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ESTIMATION OF TOTAL BODY CENTRE OF MASS DURING HUMAN WALKING

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1. Introduction

Many studies have been published about human walking. The trajectory of the body centre of mass is often a parameter of interest when studying human walking, as it reflects the motion of the whole body. Alteration of trajectory of the body mass centre may indicate a clinical manifestation of an underlying pathology or only a means of maintaining stability in gait. The centre of mass, in combination with other kinematic and kinetic data, can offer useful parameters for the total evaluation of walking.

Since small displacements of the body centre of mass are important in balance control studies, it is essential to obtain valid estimates of the body centre of mass. The main aim of this study was to describe two methods of estimation of total body centre of mass during walking.

2. Methods

The first method of estimating the trajectory of the body centre of mass is the weighted average for each segment centre of mass, using appropriate kinematic and anthropometric data. This method is called a *Full-body model* method. However, it is difficult to apply this method for clinical gait analysis, because it requires accurate kinematic measurements of all segments of the body.

The other method of estimating the position of the body centre of mass is from force plate data. If it is assumed that the human body can be considered to be a system of rigid multisegments and air resistance and power loss within the link system are absent, the change in position in three dimensions can be calculated by the second time integral of the respective component of the ground reaction force. The equation of linear motion of centre of mass of the body is represented by the following differential equation with time variable t:

$$\frac{\mathrm{d}^2\mathbf{r}_T}{\mathrm{d}t} = \mathbf{a}(t) = \frac{\mathbf{F}}{M} \tag{1}$$

where $\mathbf{a}$ represents the acceleration of centre of mass of the body which is equal F_x/M, F_y/M, $(F_z\text{-}G)/M$ for respective direction where M is mass of total body, F_x, F_y, F_z are components of ground reaction force and G is weight of body (gravity force). The solution of the above equation can be written as follows:

$$r_T(t) = r_0 + v_0 t + \int_0^t \left[\int_0^t a(t)\,\mathrm{d}t \right] \mathrm{d}t = r_0 + v_0 t + S(t) \tag{2}$$

where r_0 and v_0 are unknown initial conditions, r refers to position, v refers to velocity and S represents the definite integral term with variable t which can be calculated from force platform data. Integration of experimental data is prone to inaccuracies in determining constants. Some authors [5] applied linear correction factors to ensure that the trajectory of the body centre of mass was cyclic.

The gait analysis equipment consisted of Elite system with two CCD cameras and a 9-m walkway with Kistler force platform located in the center. Fifty-two subjects (20 women and 32 men) ranging in age from 21 to 36, with no apparent abnormalities of the locomotion system, were studied. The measurement of ground reaction forces and recording of trajectories of characteristic body points on subjects was performed at walking at normal speed (0.95 m/s $\leq v \leq$ 1.7 m/s). Special attention was given to naturalness in walking and a constant walking velocity. Subjects were walking barefoot. The 24 reflective markers have been attached to palpable landmarks at human body. The model for calculating the total body centre of mass has been designed. The landmarks allowed the definition of a 15 segment whole body model which included foot, lower leg, thigh, upper trunk (thorax and abdomen), lower trunk (pelvis), head with neck, upper arm, forearm and hand segments. Markers were placed on skin and it was necessary to approximate the joint centres and centres of mass of a segment. Joint centres have been used as reference points for estimating the positions of the segment centres of mass. The joint centres and centres of mass of segments have been approximated using the data from literature [2, 3, 4]. Values of mass have been calculated using the regression method established by Donsky and Zatsiorsky [1]. An automatised method for determination of the total body centre of mass from full body kinematics has been established. 3D-coordinates of the marked points were the input data for a computer program written in Matlab, which calculates orientations of segments, joint centres and trajectories of the body mass centre. For example, Figure 1 represents original data for three components of ground reaction force for subject No. 01 (walking speed 1.3 m/s) and Figure 2 shows a model of a subject No. 24 during natural walking with drawn calculated trajectory of the body centre of mass.

