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Estimating foot inertial parameters: A new regression approach

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ABSTRACT

Background: Estimating the inertial parameters for the foot (mass, center of mass position and inertia tensor) is important for applications involving the ankle joint such as inverse dynamics or stiffness measurement techniques (e.g. Quick-release). Scaling equations relying on foot length and body mass are widely used. However, because of the complex foot geometry, such equations may represent an oversimplified solution. Our aim was to evaluate these approaches and propose a new method.
Methods: Thirty-four right feet (17 Males, mean age and weight 30 years, 75 kg; 17 Females, 32 years, 61.5 kg) were reconstructed using a 3D surface scanner and used as geometrical references. Associated inertial parameters were calculated directly on each reference assuming a uniform density distribution and were compared to corresponding scaling and multiple regression estimates. Finally, an alternative method, based on multiple non-linear regressions, was proposed considering both foot length (L) and ankle width (W).
Findings: Comparisons showed that reference mass and moments of inertia were greater than scaling predictions with mean difference up to 33 and 16% for mass and moments of inertia respectively. The maximum standard errors of estimate for scaled moments of inertia reached 26%. The alternative solution involving ankle width in the equations lowered the gap with reference data (8.7% max standard errors of estimate) for both genders.
Interpretation: This strategy, requiring two simple and accessible measurements, may offer a better practicality/relevance compromise for clinical routine use, in regards to existing scaling and regression equations.

1. Introduction

The impact of BSP (Body Segment Parameters) on gait parameters has been widely reported (Dillon et al., 2008; Ganley and Powers, 2004; Nagano et al., 2000; Pearsall and Costigan, 1999; Rao et al., 2006) and their estimation in vivo is essential for the assessment of joint kinetics (using inverse or direct dynamic approaches). BSP assessment is also important in the use of stiffness measuring devices in which moments of inertia may be calculated based on segment accelerations (e.g. quick-release) (Goubel and Pertuzon, 1973, Pousson et al., 1990). The latter approaches are of simple use, but they may overestimate moments of inertia (Lambertz et al., 2008). Simple assessments of subject-specific BSP may rely on scaling equations using anthropometric measurements such as body mass (kg) and segment lengths (McConville et al., 1980; Young et al., 1983; Zatsiorsky and Seluyanov, 1983; Zatsiorsky et al., 1990a, 1990b). Such scaling equations were developed using gamma ray scanners (absorptiometry) or photogrammetric measurements on homogenous cohorts taking gender differences into account. Using standardized segment coordinate systems (SCS), scaling equations remain widely used (de Leva, 1996; Dumas et al., 2007) and are generally applicable to subjects fitting the same morphotypes (i.e. age, anthropometry, ethnicity). Other approaches use simple geometric models (Hanavan, 1964; Hatze, 1980; Pillet et al., 2010; Raichlen, 2004; Shan and Bohn, 2003; Yeadon, 1990) and/or multivariate regression equations (Hinrichs, 1985; Vaughan et al., 1999; Yeadon and Morlock, 1989; Zatsiorsky and Seluyanov, 1985), which may require a large number of measurements with a reasonable degree of accuracy (Vaughan et al., 1999; Yeadon and Morlock, 1989).

Specifically, the foot segment is the first link of the bottom-top approach used in inverse dynamics; its geometry may differ between individuals (Keyser et al., 1988; Nawoczenski et al., 1998). Foot inertial parameters (IPs) also have substantial impact on the calculation of intrinsic ankle joint stiffness (de Zee and Voigt, 2001; Hof, 1998; Lambertz et al., 2008; Tognella et al., 1997). For this segment, scaling equations relying solely on foot length and body mass are generally preferred (Wall-Scheffler et al., 2006). Since foot geometry may also be characterized by other parameters such as ankle width (inter malleoli distance) or foot breadth (1st–5th metatarsal head distance (Vaughan et al., 1999), the use of a unique parameter may represent an oversimplifying solution. On the other hand, the existing

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multivariate regression equations are based on small samples and/or require complex foot measurements (e.g. circumferences/perimeters; (Hinrichs, 1985; Zatsiorsky and Seluyanov, 1985; Yeadon and Morlock, 1989; Vaughan et al., 1999). Another method for assessing foot IPs may involve volume immersion assuming a uniform density distribution (Dillon et al., 2008). However, this inexpensive and simple technique remains time consuming and mainly reserved for 'customized foots' (prosthesis + shoe included). Finally, the use of 3D surface scanners was recently proposed as a fast and accurate means to obtain BSP (Davidson et al., 2008, Jones et al., 1997, Norton et al., 2002, Shan and Bohn, 2003), based on personalized volume reconstructions. However, it remains less adapted to routine use than scaling or regression equations.

In this context, the aim of this study was to assess the accuracy of a set of existing equations (scaling and multi-linear regression) for the foot segment with respect to measurements performed on surface scanner reconstructions and to potentially propose a new set of non-linear regression equations.

