Estimating foot inertial parameters and the use of scaling approaches

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SUMMARY

Estimating foot inertial parameters (mass, inertia tensor) is important for applications involving the ankle joint such as stiffness measuring techniques (e.g. Quick-release). Scaling equations relying on foot length and body mass are widely used. However, due to foot shape, such equations may represent an oversimplified solution. Our aim was to evaluate these approaches and propose a new method. Thirty-four right feet (17 Males, mean age and weight 30 years, 75 Kg; 17 Females, 31 years, 60 Kg) were reconstructed using a 3D surface scanner and used as geometrical references. Associated inertial parameters were calculated on each reference assuming a uniform density distribution and were compared to corresponding scaling estimates. An alternative method, based on multivariate regressions, was proposed considering both foot length and ankle width. Comparisons showed that reference mass and moments of inertia were greater than scaling predictions with respective mean signed difference up to 33 and 16% for mass and moments of inertia. The maximum standard errors of estimate (SEE) for scaled moments of inertia reached 26%. The proposed solution involving ankle width lowered the gap with reference data (8.7 % max SEE) for both genders. This strategy offers a good practicality/relevance compromise for routine use.

INTRODUCTION

The foot segment is the primary link of the bottom-top approach used in inverse dynamics. Its inertial properties also have a critical impact on the calculation of intrinsic ankle joint stiffness [1]. Many approaches are used including scaling equations which require both foot-length and body mass parameter [2, 3]. However, foot shape differs between individuals, and its whole shape may affect its inertial properties. In this context, the use of a unique parameter may be an oversimplifying solution. Multivariate regression equations; often requiring complex measurements; may also be used [4]. 3D surface scanning is a fast and simple way to access IP (Inertial Parameters), based on personalized volume reconstruction. However it is less adapted to a routine use. The aim of this study was first to assess the accuracy of existing scaling equations for the foot segment by comparing to direct measurements performed on surface scanner reconstructions; and hence to propose an alternative estimation.

METHODS

17 men (age 30 ± 9 y, height 1.79 ± 0.04 cm, weight 75±9.6 Kg), and 17 women (age 31 ± 11 y, height 1.67 ± 0.05 cm, weight 60 ± 8 Kg) were included in the study.

A 3D surface model of each right foot was developed using a portable infrared surface scanner (HandyScan3D®, Creaform, Canada) and was referred to as the geometrical reference.

Identification of main anatomical regions was manually performed (Figure1). Segment coordinate system (SCS) and foot parameters were defined. The parameters included: length L – as distance between clacaneous (CAL) and tip-toe (TT) landmarks and ankle width W – as distance between sphyrion (SPHY) and lateral malleoli (LM) landmarks. Model's cross-section plane was positioned at the sphyrion landmark, passing through the ankle and parallel to the foot-plane according to previous studies [2, 3]. Inertia tensor was considered principal in the defined SCS axes and was calculated at the center of mass, assuming a uniform density distribution (ρ=1100 Kg/m^3). Foot-mass (M_{Foot}) was thus estimated and compared to scaling estimates, then incorporated to the moments of inertia scaling equations ($I_{ii} = M_{Foot}.(r_{ii}.L)^2$ - i ={X, Y, Z}) [2, 3].

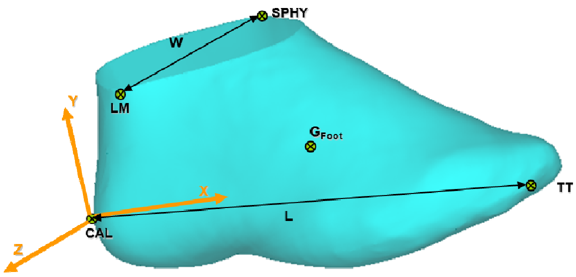

Figure 1: 3D surface reconstruction (geometrical reference) with defined SCS (in orange) and foot parameters.

Using reference data, PLS (Partial Least Squares) regression equations were investigated for IP estimation and the following were selected (LW approach):

$M_{Foot} = K_M + C1_M*L + C2_M*W$;
$I_{XX} = K_X + C1_X * M_{Foot} + C2_X *W^2$;
$I_{YY} = K_Y + C1_Y * M_{Foot} + C2_Y *L^2 + C3_Y *W^2$;
$I_{ZZ} = K_Z + C1_Z * M_{Foot} + C2_Z *L^2 + C3_Z * W^2$;

RESULTS AND DISCUSSION

Findings shows that reference mass was always greater than scaled ones. Differences were more important when comparing reference masses to Dumas' predictions, with more than 25% for males and 33% for females, versus 20% and 8% respectively when comparing to de Leva's (relative mean mass differences). The SEEs for the proposed mass equation were of 0.074 (6%) and 0.058 Kg (6%) for males and females respectively. This finding highlights the inadequacy of assuming foot mass as a percent of body mass. Thus equations included foot length (L) and ankle width (W) without body mass.