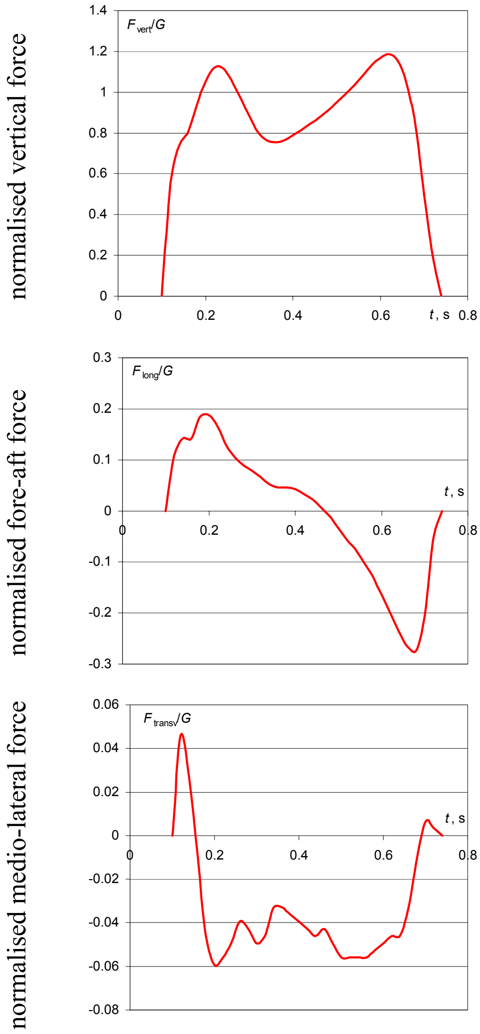


Figure 1. Three components of ground reaction force (subject No. 1, walking speed 1.3 m/s)

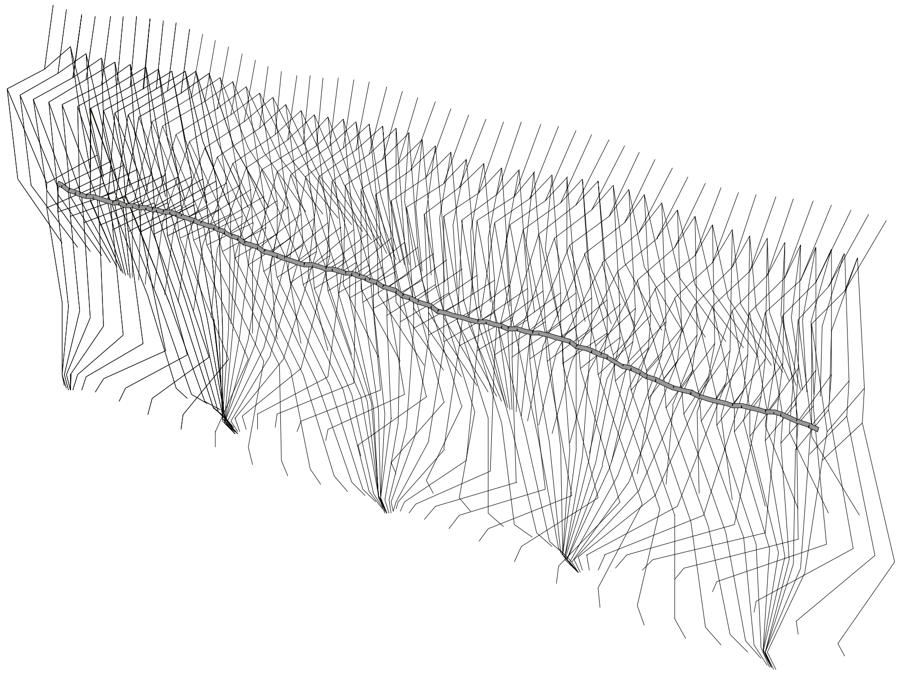


Figure 2. Model of a subject No. 24 during natural walking with drawn calculated trajectory of body centre of mass.

