr

Address: IFSTTAR, UMR_T9406 Case 24, LBMC Laboratoire de Biomécanique et Mécanique des Chocs, 25 avenue François Mitterrand, F69675, Bron, France

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ABSTRACT

The extrapolated center of mass ($XCoM$), a valuable tool to assess balance stability, involves defining the whole body center of mass (CoM_{WB}). However, accurate three-dimensional estimation of the CoM_{WB} is time consuming, a severe limitation in certain applications. In this study, twenty-four subjects (young and elderly, male and female) performed three different balance tasks: quiet standing, gait and balance recovery. Three different models, based on a segmental method, were used to estimate the three-dimensional CoM_{WB} absolute position during these movements: a reference model based on 38 markers, a simplified 13-marker model and a single marker (sacral) model. CoM_{WB} and $XCoM$ estimations from the proposed simplified model came closer to the reference model than estimations from the sacral marker model. It remained accurate for dynamic tasks, where the sacral marker model proved inappropriate. The simplified model proposed here yields accurate three-dimensional estimation of both the CoM_{WB} and the $XCoM$ with a limited number of markers. Importantly, using this model would reduce the experimental and post-processing times for future balance studies assessing dynamic stability in humans.

INTRODUCTION

Falling is a major health problem for the elderly [1]. Position and velocity of the whole body center of mass (CoM_{WB}), combined in the extrapolated center of mass ($XCoM$), are essential variables for dynamic balance characterization [2–5]. However, measuring these variables is not straightforward.

Usually, a segmental method [6,7] is used to estimate the position of each segmental center of mass (CoM_S) from regression equations [8–13]. The CoM_{WB} is then computed as the weighted sum of the CoM_S. However, correct three-dimensional (3D) estimation of the position and orientation of every segment requires placing and tracking numerous skin markers [14,15], which is cumbersome and time consuming. This may be a severe limitation in certain applications (e.g. very young, very old and/or pathological subjects).

Previous studies suggested methods reducing the number of markers used to estimate the CoM_{WB} movement. Recording only the sacral marker trajectory yields satisfactory estimations of CoM_{WB} relative displacement during gait [16,17]. However, 3D absolute position estimation is limited and variability during the movement is high. Applying calibrated punctual masses on specific markers gives satisfactory results with a considerably reduced number of markers [18]. However, this method is movement- and population-dependent, involving preliminary measurement of the CoM_{WB} using a reference method. Other studies computed the CoM_{WB} from the double integration of the reaction forces [19–22]. But this often-recommended method, based on platform measurements, is not suitable for whole body movement capture involving large displacements like gait [23,24].

Our aim was therefore to suggest a method of estimating the CoM_{WB} 3D trajectory that is: 1) based on a reduced marker set; 2) applicable to any type of movement performed by the subject; 3) not subject to a preliminary calibration process; 4) accurate enough to estimate risk of fall based on the $XCoM$.

MATERIALS and METHODS

1. Experiments

24 healthy adults, 12 young (5 females, 7 males, mean age 24.9, height 1.69 m and BMI 23.3) and 12 elderly (6 females, 6 males, mean age 76.1, height 1.66 m and BMI 26.4) participated in this study approved by the local ethical committee. Subjects were equipped with 39 reflective markers located on anatomical landmarks (Figure 1), based on [25]'s palpation method (Table 3 in Appendix) and recorded by 8 cameras (Motion Analysis®). Marker trajectories were filtered at 6 Hz with a double passed Butterworth filter.

Subjects performed three different tasks: quiet standing with eyes open for 25 seconds (T1); straight walk for 10 meters at their comfortable speed (T2); balance recovery task following a waist-pull [26] (T3). The perturbation, applied anteriorly and horizontally, was a squared signal controlled in force (plateau corresponding to 23% of subject's weight) and duration (200 ms), sufficient to induce protective steps [27].