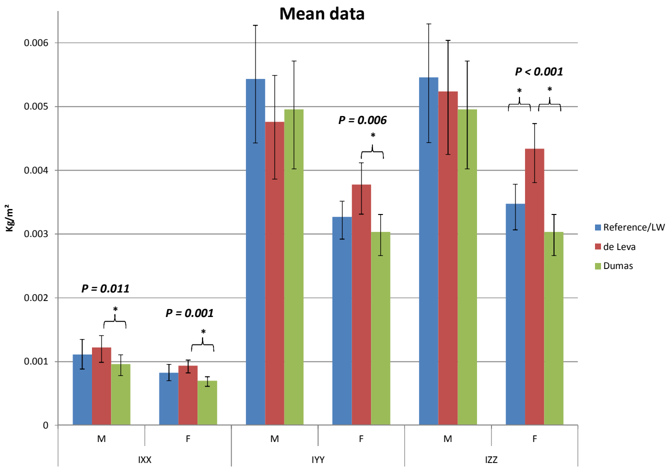

Figure 2: Mean moments of inertia. Reported *P* values (ANOVA) shows significant differences between approaches. ***** Significant difference in Tukey's test.

For moments of inertia, comparisons were performed considering the same reference foot mass in all approaches, in order to exclude the substantial influence of density. Thus, reference moments were larger than those predicted by scaling equations (Figure 2), except when comparing female subjects to de Leva's estimations. This finding questions the use of a single parameter (foot length), which may lead to underestimating moments of inertia. The choice of a multivariate non-linear regression was preferred for an expected better accuracy in regards to univariate (using only foot length) and/or linear regression, as nonlinear regression may provide reasonable estimates in case anthropometric measurements are outside the sample range for a given subject. When comparing accuracies (Figure 3), the proposed equations (LW approach) showed marked improvement along the X-axis for both genders, along the Y-axis for male subjects and the Z-axis for female subjects, with a slight improvement for females along Y-axis and males along Z-axis.

Coefficient values of calculated equations are available in Table 1.

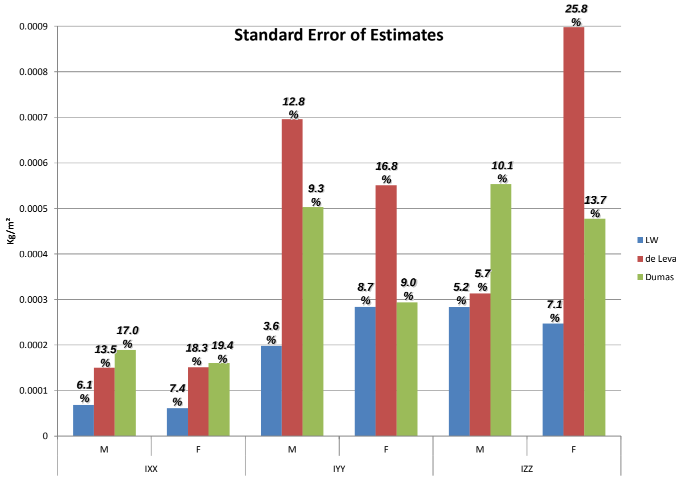

Figure 3: Moments of inertia accuracies.

CONCLUSIONS

The purpose of this study was to investigate the applicability of scaling equations on the foot segment by comparing to IPs measured on personalized surface scanning reconstructions and to propose a new set of regression equations. By means of two simple measurements (foot length and ankle width), foot IPs may be easily and accurately assessed. While good accuracy for foot IP may not seem critical when studying normal gait, it becomes important when studying isolated ankle joint motion, foot dynamics (e.g. quick-release measurements) or designing personalized foot-wear/shoes equipment.

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Table 1: Coefficient values for the proposed equations.

	M_{Foot}			I_{XX}			I_{YY}				I_{ZZ}			
Sex	K_M	$C1_M$	$C2_M$	K_X	$C1_X$	$C2_X$	K_Y	$C1_Y$	$C2_Y$	$C3_Y$	K_Z	$C1_Z$	$C2_Z$	$C3_Z$
M	-2.08	6.88	19.78	-8.9e-4	8.1e-4	0.17	-4.8e-3	2.7e-3	0.06	0.50	-4.8e-3	2.7e-3	0.06	0.53
F	-2.02	4.62	27.18	-1.0e-4	7.9e-4	0.25	-4.1e-3	2.3e-3	0.04	0.61	-4.4e-3	2.5e-3	0.04	0.63