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TRAJECTORY OF THE HUMAN BODY MASS CENTRE DURING WALKING AT DIFFERENT SPEED

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1. Introduction

Many studies have been published about human walking. Human walking is result of a series of processes that take place in the neuromusculoskeletal system. The interest in human walking analysis arises from the fact that motion analysis will yield information on underlying (possibly pathological) processes which are not directly observable except by using highly invasive techniques.
The body's centre of mass is a key factor in the analysis of human gait, as it reflects the motion of the whole body. The knowledge of the three-dimensional movements of body mass centre is prerequisite for calculation of walking parameters and design of artificial joints. 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. In balance control studies the body centre of mass can be related to the ground reaction force or to the base of support, which is quite small in biped. 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 centre of mass, in reflecting the whole body motion, can offer useful parameters for the total evaluation of walking, and, in combination with other kinematic and kinetic data, will give a more precise analysis such that practical application is possible.
In clinical gait analysis it is imperative to determine normal walking variations, because this has not, to date, been done. The primary objectives of this study were to describe the inter-subject variation of the motion of the centre of mass in normal walking through determination of the mean and standard deviation and to investigate the influence of walking speed on trajectory of the body mass centre.

2. Methods

The model for calculating the total body centre of mass has been designed. The actual positions of the centre of mass have been calculated from full body kinematics using appropriate kinematic and anthropometric data. The first premise of this method was that the human body could be considered as a system of rigid segments.
Values of mass and centre of mass for each segment have been calculated using the regression method established by Donsky and Zatsiorsky [Donsky 1979]. The 24 reflective markers were used to define a whole body model [Jurcevic 1998, Jurcevic Lulic 1999]. Markers have been attached to palpable landmarks at human body. 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 and 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 centres of mass of upper leg, lower leg, upper arm and forearm lie on lines joining neighbour joint centres. The joint centres and centres of mass of segments have been approximated using the data from literature [Donsky 1979, MacKinnon 1993, De Leva 1996].
A gait analysis has been performed on 52 subjects (20 women and 32 men) in age from 21 to 31 years. None of the subjects had complaints to the locomotion system. Marker coordinates were collected using the Elite system with two CCD cameras. A 9-m walkway has been used for the gait analysis. Special attention was given to naturalness in walking and a constant walking velocity. Ample space at both ends of the walkway has been available to allow the subject to walk at approximately constant velocity. Subjects were walking barefoot and they were asked to walk successively as they felt to be their normal and fast speed. In a set of experiments on each subject, the subject was instructed to walk 20 times: ten were at normal walking speed and ten were at fast walking speed. 3D co-ordinates of the recorded markers were the input data for the computer program which calculates orientations of segments, joint centres, segment mass centres and trajectories of the whole body mass centre. For example, Fig. 1 shows a model of a subject during natural walking with drawn trajectory of the body centre of mass.

