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An individual and dynamic Body Segment Inertial Parameter validation method using ground reaction forces

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ABSTRACT

Over the last decades a variety of research has been conducted with the goal to improve the Body Segment Inertial Parameters (BSIP) estimations but to our knowledge a real validation has never been completely successful, because no ground truth is available. The aim of this paper is to propose a validation method for a BSIP identification method (IM) and to confirm the results by comparing them with recalculated contact forces using inverse dynamics to those obtained by a force plate. Furthermore, the results are compared with the recently proposed estimation method by Dumas et al. (2007). Additionally, the results are cross validated with a high velocity overarm throwing movement. Throughout conditions higher correlations, smaller metrics and smaller RMSE can be found for the proposed BSIP estimation (IM) which shows its advantage compared to recently proposed methods as of Dumas et al. (2007). The purpose of the paper is to validate an already proposed method and to show that this method can be of significant advantage compared to conventional methods.

1. Introduction

Calculating Body Segment Inertial Parameters (BSIP) has been shown to be of critical importance for clinical and biomechanical research (Andrews and Mish, 1996; Kingma et al., 1995; Silva and Ambrósio, 2004; Rao et al., 2006; Pai, 2010). The measurement of the inertia and the position of the COM of each body part allows us to monitor variations in muscle-mass during hospitalization, rehabilitation or neurological examination. Consequently the knowledge of the individual inertial parameters is of crucial importance to support personalized healthcare. The better the inertial estimation of those segments is, the better are the resulting joint loads (force and moment) obtained by inverse dynamics (Pearsall and Costigan, 1999; Rao et al., 2006; Pàmies-Vilàa et al., 2012). Previous research has been conducted to improve the BSIP estimation using geometric models based on numerous anthropometric measurements (Hanavan Jr., 1964) or taking results from cadavers' studies (Dempster, 1955; Chandler et al., 1975) as well as in vivo body scanning methods (Zatsiorsky and Seluyanov, 1983; Zatsiorsky et al., 1990; de Leva, 1996; Ma et al., 2011). Even though the estimations have been improved (Dumas et al., 2007) there are still regression methods based on earlier collected databases e.g. (McConville et al., 1980; Young et al., 1983). Geometrical methods are precise and based on complex acquisition systems such as 3D scanner, IRM or X-ray absorptiometry which are expensive and may expose subjects to radiations. Recently, identification methods used in Mechanical Engineering have been applied to the estimation of human BSIP (Atchonouglo et al., 2008; Venture et al., 2009b, 2009c; Ayusawa et al., 2011). These methods are based on human body mechanical models whose parameters are expected to match kinematic and dynamic recorded data. Therefore, they allow evaluating BSIP on a subject-by-subject basis using an optoelectronic motion capture system and a force platform.

In this framework, this paper proposes to evaluate an identification method (IM) to assess the inertial parameters of humans without considering joint torques. It is based on the fact that the dynamics of such systems can be written using the Newton–Euler formalism for the base-link (chosen arbitrarily) and the Lagrangian formalism for the rest of the kinematic chains (Venture et al., 2009b, 2009c; Ayusawa et al., 2011). It can be thus, demonstrated that to identify the dynamics of the whole system only the six equations obtained for the base-link are necessary. Since no ground truth value of the BSIP is available, the IM is validated twofold. First the recalculated contact forces, using inverse dynamics, are compared with the ground reaction forces (GRF) measured from a force platform. Secondly the results are compared with the GRF computed using a regression based model (RM)

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proposed by (Dumas et al., 2007). Additionally, the results are cross validated with a high velocity overarm throwing movement.

The paper is structured as follows: in the *Methods* section the obtained identification model from the base link equation is briefly described and the experimental identification of the whole-body parameters is presented. In the *Results* section, the experimental results obtained from both methods are presented and discussed.

2. Methods

To obtain accurate identification results it is important to define the kinematic model used to describe the human body, and to obtain its characteristic geometric parameters.

