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An Image-Based Approach to Obtaining Anthropometric Measurements for Inertia Modeling

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This study aimed to develop and evaluate an image-based method of obtaining anthropometric measurements for accurate subject-specific inertia parameter determination using Yeadon's (1990) inertia model. Ninety-five anthropometric measurements were obtained directly from five athletic performers and indirectly from digitization of subject-specific whole-body still images. The direct and image-based measurements were used as input into Yeadon's (1990) inertia model. The overall absolute error in predicted whole-body mass achieved using the image-based approach (2.87%) compared well to that achieved using the direct measurements (2.10%). The inclusion of image-based anthropometric measurements obtained from extremity (hand and feet) images was not found to consistently improve model accuracy achieved using whole-body images only. The presented method provides a successful alternative to direct measurement for obtaining anthropometric measurements required for customized inertia modeling. The noninvasive image-based approach is benefited by the potential for obtaining subject-specific measurements from large samples of subjects and elite athletic performers for whom time-consuming data collections may be undesirable.

Keywords: human body, subject specific, two dimensional, athletic performers

The accuracy of biomechanical analyses can depend upon the extent to which the approximation of the body represents the true anatomical structure. One important set of mechanical properties is body segmental inertia parameters (BSIP; Pearsall & Reid, 1994) and, in many applications, including the analysis of sports performance, a parameter set for the particular individual under study is desirable (Yeadon et al., 1993).

Cadaver data (Clauser et al., 1969; Chandler et al., 1975) have previously been used to estimate the BSIP of individuals if their body mass and stature are known (Forwood et al., 1985). However, de Leva (1993) showed that the generalization of cadaver data, which in the main have been from elderly male Caucasians, leads to large errors in segmental center of mass estimations when applied to other populations. Zatsiorsky et al. (1990) obtained BSIP for male and female college students using a gamma-ray scanning technique, which de Leva (1996) adjusted so the parameters were determined with reference to more commonly used body landmarks.

The use of ratio and regression methods in determining BSIP has the advantage that the time required with the subject is minimal, although the parameters determined are not fully customized to the individual's geometry. The modeling of body segments as simple shapes can influence BSIP substantially, particularly in segments comprising complex geometries (Rao et al., 2006). Segmental inertia parameter values derived using ratio and regression may be adequate for biomechanical analysis in simple situations. However, as the biomechanical representation of the human body becomes more complex, the requirement of specific inertia parameters becomes essential so as to avoid inaccurate kinetic analyses (Pearsall & Reid, 1994). Joint kinetics describing gait and derived using an inverse dynamics approach have been reported to be particularly sensitive to BSIP (Rao et al., 2006). Given the precision of current motion analysis systems, the accuracy of the inertia parameters is therefore a potentially limiting factor in carrying out accurate dynamic analyses.

Mathematical models, which represent the body segments using a number of geometric solids, are capable of estimating values of all BSIP (Yeadon, 1990). Since these models generally require the anthropometric measurements of the individual, the inertia parameters

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are subject specific and consider the geometry of the individual under study. The number of measurements taken depends on the number of solids that comprise the model. Yeadon's (1990) model, which estimates total body mass with a maximum error of 2.3% across three subjects, comprises 40 geometric solids, specified by 95 anthropometric measurements. The time to record these measurements can be less than 30 min for an experienced operator, although when time with the subject is limited this technique may not be feasible. Jensen (1976) developed an inertia model comprising elliptical zones, the dimensions of which were obtained by digitizing photographic images of the subject. Although this method is less time consuming for the subject than direct measurement, reference points need to be marked before the subject is photographed. More recently, Baca (1996) developed a method for determining 220 anthropometric measurements from video images to be used as input to Hatze's (1980) model and concluded that the video-based method was useful in situations where ease of application and rapid availability are of importance. The BSIP estimated using the video-based measures of Baca (1996) were similar to those obtained using direct measurement. However, an examination of the "true" accuracy of the video-based and direct approach in replicating the actual, known BSIP of each subject was not conducted. A quantitative comparison of an actual measure, such as whole-body mass, with the corresponding predicted measure is desirable to indicate the level of confidence associated with a modeling approach. The aim of this study was to develop a method of obtaining anthropometric measurements from athletic performers, which requires reduced collection time, and to examine the accuracy of the approach in determining actual subject-specific inertia parameters using Yeadon's inertia model.