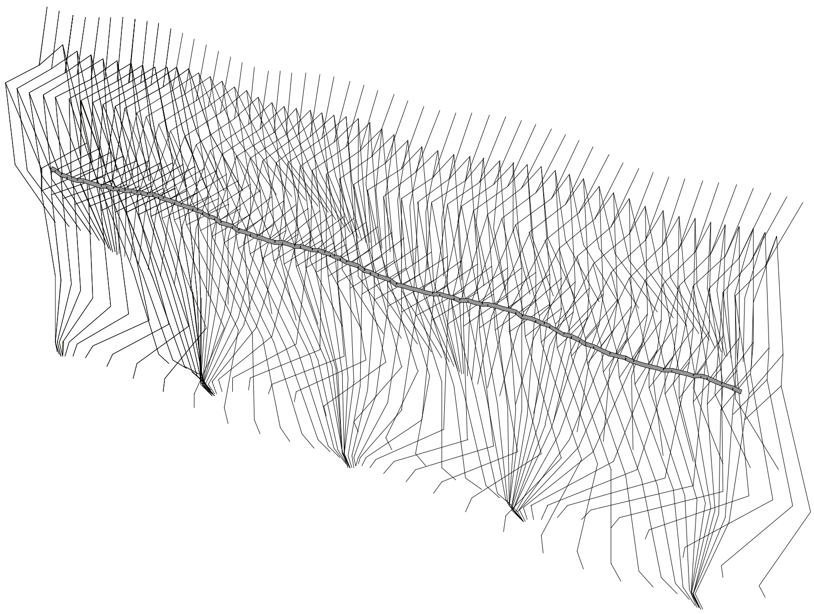
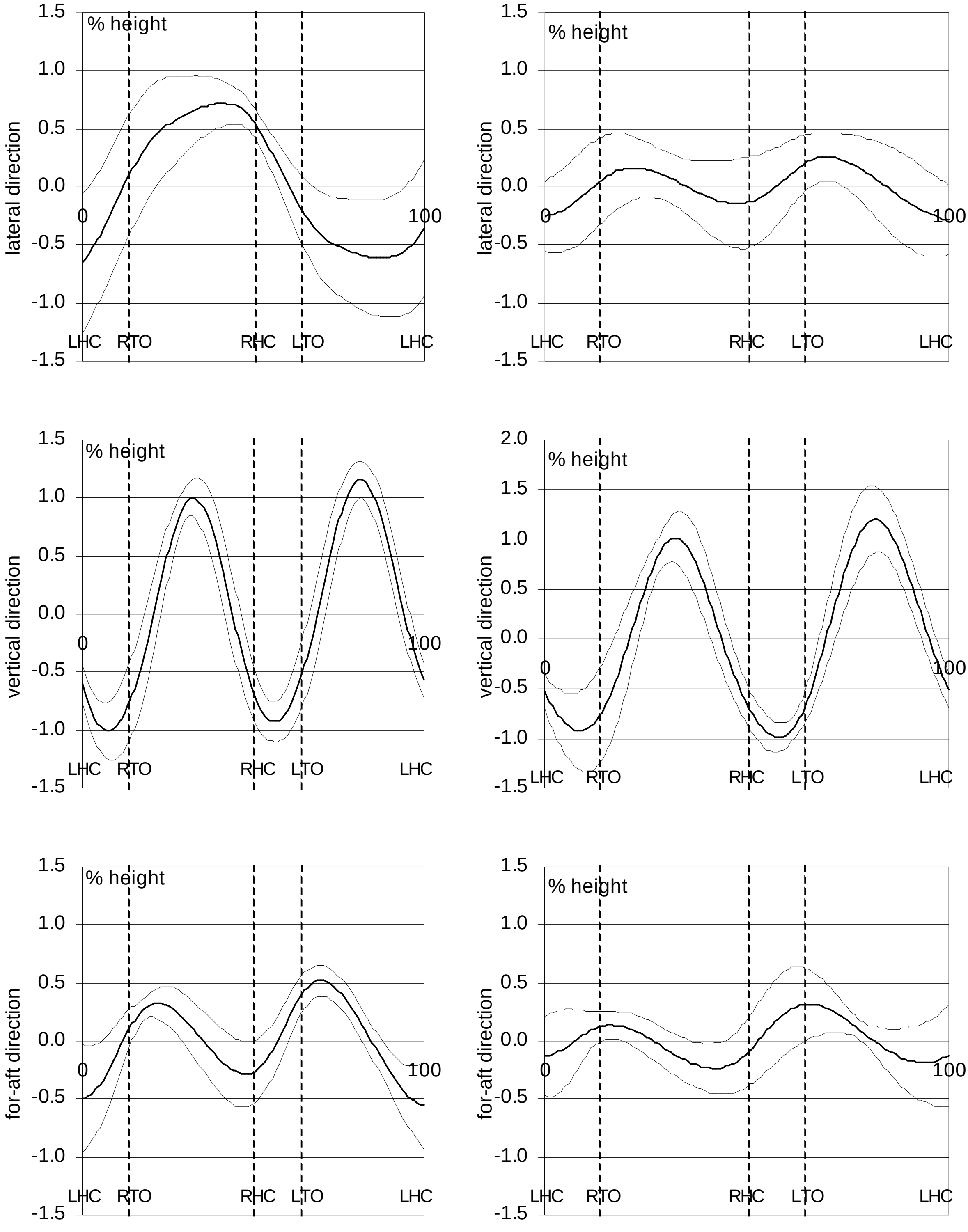


Figure 1. Model of a subject during natural walking with drawn calculated trajectory of body centre of mass

