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Evaluation of force plate-less estimation of the trajectory of the centre of pressure during gait. Comparison of two anthropometric models

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ABSTRACT

The estimation of the trajectory of the centre of pressure during gait is possible without using force plate by modelling the whole body as a multi-segment chain. The kinematics and inertial parameters of each segment are necessary to determine the ground reaction forces and moments. The position of the centre of pressure can then be calculated at each frame of time. The objective of the study was to evaluate the accuracy of the estimation of the position of the centre of pressure during gait obtained without force plate data. Segment inertial parameters were determined using a proportional model and a geometric model. The modelling and calculations were computed for six volunteers and the estimated centres of pressure were compared to the centre of pressure measured using force plates considered as the gold standard. The estimation was better using the geometric model with an accuracy of 33 mm (4.1% of the peak-to-peak amplitude) on the longitudinal axis and 14.2 mm (12.9% of the peak-to-peak amplitude) on the lateral axis.

1. Introduction

The evolution of the position of the centre of pressure during the stance phase of gait characterizes the foot progression on the ground. Because of this, the determination of the centre of pressure is of great interest particularly during pathological gait [1]. The centre of pressure is defined as the point where the components of the ground reaction moment in the ground plane are null. When using force plates for gait analysis, the position of this point is automatically calculated from force plate data. However, the zone of measurement is limited by the dimensions of the force plate. To obtain data in a large space, a number of force plates are necessary, which is not always possible due to economical and space constraints. It would be ideal to calculate the dynamic position of the centre of pressure during gait without using force plates. To achieve this goal, it is necessary to build a whole body multi-segment model that incorporates measured kinematic data to compute the dynamics of each segment. Given the inertial characteristics of each segment, the ground reaction forces and moments and the position of the centre of pressure can then be assessed. In the literature, very few authors proposed whole body model for dynamic analysis of gait [2] or specific movements like load carriage [3] and balance recovery [4]. Only Ren et al. [2] validated his model by comparing the six components of ground reaction forces and moments to actual force plate data. However, he did not calculate the dynamic position of the centre of pressure. There is a need to evaluate the ability of multi-segment models at accurately determining the position of the centre of pressure during locomotion.

The determination of segment inertial parameters (SIP) is an important step of the method and must be as accurate as possible. Several authors [5,6] proposed methods for direct measurement of SIP but these methods could not be used in extensive studies because they are complex and time consuming. Segment inertial parameters can also be estimated from proportional [6,7] or geometric methods [8–10]. To assess the SIP, numerous studies use the proportional model of De Leva [7]. This author assessed regression equations from the experimental study of Zatsiorsky and Seluyanov [5]. For each segment, mass, position of the centre of mass and components of inertia matrix were expressed as a fraction of the total body mass and/or a proportion of the segment length. Although this method is simple and fast, it is not suitable for most populations as the equations were obtained from a specific population of young athletes. To improve the estimation of the SIP, while accounting for individual variability, geometric models can be implemented [8–10]. These models are based on the acquisition of the external geometry of body segments. To be subject specific, most models are time consuming because they are based on numerous anthropometric measurements [8,9,11], or because they necessitate 3D reconstruction of both bones and

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external geometries of body segments from imaging. Some authors used the EOS system [12], a low irradiation dual X-ray imaging system or magnetic resonance imaging (MRI) [13], which are expensive equipments that most researchers do not have access. Jensen [14] proposed a photographic technique to acquire external geometry, which has been improved upon using a 3D modeller [15]. However, the validation of the model is limited to volume measurement of only one segment. Keeping in mind that these models are used in inverse dynamic methods, we propose to evaluate the impact of a similar geometric model on inverse dynamic results compared to the most used proportional model of De Leva.

The aim of the present study was to (1) propose a method to calculate the position of the centre of pressure during gait without force plate data and (2) compare the estimations of the position of the centre of pressure obtained with a proportional model (De Leva) and a geometric model (using a photographic technique) with the position of the centre of pressure given by force plates.

2. Materials and methods

2.1. Multi-segment model

The body was divided in 13 segments (feet, shanks, thighs, pelvis, trunk, upper arms, forearms and head). The kinematics of these segments was measured using an optoelectronic Vicon system (eight cameras). The anatomical coordinate systems, used for the segments, were presented in previous studies [16,17]. For evaluation purpose, two AMTI force plates were used to measure the ground reaction forces and moments. For each subject equipped with 35 markers, a static acquisition was performed and two photographs (10 megapixels) were simultaneously taken from front and lateral sides of the subject. Four markers were added on the ground. Markers positions in the photographs were registered by simultaneous collection using the motion capture system. These spatial coordinates were subsequently used for calibration of the image using DLT algorithm [18].

2.2. Segment inertial parameters

Anthropometric data for each body segment were measured according to De Leva [7]. They allow calculating segment inertial parameters from proportional model.

To obtain segment inertial parameters from geometric model, custom software was developed and a parametric geometric model was built. Except for the head, this model consisted of a series of ellipses and was automatically computed from the positions of the segment markers. Two ellipses at the extremities of each segment were determined from the position of the markers placed on the subject (Fig. 1). From this model, a number of ellipses, which centres were linearly distributed along the axis between the centres of the two extreme ellipses, were created (in the example five for the torso and three for the other segments) and used as an initial guess of the 3D geometric shape for each segment. For the head, a sphere, which a radius was calculated from marker positions, was used. The models of all the segments were then projected on the calibrated photographs and the axes of the ellipses were manually modified to match the photographs (Fig. 2). The overall time of this phase took less than 5 min. The personalized model (Fig. 3) allowed us to compute the volume of each segment of the body. Using Dempster's densities [19], the SIP were then calculated.