2. Data processing

The 3D position of the CoM_{WB} is estimated from skin markers using three different models:

- Reference model (REF) is a 16-segment whole-body model built on 38 markers (Figure 1 and Table 3 in Appendix). The positions of the CoM_S with respect to the segmental coordinate systems are determined according to regressions from [11,28,29].
- Simplified model (SIMP) uses 13 markers to reconstruct 9 segments (Figure 1). The positions of the CoM_S are considered to be at a percentage of the length between proximal and distal endpoints (Table 1). These percentages were estimated from [12,13]. Hip joint centers are computed using the regression method of [11]. The most distal segments (head, hand and foot) are merged with their respective proximal segments (torso, forearm and leg).

- Sacral model (SAC) estimates the position of the CoM_{WB} as the position of the sacral marker offset by a constant vector (170 mm in anteroposterior, 20 mm in mediolateral and 30 mm in vertical axes according to [17]).

The position of the $XCoM$ in the horizontal plane is then computed with the method described in [2].

In order to compare predictions by the three models we extracted, for each trial, the mean distance (Δ) between CoM_{WB} (and $XCoM$) trajectories estimated by REF, and one of the two other models (SIMP or SAC), in 1D (i.e. X, Y or Z axis) or in 3D. For example, the mean distance between the CoM_{WB} trajectory estimated with REF and SAC models in 3D is:

$$\Delta_{XYZ} = \frac{1}{p}\sum_{i=1}^{p}\sqrt{\left(x_{REF_i} - x_{SAC_i}\right)^2 + \left(y_{REF_i} - y_{SAC_i}\right)^2 + \left(z_{REF_i} - z_{SAC_i}\right)^2} \quad (1)$$

where p is the number of recorded images.

For statistics, Δ distances were compared using Kruskal-Wallis non-parametric tests.

RESULTS

In T1, the mean distances Δ in CoM_{WB} position between REF and the two others models (SIMP and SAC) are comparable, with larger values for Δ_X (Table 2). However, the standard deviations for the SAC model are higher than for the SIMP model.

In both tasks T2 and T3, the SIMP model provides an estimate of the CoM_{WB} position with a Δ_{XYZ} of 10 mm, whereas the SAC model Δ values are three times higher (Table 2). There are no statistical differences between groups and, as for T1, Δ_{XYZ} is largely explained by Δ_X.

Not surprisingly, results for the $XCoM$ are very similar to those of the CoM_{WB}.

DISCUSSION

As found in the literature, the SAC model satisfactorily estimates the CoM_{WB} position in the static task (T1). However, estimation of the 3D absolute position becomes inaccurate in dynamic tasks. This is probably due to the torso and upper limb movements, and decreases the relevance of this model [22,30]. In particular, the SAC model's $XCoM$ estimation in mediolateral axis, which is the most critical for assessing risk of fall [31], gives five time higher Δ values than the SIMP model, roughly the same as the stability margin reported for normal walking [32]. The SAC model thus appears inappropriate to estimate mediolateral stability in dynamic tasks.

Estimations of CoM_{WB} and $XCoM$ positions by REF and SIMP models are very close, as they are based on the same anthropometric data [11–13,28]. Generally, the greatest error is for Δ_X, which is consistent with the literature [14,17,33]. Moreover, 3D errors with the SIMP model are of the same order with marker positioning errors [6] and soft tissue artifact [34].

The proposed simplified marker set resembles that suggested by [22], but differs in including hand and foot segments. Moreover, the present model shows a mean 3D error of 10 mm from the reference method, based on 24 subjects, both young and elderly males and females. In comparison, [22] have a mean 3D error of 30 mm based on 3 young men. This difference in accuracy could be explained by differences between our studies, in the reference method chosen (segmental method versus platform integration) and/or in the movements performed by the subjects.

In this study, we propose a simplified segmental method using a limited number of skin markers (13) that accurately estimates CoM_{WB} and $XCoM$ trajectories. It reduces experimentation and post-processing times, is appropriate for studying stability in dynamic situations and works well for healthy populations, regardless of age and gender. Representing a trade-off between accuracy and simplicity, this model would be useful for estimating CoM_{WB} and/or $XCoM$ positions during movement, in particular for balance analysis.

CONFLICT OF INTEREST STATEMENT

None.