3. Results

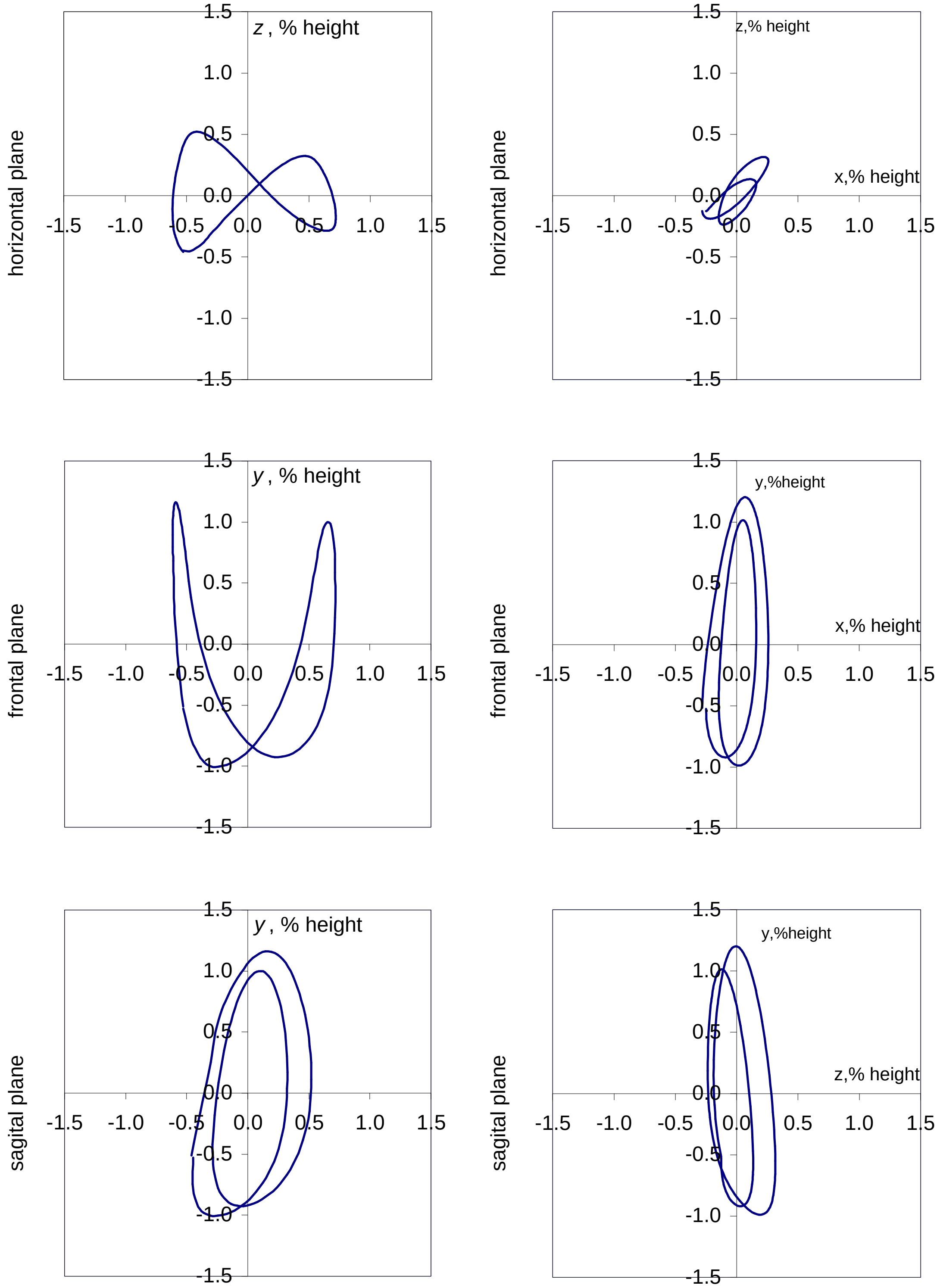
Recorded data have been processed. The range of the normal gait speed was 0.95 m/s ≤ v ≤ 1.7 m/s (mean speed 1.27 m/s, S.D. 0.12 m/s) and the range of the fast gait speed was 1.7 m/s ≤ v ≤ 2.4 m/s. (mean speed 1.96 m/s, S.D. 0.20 m/s). The determined trajectories of the body centre of mass have been normalized by the subject height to give displacements of centre of mass in percentage of the body height. The original data of the body centre of mass displacement have been averaged by normalizing them to one hundred sample points per one walking cycle through spline interpolation.
Typical patterns of displacements of the body mass centre in lateral, vertical and fore-aft direction during gait cycle have been established for every subject. *General patterns* and variation bandwidth of one standard deviation for a particular walking manner have been determined from *typical patterns* of all subjects for the same manner of walking (Fig. 2). *A general pattern* represented the mean curve of the entire group of subjects studied. Figure 3 shows the three-dimensional displacements of the body centre of mass in three planes.