Methods

Anthropometric measurements were obtained from five physically active males (age: 22.8 ± 2.6 years; whole-body mass: 70.9 ± 6.8 kg; height: 1.729 ± 0.114 m). Approval for the study was provided by the University's Research Ethics Committee and each subject gave written informed consent. Subjects, who were of various morphologies, wore only tight-fitting shorts, allowing identification of body segment landmarks.

Ninety-five anthropometric (direct) measurements, detailed for Yeadon's (1990) inertia model, were taken from each subject by an experienced researcher. Measurements were obtained using a tape measure and anthropometric calipers. The whole-body mass (Table 1) and height of each subject were measured directly using laboratory weighing scales (Avery Berkel Ltd, model ED01) and a stadiometer (Holtain Ltd), respectively. Direct measurements for each subject were obtained within 30 min.

A Canon EOS 400D digital camera was used to obtain frontal and left and right sagittal plane whole-body images of each subject in a stationary, upright position (Figure 1). Six calibration points of known location were positioned on an upright, rectangular frame (1.800 m × 0.916 m) within the field of view of each whole-body image. The potential for parallax error in image processing was minimized by positioning the subject such that the body landmarks to be obtained from each image were located within the calibration plane.

Images of the extremities (hands and feet) were also obtained for each subject. A calibration object (0.300 × 0.024 m) was located in the field of view of each extremity image. Images of the hands in the frontal and sagittal planes were obtained. One transverse plane image of both feet and separate sagittal plane images of the left and right foot were taken.

Images were cropped to a maximum resolution of 720 × 576 pixels using Zoom Browser EX (Canon Inc., version 5.7), converted to .avi format using DVgate Plus (Sony Corporation, version 2.2.01), and then imported into Peak Motus (Vicon Motion Systems, version 9.0.0.27-GM) for digitizing. Each image was digitized for 10 fields to obtain two-dimensional (2-D) coordinate data of the calibration object and the body segment contours at 45 defined landmarks as detailed by Yeadon (1990). Coordinates were reconstructed using the 2-D direct linear transformation (Walton, 1981), and were then used to obtain lengths, perimeters, widths, and depths corresponding to the measurements required by Yeadon's (1990) inertia model. Perimeter measurements were not obtainable directly from the images, so 2-D width and depth images were used to derive perimeter measurements required as input into the inertia model.

Coordinate data from the left and right whole-body sagittal plane images were used to obtain depths at each landmark (i) such that

$$d_i = xa_i - xp_i$$

where d_i = segment depth, and xa_i and xp_i = x coordinate of the most anterior and posterior location on the segment, respectively, at each landmark.

The frontal plane whole-body image data defined image-based lengths and widths of body segments so that

$$l_i = z_i - z_{i-1}$$

where l_i = length measure at respective landmark, z_i = z coordinate of respective landmark, and z_{i-1} = z coordinate of preceding landmark and

$$w_i = ym_i - yl_i$$

where w_i = width, and ym_i and yl_i = y coordinate of the most medial and lateral location on the segment, respectively, at each landmark.