2.3. Subjects

A group of six young volunteers (anthropometric data are given in Table 1) walked at a self-selected walking velocity, which ranged between 1.2 m/s and 1.4 m/s.

2.4. Calculation of the centre of pressure

During static acquisition, the position of the centre of pressure could be calculated as the projection on the ground of the centre of gravity of the body.

During gait acquisition, the dynamics of each rigid body were obtained using the method proposed by Doriot and Cheze [20] based on homogeneous matrix formalism. For double differentiation, the data were filtered with a zero-phase forward and reverse butterworth 4th order filter at each step. The cut off frequency was 5 Hz [21]. A fourth order finite difference was used to calculate the acceleration [22]. The dynamic equation for the entire body could then be written in the reference frame Ro:

$$[\Phi_{\mathrm{ground}\rightarrow\mathrm{rightfoot}}]_{\mathrm{Ro}} + [\Phi_{\mathrm{ground}\rightarrow\mathrm{leftfoot}}]_{\mathrm{Ro}} = \sum\nolimits_{\{\mathrm{segments}\}} ([A_{\mathrm{s/o}}]_{\mathrm{Ro}} - [\Phi_{\mathrm{grav}\rightarrow s}]_{\mathrm{Ro}})$$

where $[A_{\mathrm{s/o}}]_{\mathrm{Ro}}$ represents the generalized forces and moments due to the dynamics of the segment s, $[\Phi_{\mathrm{grav}\rightarrow s}]_{\mathrm{Ro}}$ the forces and moments due to the gravity and applied

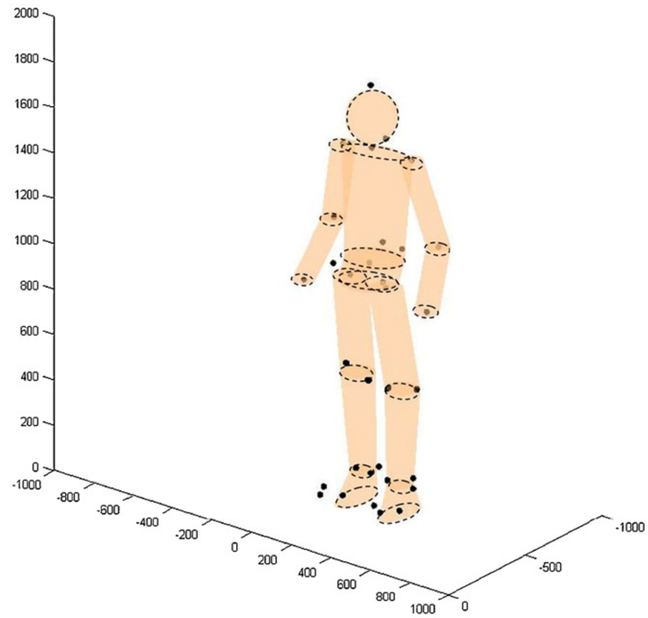

Fig. 1. Parametric model defined from markers' positions on the body—the ellipses, created from markers, for each segment are represented in dash black lines.

on the segment s and $[\Phi_{\mathrm{ground}\rightarrow\mathrm{rightfoot}}]_{\mathrm{Ro}} + [\Phi_{\mathrm{ground}\rightarrow\mathrm{leftfoot}}]_{\mathrm{Ro}}$ the total ground reaction forces and moments. Given the kinematics of the segments and their inertial properties, it was possible to deduce the external forces and moments applied to the system, which corresponded to the sum of the forces and moments applied on the right and left feet. The location of the centre of pressure was then inferred at each step of time. To validate the method, the results were compared with force plate results. The force plate data were filtered with the same parameters as the kinematic data [23].

2.5. Comparison of the proportional and the geometric models

For each subject, segment inertial parameters were calculated using both proportional and geometric model.

During the static acquisition, using these SIP, the total body mass and the position of the centre of pressure were obtained and compared to the reference data coming from force plates.

During the gait acquisition, the ground reaction forces and moments and the centre of pressure were computed in the reference frame. The ground forces and moments were then calculated at the centre of pressure. The ground force was defined by the three components Fx (antero-posterior), Fy (medio-lateral), Fz (vertical). Expressed at the centre of pressure, the ground reaction moment was reduced to only one component Mz_C (in the transverse plane). Xcop and Ycop were the coordinates of the centre of pressure along the longitudinal axis and the lateral axis, respectively. The ground reaction forces and moments obtained from the models (GRFmod) were compared with ground reaction forces and moments and centre of pressure measured by the force plates (GRFmeas) during a period of time when the two lower limbs were either in contact with a force plate or in swing phase as defined by Gillet et al. [23]. For each subject and each acquisition, the differences between each component of GRFmod and GRFmeas were computed. The RMS was then calculated for each subject. The relative RMS (normalized to the peak-to-peak amplitude) was also computed as proposed by Ren [2].

3. Results

3.1. Statics

The error on the body mass estimation was obviously null for the proportional model of De Leva as segment masses were expressed in percentage of the total body mass. With the geometric model, the body mass was initially estimated with an error between 0.2 kg and 4.1 kg (corresponding to 0.2–5.9% of the total body mass). To correct this error, the missing mass was proportionally distributed between the segments.

For the geometric and proportional models, the centres of pressure were estimated as the projection of the centre of mass on