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# A new geometric-based model to accurately estimate arm and leg inertial estimates

Jason Wicke [a],*, Geneviève A. Dumas [b]

[a] Kinesiology Department, William Paterson University, 300 Pompton Rd, Wayne, NJ 07470, USA
[b] Department of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario, Canada

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ABSTRACT

Segment estimates of mass, center of mass and moment of inertia are required input parameters to analyze the forces and moments acting across the joints. The objectives of this study were to propose a new geometric model for limb segments, to evaluate it against criterion values obtained from DXA, and to compare its performance to five other popular models. Twenty five female and 24 male college students participated in the study. For the criterion measures, the participants underwent a whole body DXA scan, and estimates for segment mass, center of mass location, and moment of inertia (frontal plane) were directly computed from the DXA mass units. For the new model, the volume was determined from two standing frontal and sagittal photographs. Each segment was modeled as a stack of slices, the sections of which were ellipses if they are not adjoining another segment and sectioned ellipses if they were adjoining another segment (e.g. upper arm and trunk). Length of axes of the ellipses was obtained from the photographs. In addition, a sex-specific, non-uniform density function was developed for each segment. A series of anthropometric measurements were also taken by directly following the definitions provided of the different body segment models tested, and the same parameters determined for each model. Comparison of models showed that estimates from the new model were consistently closer to the DXA criterion than those from the other models, with an error of less than 5% for mass and moment of inertia and less than about 6% for center of mass location.

## 1. Introduction

Segment estimates of mass, center of mass and moment of inertia are required input parameters to analyze the forces and moments acting across the joints. These segment inertial estimates are only possible through indirect measures by adopting a body model. Geometric based models represent the segments as various shapes from which a volume and a density function are combined to calculate the segment inertial estimates.

Earlier geometric based models use a single shape to capture the volume of each segment. Hanavan (1964) used anthropometric measurements to determine the dimensions of either a right elliptical cylinder or right frustum of a circular cone to represent the segments of the body. More advanced models have been developed that capture the intra-segmental changes in volume along the longitudinal axis. The Jensen (1978) elliptical model represents each segment as a series of zones with a predetermined height, stacked on top of each other. Although the ellipse has been found to a more accurate representation of the cross-sectional area of the trunk region (Wicke and Lopers, 2003), this model produces cavities and thus large volume errors in regions of the body where two adjacent segments meet such as between the upper arm+upper trunk, and lower trunk+thigh (Wicke and Dumas, 2010).

The Hatze (1980) model requires 242 anthropometric measures and uses several different shapes to represent the various segments, making this model the most accurate measure of segment volumes. However, even with its revised set (Hatze, 2005) of 133 measures, this model has not been utilized in any known study, likely due to the time constraints. Wicke et al. (2009) developed a trunk model that uses both ellipses in the same manner as the Jensen model but also includes sectioned ellipses to eliminate the cavities formed at adjoining segments by separate ellipses. In addition, a non-uniform density function, unique for each sex was developed, eliminating the uniform density assumption for that segment. Therefore, the new model eliminates many of the constraints of previous geometric models by, (a) only requiring approximately 15 min of participant time, (b) capturing volume changes along each segment, and (c) including non-uniform density functions for the trunk.

The overall accuracy of any geometric model is based on its sensitivity to both the volume function and the density function.

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* Corresponding author. Tel.: +1 973 720 3271; fax: +1 973 720 2034.
*E-mail address:* wickej@wpunj.edu (J. Wicke).

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Previous studies have found that overall accuracy is much more sensitive to the volume function and that even with a uniform density value segment inertial estimate errors increase only minimally (Ackland et al., 1988; Wicke et al., 2009). For this reason, the ability of a geometric model to accurately capture the intra-individual variations as well as the inter-individual differences between populations in its volume function (e.g. males vs. females) is the key factor for how well a specific model can estimate segment inertial parameters. Therefore, water-immersion techniques (Piovesan et al., 2011) can provide accurate volume estimates (and in turn, segment inertial estimates), primarily for the limb segments. However, this technique might become more complicated for whole-body segment inertial estimates. Nonetheless, if a non-uniform density function is possible, there will be some improvement to a model.

Compared to regression and cadaver-based models, the more advanced geometric models with a highly sensitive volume functions are significantly more accurate but require more resources and time to obtain the inertial estimate input parameters to ultimately calculate joint moments and forces (i.e. kinetic output measures). For this reason, most commercial motion capture systems integrate regression and/or cadaver-based models. In addition, other input parameters, such as kinematic data and external forces, have a greater influence on the accuracy for calculating joint moments and forces during certain movements and errors in inertial estimates have little overall effect (Pearsall and Costigan, 1999). During lifting, segment masses had no influence on a bottom-up model for calculating the net moments at the L5/S1 joint but were the most influential input parameter using a top-down model (Plamondon et al., 1996).