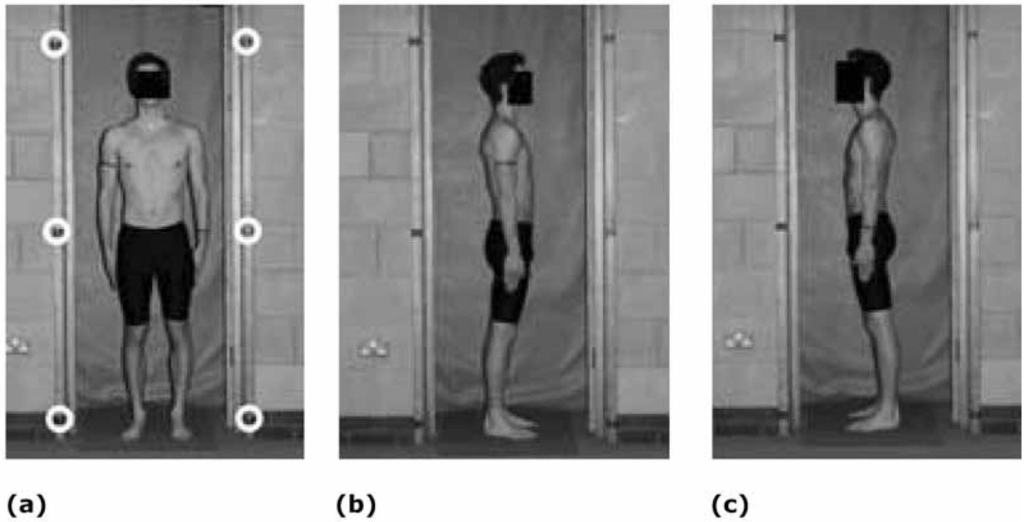

Figure 1 — Whole-body images of the frontal plane view (a) and right (b) and left (c) sagittal plane view of one subject. The six calibrations points are highlighted in image a.

Perimeter measurements required for the body segments modeled with circular cross-sectional areas (head, neck, and limbs) in Yeadon's (1990) inertia model were derived using the 2-D depths and widths such that

$$p_{hnli} = \pi\left(\frac{d_{hnli} + w_{hnli}}{2}\right)$$

where p_{hnli} = perimeter measure, d_{hnli} = depth, and w_{hnli} = width, at the respective head, neck, or limb landmark. Perimeter measurements required for the body segments comprising stadium solids (trunk and extremities) were derived using the 2-D depths and widths so that

$$p_{tei} = 2(w_{tei} - d_{tei}) + \pi d_{tei}$$

where p_{tei} = perimeter measure, d_{tei} = depth, and w_{tei} = width, at the respective trunk or extremity landmark. The image-derived measurements of the extremities were obtained firstly using only the whole-body images and secondly using the extremity images.

The measurements derived directly, using whole-body images only and whole-body images combined with the extremity images were independently input into Yeadon's (1990) inertia model. Density values from Dempster (1955) were combined with Yeadon's (1990) inertia model to provide three sets of customized BSIP for each subject. The inertia model's accuracy in replicating each subject's measured whole-body mass was derived for the three sets of model input data as the quantified difference (error) between the predicted and measured whole-body mass such that

$$\text{Error} = \left(\frac{M_p - M_m}{M_m}\right)100$$

where M_p = whole-body mass predicted by the model and M_m = measured whole-body mass.

The accuracy of the image-based approaches for obtaining anthropometric measurements for inertia modeling was compared with the accuracy achieved using direct measurements. Within- and between-digitizer reliability was assessed by comparing the model error produced using whole-body image data derived from repeated digitizations of one subject.

A sensitivity analysis of the model accuracy was conducted using whole-body image-based data comprising circular segment perimeters derived firstly using the mean depths and widths, secondly using only depths, and thirdly using only widths. Only the segments comprising a circular cross-section were modified in the sensitivity analysis.