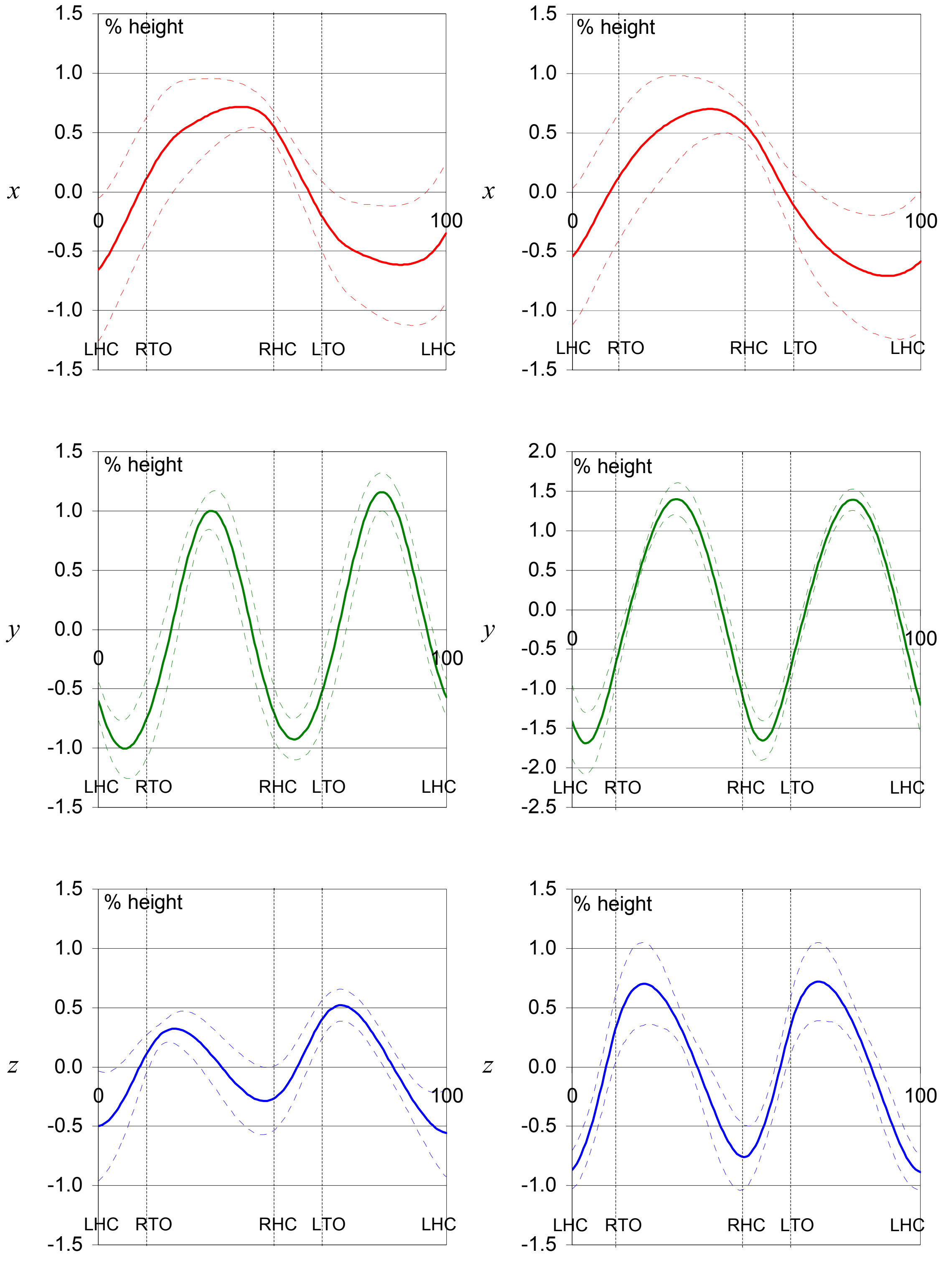
Recorded data were processed and the walking trials with no contact of the entire foot with the Kistler force plate were rejected. Total ground reaction force was calculated from the data obtained by the use of one force plate. When the one foot made initial contact with the force plate, the other foot was still in contact with the ground, but its force were unrecordable. To achieve force data for a full gait cycle, the portion of data that was recorded when the other foot was still in contact at the end of the gait cycle was moved to beginning of the cycle.

In order to be able to compare trajectories of the body centre of mass, the determined data were normalised. The determined trajectories of the body centre of mass were normalised by the subject height to give displacements of centre of mass in percentage of the body height. The original data were averaged by normalising them to one hundred sample points per one walking cycle through spline interpolation. Ground reaction forces for both feet were normalised by body weight and shown as a function of duration of gait cycle. The constants in integration of ground reaction forces were defined as the values reducing the average of acceleration, velocity and displacement per one cycle to zero.

Typical patterns of displacements of the body mass centre in lateral, vertical and fore-aft direction during gait cycle, calculated from two methods, have been established for every subject. *General patterns* and variation bandwidth of the standard deviation have been determined from *typical patterns* of all subjects for both methods. A *general pattern* represented the mean curve of the entire group of subjects studied.