2. Methods

2.1. Subjects

Seventeen men (mean age 30 years, range [19–63], height 1.79 m [1.63–1.85] and weight 75 kg [51–90]) and 17 women (31 years [18–63], 1.67 m [1.60–1.80] and 60.6 kg [53–78]) recruited during a scheduled visit to a podiatry clinic consented to participate in this study, which was designed according to the Helsinki declaration principles. All subjects were Caucasian. Subjects were seated with the tested shank resting horizontally on an adjustable stool (knee fully extended), actively maintaining the ankle in neutral position (foot vertical). Only the right foot was used; the measurement session lasted 3 to 6 minutes.

2.2. Foot model—geometrical reference definition

For each subject, a 3D surface model of the foot was obtained using a portable infrared surface scanner (REVscan, HandyScan3D®, Creaform, Canada). The scanner had a spatial resolution of 0.1 mm (along the Z axis), an accuracy of up to 50 μm and a volumetric accuracy of 20 μm ± 0.2 L/1000. The whole foot, including both malleoli, was scanned; identification of selected anatomical regions was manually performed on the reconstructed foot. According to previous studies (de Leva, 1996; Dumas et al., 2007) these landmarks comprised: Sphyrion (SPH); Lateral Malleolus (LM); Calcaneum (CAL); 1st Metatarsal Head (MH1); 5th Metatarsal Head (MH5) and the longest among 2nd and 1st Toe Tip (TT). The geometric center of each region was then calculated and considered as the corresponding bony landmark, to define the same foot SCS as used previously (Fig. 1):

- CAL was defined as the origin of the SCS.
- The X axis connected CAL to the midpoint between MH1 and MH5.
- The Y axis was normal to the foot plane containing CAL, MH1 and MH5, pointing cranially from CAL.
- The Z axis was the cross product of the X and Y axes, pointing laterally.

The cross section plane was parallel to the foot plane passing through the SPH level (McConville et al., 1980; Young et al., 1983, Zatsiorsky and Seluyanov, 1983; Zatsiorsky et al., 1990a, 1990b). This plane was assumed to pass through the tibio-talar joint. Foot reconstruction and landmark definitions were performed using Geomagic studio 9® (SolidWorks San Antonio – TX, USA) and subsequent calculations used Matlab®.

2.3. Estimators definition and foot IPs calculation

The following parameters were defined and calculated for each foot (Fig. 1): Foot Length (L), distance CAL-TT; foot breadth (B), distance MH1–MH5 and ankle width (W), distance LM-SPH.

Based on the calculated volume from these geometrical references, foot masses ($M_{\text{Foot-ref}}$) were estimated using an average density factor (ρ) of 1100 kg/m^3 (Dempster, 1955). Foot masses were then compared to previously published scaling predictions giving $M_{\text{Foot-scaled}}$ as a percent of body mass (mass) (de Leva, 1996; Dumas et al., 2007).

The volume centroid (G_{Foot}) of each geometrical reference was calculated in the defined SCS and compared to those predicted by scaling approaches. The inertia tensor was first calculated according to the axes of the object inertial reference system (IRS), by numerically integrating the following equation (Eq. (1)):

$$[I]_{\text{IRS}} = \rho \iiint \left\| \vec{\Delta} \wedge \overrightarrow{G_{\text{Foot}}M} \right\|^2 .dV$$

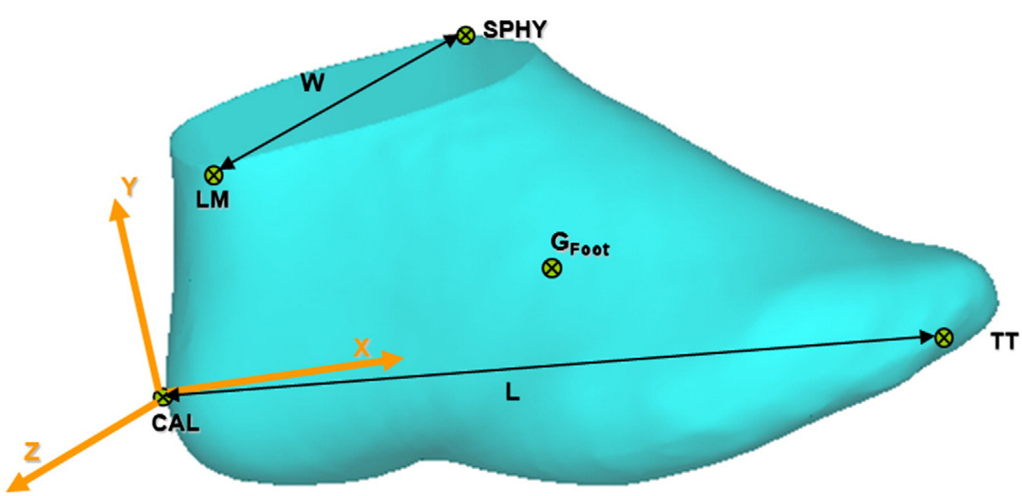

Fig. 1. Reconstructed foot envelop with defined bony landmarks, parameters and SCS (Segment Coordinate Segment)—example for male subject number 9, age: 25, weight (kg): 73, foot-volume (l): 0.94, M_{Foot} (kg): 1.03.