2.1. Modeling the human body

Previous studies have considered the human body as a model of multiple segments from 11 (Riley et al., 1990; Yeadon, 1990a; Yeadon and Morlock, 1989), over 14 (Pavol et al., 2002), 15 (Wei and Jensen, 1995; Arampatzis and Brüggemann, 1998; Dumas et al., 2007), 17 (Hatze, 1980; Baca, 1996) up to 40 geometric solids (Yeadon, 1990b) with BSIP values estimation for 20 segments. Most of the dynamic parameters estimations are based on databases which involve anthropometric measurements, scaling functions and/or regression methods to obtain the BSIP specifications such as the segments' mass, center of mass (CoM) and the inertia matrix. As discussed in previous works from (Venture et al., 2009b, 2009c; Ayusawa et al., 2011), the modeling depends on the purpose of the motion studied and the experimental constraints such as the measurement facility. We consider a model of the human body with 34 degree of freedom (DOF) and 15 rigid links (Venture et al., 2009b, 2009c; Ayusawa et al., 2011): upper torso, lower torso, head, upper arms, lower arms, hands, thighs, shanks, and feet. The waist, the neck, the shoulders, the wrists, the hip joints and the ankles are modeled with spherical joints, and the elbows and the knees are modeled with rotational joints.

2.2. BSIP identification method

In this section, the principle of the BSIP identification method is recalled briefly (Venture et al., 2009b, 2009c; Ayusawa et al., 2011). The equations of motion of legged systems are given by

$$\begin{bmatrix} \boldsymbol{H}_{11} & \boldsymbol{H}_{12} \\ \boldsymbol{H}_{21} & \boldsymbol{H}_{22} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}}_0 \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{b}_1 \\ \boldsymbol{b}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{n_c} \begin{bmatrix} \boldsymbol{K}_{k1} \\ \boldsymbol{K}_{k2} \end{bmatrix} \boldsymbol{F}_k, \tag{1}$$

where $\boldsymbol{H_{ij}}$ is the inertia matrix, q_0 the generalized coordinates which represent the six DOF of the base link, $\boldsymbol{\theta}$ represents the vector joint angles, $\boldsymbol{b_i}$ is the bias force vector including centrifugal, Coriolis, gravity forces and $\boldsymbol{\tau}$ represents the joint torque vector. Eq. (2) is represented as a minimal identification model:

$$\begin{bmatrix} \boldsymbol{Y}_{B1} \\ \boldsymbol{Y}_{B2} \end{bmatrix} \emptyset_{\boldsymbol{B}} = \begin{bmatrix} 0 \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{n_c} \begin{bmatrix} \boldsymbol{K}_{k1} \\ \boldsymbol{K}_{k2} \end{bmatrix} \boldsymbol{F}_k, \tag{2}$$

where $\boldsymbol{n_c}$ is the number of contact points with the environment, $\boldsymbol{F_k}$ is the $\boldsymbol{k}$th vector of external forces, $\boldsymbol{K_{k1}}$ and $\boldsymbol{K_{k2}}$ are matrices that are multiplied by $\boldsymbol{F_k}$ representing the generalized force vector.

Using the least square method from the external forces and positions of each segment it is possible to identify the base parameters $\emptyset_{\boldsymbol{B}}$

$$\boldsymbol{Y}_{B1} \emptyset_{\boldsymbol{B}} = \sum_{k=1}^{n_c} \boldsymbol{K}_{k1} \boldsymbol{F}_k. \tag{3}$$

The regressor $\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{Y}_{B1} \\ \boldsymbol{Y}_{B2} \end{bmatrix}$ is the function of the systems joint angles, velocity, acceleration and the vector of generalized coordinates $\boldsymbol{q_0}$ and its derivatives. $\emptyset_{\boldsymbol{B}}$ is the vector of inertial parameters. The method has to be proven to be sensitive to changes of body mass as e.g. detecting attached masses on the body as the foot (Ayusawa et al., 2009).