The effect of the accuracy of segment inertial estimates on kinetic output measures is dependent on the movement and sample being analyzed. Studies that require a model to provide highly accurate segment inertial estimates specific to the sample being analyzed are limited to college-aged individuals or a model that is costly in terms of time commitment from the participants and computations (Hatze, 2005) or monetarily and resources as those derived directly from imaging techniques. This limitation in model selection may be one reason why there appears to be limited studies in kinetic measures in certain areas in biomechanics such as where ballistic movements occur (e.g. Wicke et al., 2013), or examining effects of morphological changes during pregnancy (Jensen et al., 1996) or puberty (Jensen, 1993). The purpose of this study was to develop and test a geometric model of the appendages that can capture both intra-individual variations along a segment and inter-individual differences to yield accurate inertial estimates, but without the limitations of other highly accurate models. The results of the new model are compared to DXA, a method known to accurately (within 1% error) estimate segment inertial estimates (Wicke and Dumas, 2008a) and five other commonly cited models including Dempster (1955), Clauser et al. (1969), Hanavan (1964), deLeva (1996), and Zatsiorsky et al. (1990).

## 2. Methods

### 2.1. Participants

A total of 25 females and 25 males were recruited for the study. The data file for one male participant was corrupt and could not be recovered. Average age for the 25 females was 22.2 ± 4.0 years and 22.5 ± 4.7 for the remaining males. The average and standard deviation for both height and mass, for the females was 165.1 ± 6.0 cm and 61.0 ± 4.2 kg and for the males, 181.7 ± 5.9 cm and 79.1 ± 11.3 kg, respectively. Prior to any testing, participants read and signed a consent form approved by the Queen's University's (Kingston, ON, Canada) Ethics Board.

### 2.2. Criterion inertial measures from dual X-ray absorptiometry (DXA)

Initial testing consisted of participants lying supine on a Hologic QDR Delphi-A DXA machine with arms extended to the side but not touching the torso, forearms placed in a neutral position (i.e. thumbs up), legs straight and separated to the point where the medial thighs were not touching, and ankles plantar-flexed to 45°. Participants were asked to remain still while a whole body scan was taken, from which a 145 × 109 high-tissue attenuation values were captured.

### 2.3. Geometric model procedures and anthropometric measures

Immediately following the DXA scan, the height (to the nearest 0.1 cm) and mass (to the nearest 0.1 kg) of each participant were measured using traditional devices. Next, reflective markers were placed on the anterior and right side of the body at the level of each joint center (Jensen, 1978). A frontal and right sagittal plane image of the participant was taken simultaneously with two digital cameras while the participant was in the same position as during the DXA scan, but standing. Within the image area was one meter stick placed horizontally and one vertically, required to convert image pixels to real units. The images were used for estimating segment inertial parameters from the geometric model.

A series of anthropometric measurements were then immediately taken by directly following the definitions provided of the different body segment models tested. Actual descriptions for each anthropometric measure can be found in their respective publications. These measures were used to determine the arm and leg inertial estimates for these models.

### 2.4. Non-uniform density estimates

Non-uniform density functions for the four appendages for each sex separately were developed using the same procedures as Wicke et al. (2008b). In short, each volume slice (see below) was combined with the corresponding mass estimate (obtained from DXA) along the length of each segment. A polynomial regression function was fitted to each individual density profile. The functions were normalized such that 0 represented the proximal end of the segment and 1 represented the distal end. Combining the individual functions yielded an average density function for each segment separately and for both sexes (Table 1).

### 2.5. Inertial estimates from the new geometric model

The front and side images of the participants were imported into the 'Slicer' (McIlwain, 1998) program and the outlines for the arms and legs were digitized.

**Table 1**

Density profile functions, standard error of the function, and average densities for female and male upper arm, forearm, thigh and shank. All units of measure are g/cm$^3$. Profiles are polynomial functions in the form: Density$=m1x+m2x^2+m3x^3+m4x^4+m5x^5+b$, where m=coefficient, $x$=decimal percent of segment length.

| | Upper Arm | | Forearm | | Thigh | | Shank | |
|---|---|---|---|---|---|---|---|---|
| | Female | Male | Female | Male | Female | Male | Female | Male |
| $m1$ | 0.08792 | −0.01573 | 0.00714 | −0.01120 | −0.00702 | −0.09243 | 0.02172 | 0.12870 |
| $m2$ | 0.06404 | 0.07463 | −0.09761 | −0.07340 | −0.07908 | −0.07533 | 0.00279 | 0.00027 |
| $m3$ | −0.04670 | 0.11500 | −0.01186 | 0.01849 | 0.11620 | 0.05331 | 0.10040 | −0.09009 |
| $m4$ | −0.03825 | −0.17570 | 0.04377 | 0.05753 | −0.04042 | 0.11260 | −0.07765 | 0.00936 |
| $m5$ | 0.01899 | 0.05229 | −0.0108 | −0.02518 | – | −0.05758 | – | 0.01004 |
| $b$ | 1.006 | 1.051 | 1.092 | 1.104 | 1.017 | 1.086 | 1.006 | 1.029 |
| Standard error | 0.000001 | 0.000006 | 0.000001 | 0.000001 | 0.00001 | 0.000001 | 0.00002 | 0.000002 |
| Average | 1.0546 | 1.0704 | 1.0668 | 1.0858 | 1.0078 | 1.0410 | 1.0279 | 1.0736 |