3. Results

Figure 3 shows *general patterns* of displacements of the body centre of mass in three directions calculated by using two different methods - weighted average for each segment centre of mass and twofold integration of ground reaction force data. *General patterns* of displacements were compared (Figure 4) and Table 1 shows the comparison of maximum displacements of the body centre of mass in three directions determined by using both methods.



a) Displacements calculated as weighted sum of the centre of mass of each segment

b) Displacements calculated from ground reaction force data

Figure 3. ***General pattern*** **(mean value ± standard deviation) of normalised displacements of body centre of mass in lateral (*x*), vertical (*y*) and fore-aft (*z*) direction (LHC: left heel contact, RTO: right toe off, RHC: right heel contact, LTO: left toe off)**

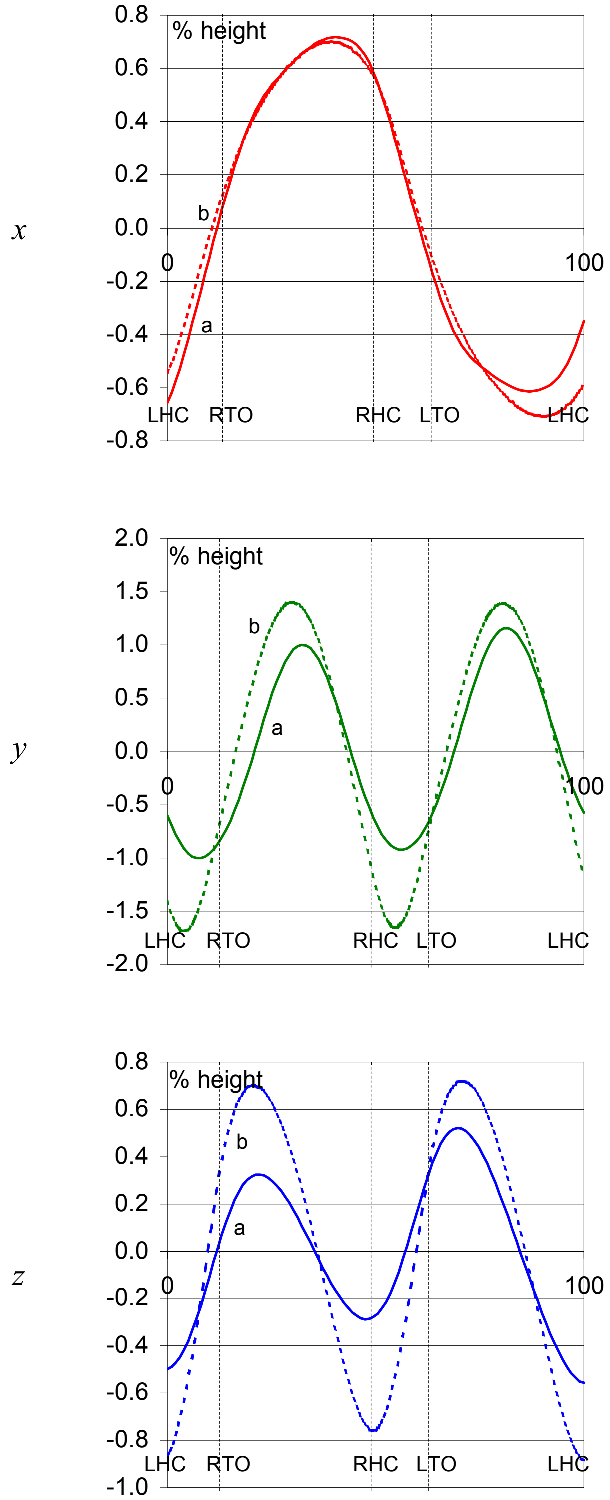


Figure 4. Comparison of *general patterns* of displacements of body centre of mass calculated by using two different methods: a - weighted average for each segment centre of mass (continuos line), b - twofold integration of ground reaction force data (dashed line)

Table 1. Maximum displacements of the whole body centre of mass in three directions determined by using both methods

	maximum displacement in percentage of body height	
direction	weighted average for each segment centre of mass	twofold integration of ground reaction force data
lateral (x)	1.34	1.41
vertical (y)	2.16	3.09
fore-aft (z)	1.07	1.60

4. Conclusion

In this study the 3D displacements of the human body mass centre during walking have been computed by using two methods: weighted average for each segment centre of mass and twofold integration of ground reaction force. We have developed a model and automatised procedure for determination of whole body centre of mass during human walking from full body kinematics. Using this technique we have found similar patterns and displacements of the body centre of mass as we have calculated using the force platform data.

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