2.3. Methods

In this experiment twelve subjects (22 ± 3 years) voluntarily participated after signing a statement of informed consent as required by the Helsinki declaration. The BSIP identification requires the simultaneous recording of movement kinematic data and GRF information. The identification sequence involves movements with both large and small amplitudes executed at different velocities and accelerations (Venture et al., 2009b, 2009c; Ayusawa et al., 2011) e.g. arm-swinging and squatting. The sequence involves movements that simultaneously involve both the upper and the lower body and with the goal to exploit all DOF of the human body (see Supplementary data). The subjects were asked to rehearse the motions from a video clip at least once, before performing the 120 s sequence for the identification purpose. Kinematic data were measured by an 8-camera motion analysis system (T160 series, VICON, UK) at 100 Hz while the GRF was measured by one force plate (Bertec Corporation, USA) at 1000 Hz. 35 passive reflective markers were attached to the body of the subject at defined anatomical points (Venture et al., 2009a) to insure accuracy of the inverse kinematics computations. To obtain the joint angles and their derivatives from the markers location, inverse kinematics computation is performed by an in-house software (Venture et al., 2009b, 2009c; Ayusawa et al., 2011; Yamane and Nakamura, 2007) using the human model. In order to give an exemplary indication of the values of the individual segment parameters Table 1 shows the BSIPs of the trunk obtained for three subjects and BSIPs from the literature (Pearsall et al., 1994, 1996).

Table 1
An example of the obtained BSIP using the IM and values from the literature.

Segment	Mass (kg)	I_{xx} (kg m^2)	I_{yy} (kg m^2)	I_{zz} (kg m^2)
S1 Trunk IM	23.55	0.4873	0.6074	0.1641
S2 Trunk IM	22.64	0.3430	0.3022	0.2744
S3 Trunk IM	20.62	0.3448	0.3970	0.2040
Trunk Pearsal 1994	–	2.1	2.3	0.54
Trunk Pearsal 1996	–	0.71	0.82	0.31

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.jbiomech.2014.03.004.

In order to cross-validate the results, four of the 12 candidates were randomly selected and performed five over arm throwing movements. This specific activity involves high accelerations and the open chain movement emphasizes the role of the BSIP in inverse dynamics computations (Pearsall and Costigan, 1999). The data acquisition rate was increased for those trials to 250 Hz in order to capture the high accelerations.

2.4. Data analysis

The obtained results cannot be validated directly neither with the RM nor with the IM, as no ground truth of the individual in-vivo parameters exists. We thus propose to validate the results using the measured contact forces as the ground truth, and reconstruct the six components (Fx, Fy, Fz, Mx, My, and Mz) using the inverse dynamics with movement data and the identified BSIP as inputs. The calculation was performed using the IM and compared to the results obtained by the RM. The model of Dumas et al. (2007) (RM) was chosen because it relaxes two important biomechanical assumptions that are made in the majority of BSIP estimation studies (de Leva, 1996; Zatsiorsky et al., 1990; Hatze, 1980; Hanavan, 1964), i.e. first the center of mass and the proximal and distal endpoints are not assumed to be aligned and second the inertia tensor is not assumed to be aligned with the principal axes of the segment itself. Moreover the inertial parameters are given in the joint coordinate system following the ISB recommendation (Wu et al., 2005).

To compare and validate both methods, the Root-Mean Square Error (RMSE), the Pearson Correlation Coefficient and the metric according to Schwer (2007) were applied as statistical analysis techniques. The Phase dependent error (*P*), the magnitude dependent error (*M*) and the combined error (*C*) provide a solution to quantify the numerical results due to differences of the computation. The error in magnitude (*M*) is insensitive to phase discrepancies and based upon the area under the squared response time series. The ratio of both integrals represents the magnitude differences. A zero metric value means that both integrals are identical. The phase error (*P*) is insensitive to magnitude differences and a zero metric value means that no time shift between the two signals exists. The combined error (*C*) is the combination of the magnitude (*M*) and phase (*P*) metrics, and a useful global indicator.

To test if correlations between both estimation techniques with the contact forces statistically differ, significance test on the difference of Pearson's correlation was also performed.

3. Results

In this section we present the results of the comparison between IM and RM. The RMSE, the Pearson Correlation Coefficient, the phase dependent (*P*) and magnitude dependent (*M*) and combined error (*C*) computations are shown in Table 2. The correlation between the IM and the force plate is very high (> 0.99) and the RMSE and *P*, *M* and *C* are smaller compared to the obtained results by RM (Table 3).