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FIGURE CAPTION

Figure 1: Representation of the three marker sets, adapted from [18]'s picture. Markers used for the REF model are presented on the left. Markers used for the SIMP model are presented in the center. SAC model is presented on the right. White circles represent markers placed in the back with respect to the current position of the picture.

TABLE 1

Segment	Proximal point	Distal point	Coefficients	
			Men	*Women*
Head + Torso	Middle of SAT	Middle of HJC	0.3705	0.3806
Arm (R & L)	SAT	HLE	0.5437	0.5664
Forearm + hand (R & L)	HLE	USP	0.6364	0.6377
Thigh (R & L)	HJC	FLE	0.4260	0.3812
Leg + foot (R & L)	FLE	FAL	0.5369	0.5224

Table 1: CoM_s positions for the SIMP model on longitudinal axis calculated from McConville [12] (for men) and Young [13] (for women) regression tables. Torso segment includes Thorax, Abdomen and Pelvis. Marker names and abbreviations are taken from [25]. SAT = Scapular Acromial Tip. HJC = Hip Joint Center. HLE = Humeral Lateral Epicondyle. USP = Ulnar Styloid Process. FLE = Femoral Lateral Epicondyle. FAL = Fibular Apex of Lateral Malleolus. R = Right. L = Left.

TABLE 2

			Mean distance in mm			
			Young adults		Elderly adults	
		Axis	*SIMP*	*SAC*	*SIMP*	*SAC*
CoM_{WB}	Static (T1)	Δ_X	8.2 (3.7)	10.7 (9.0)	9.7 (1.5)	11.0 (6.5)
		Δ_Y	2.3 (1.7)	3.6 (2.5)	2.8 (2.0)	1.1 (1.6)
		Δ_Z	1.6 (0.6)	2.5 (4.9)	0.9 (0.6)	1.7 (1.6)
		Δ_{XYZ}	8.6 (2.4)	11.5 (6.7)	10.1 (2.8)	11.2 (5.6)
	Gait (T2)	Δ_X	8.0 (3.3)	30.7 (7.9)*	8.5 (2.8)	26.2 (3.3)*
		Δ_Y	2.1 (1.5)	10.8 (6.5)*	2.3 (1.3)	10.2 (8.0)*
		Δ_Z	0.9 (0.6)	8.3 (5.2)*	1.0 (0.6)	9.5 (7.9)*
		Δ_{XYZ}	8.3 (3.2)	33.6 (8.3)*	8.8 (1.9)	29.6 (5.2)*
	Balance Recovery (T3)	Δ_X	7.4 (3.5)	23.7 (10.7)*	9.9 (4.6)	27.1 (6.6)*
		Δ_Y	2.4 (2.4)	9.8 (6.7)*	2.5 (1.5)	13.5 (7.8)*
		Δ_Z	1.7 (0.6)	7.2 (7.0)*	1.4 (0.7)	13.5 (9.4)*
		Δ_{XYZ}	7.9 (2.9)	26.6 (11.2)*	10.3 (2.5)	33.1 (5.7)*
$XCoM$	Gait (T2)	Δ_X	8.1 (3.3)	20.4 (14.7)*	8.9 (4.2)	25.2 (2.4)*
		Δ_Y	2.4 (1.6)	13.1 (10.7)*	2.3 (1.2)	10.1 (8.2)*
		Δ_{XY}	8.5 (2.8)	24.2 (12.8)*	9.2 (2.8)	27.1 (10.1)*
	Balance Recovery (T3)	Δ_X	7.4 (5.0)	21.2 (12.9)*	9.7 (4.8)	23.8 (12.5)*
		Δ_Y	2.3 (1.6)	16.8 (12.0)*	2.3 (1.4)	13.8 (8.0)*
		Δ_{XY}	7.8 (3.4)	27.1 (14.3)*	9.9 (3.5)	27.5 (9.8)*

*Table 2 : Mean distances Δ (standard deviation) of CoM_{WB} and $XCoM$ estimations between tested models (SIMP and SAC) and reference model (REF). * indicates a significant difference ($p < 0.001$) between SIMP and SAC models.*

7b. Figure(s)