a) walking at normal speed

b) walking at fast speed

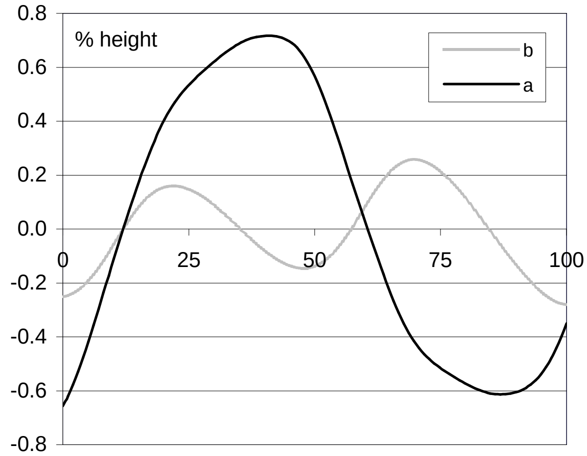
Figure 2. ***General pattern*** **(mean value ± standard deviation) of normalized displacements of body centre of mass in lateral (x), vertical (y) and fore-aft (z) direction for walking at normal (a) and fast (b) walking speed (LHC: left heel contact, RTO: right toe off, RHC: right heel contact, LTO: left toe off)**



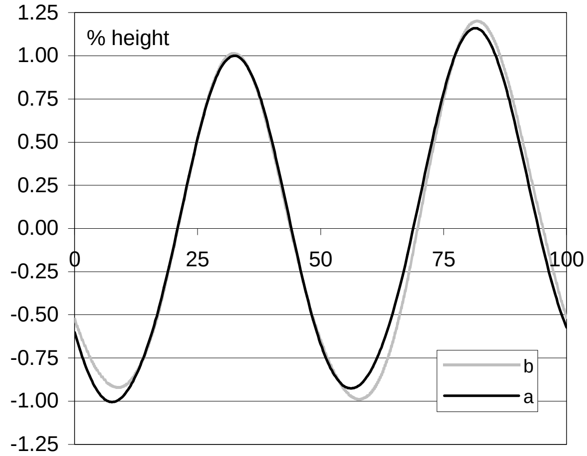
a) walking at normal speed

b) walking at fast speed

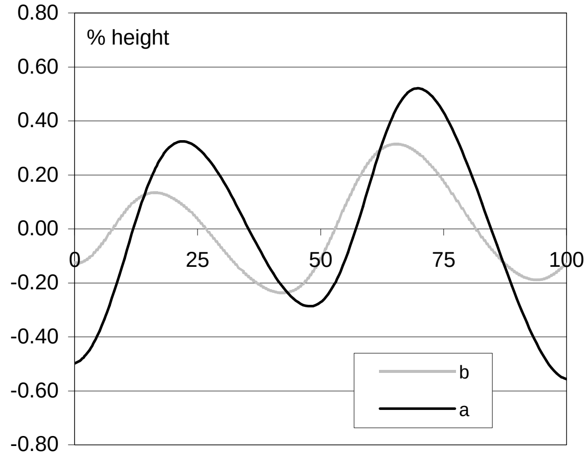
Figure 3. Mean values of *general pattern* of normalized displacement of the body centre of mass in three planes for walking at normal (a) and fast (b) walking speed



lateral direction



vertical direction



fore-aft direction

Figure 4. Comparison of *general patterns* of displacements of the body centre of mass for walking at normal speed (a) and fast speed (b)

General patterns of displacements of the body centre of mass, for walking at normal and fast speed have been compared (Fig. 4) and maximum displacements of the body centre of mass in all three directions are shown in Table 1.

Table 1. Maximum displacements of general patterns of body centre of mass in x, y and z direction

	maximum displacement in percentage of body height	
direction	normal walking speed	fast walking speed
lateral (x)	1.34	0.25
vertical (y)	2.16	2.20
fore-aft (z)	1.07	0.56

4. Conclusion

An automatised method for determination of whole body centre of mass during human walking has been established. *General patterns* and variation bandwidth of one standard deviation of displacement of body centre of mass for a normal and fast speed walking have been determined.

In the vertical direction, for normal and fast speed walking, the centre of mass describes a smooth regular sinusoidal curve with two cycles for every gait cycle; i.e. the centre of mass is displaced in the vertical direction twice during the gait cycle. In the lateral direction, centre of mass for normal speed walking is displaced to the right and to the left, in association with the support of the weight-bearing extremity. For fast speed walking, the centre of mass is displaced in lateral direction twice during the gait cycle.

Considering normal and fast speed walking, the displacements of the body centre of mass for fast speed walking have been decreased in lateral and fore-aft direction.

The average pattern of the displacement diagram on the horizontal plane showed a distorted figure "eight" for walking at normal speed, while that of fast walking speed showed an O-shaped figure.

In the frontal plane, the curvature shapes were different for normal and fast speed walking. The diagram of *general pattern in* frontal plane showed U-shaped figure for normal speed walking and O-shaped figure for fast speed walking.

In sagital plane, the curvature sizes were different for normal and fast speed walking, but there was little difference in the shapes (O-shaped figure).

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