Results

The levels of agreement between the measured and predicted whole-body mass derived using the inertia model and three sets of anthropometric input data are illustrated in Table 1. On average, the direct measurements produced the most successful replication of the measured whole-body mass compared with the image-based approaches. Mean ± *SD* absolute errors were 2.10 ± 1.61%, 2.87 ± 1.57%, and 2.55 ± 1.54% using the direct, digitized whole-body, and digitized whole-body combined with extremity image measurements, respectively. Within- and between-digitizer repeatabilities of within 0.20% and 0.35%, respectively, of the error produced using the whole-body image data for Subject A (Table 1) were achieved.

The whole-body image-based data comprising circular perimeters derived using the mean of the respective width and depth measures produced a notably more

Table 1 Subject-specific measured whole-body mass and model error (%) produced using direct, digitized whole-body image and digitized whole-body combined with extremity image anthropometric measurements

		Error (%)		
Subject	Measured whole-body mass (kg)	Direct	Whole-body image	Whole-body and extremity image
A	74.40	1.37	3.12 [a]	3.08 [b]
B	80.90	−1.84	−2.52	−1.87
C	67.70	1.77	−1.33	−0.46
D	67.90	4.86	1.96	2.71
E	63.70	0.66	−5.42	−4.65

[a]Within-digitizer repeatability: 3.32%; between-digitizer repeatability: 3.47%.
[b]Within-digitizer repeatability: 3.84%, between-digitizer repeatability: 2.65%.

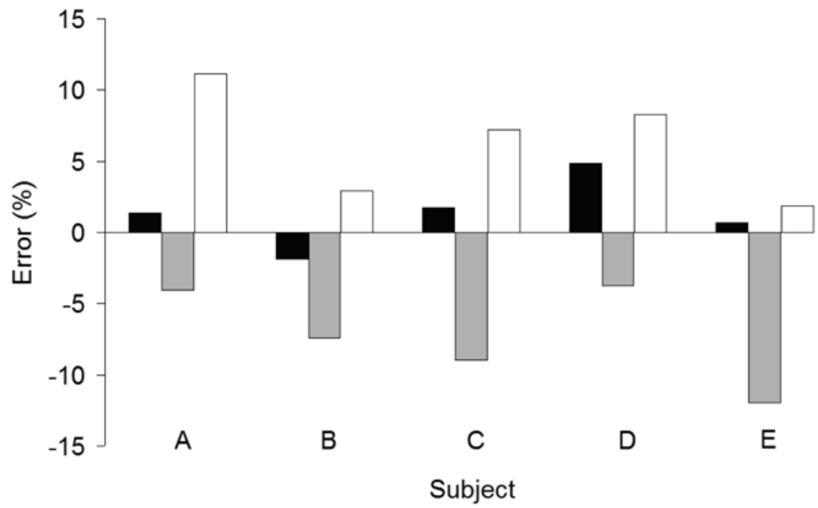

Figure 2 — Subject-specific inertia model error (%) produced using 2-D digitized whole-body images comprising circular perimeters estimated using combined width and depth (black), width only (gray), and depth only (white) digitized measurements.

successful replication (mean absolute error: 2.10%) of whole-body mass compared with the width and depth only approaches (Figure 2), and produced no systematic under- or overestimation of whole-body mass. Width (mean absolute error: 7.22%) and depth (mean absolute error: 6.27%) only measures consistently under- and overestimated whole-body mass, respectively.

Discussion

An image-based approach for obtaining indirect personalized anthropometric measurements for inertia modeling of body segments was developed and evaluated. The inertia modeling approach was favored over traditional cadaver-based approaches for deriving BSIP because of the associated benefits of obtaining BSIP customized to the geometry of individual subjects.

The level of confidence in the image-based approach was assessed by determining the inertia model accuracy in replicating actual whole-body masses compared with that achieved using traditional direct measurements. Individual BSIP are difficult to measure in vivo but can be estimated using direct techniques such as gamma scanning and immersion (Kingma et al., 1996). The use of direct methods in biomechanical analyses estimating BSIP are, however, inhibited by the complexity and cost of the procedures involved, and minor discrepancies between the actual and derived measure that can still exist (Kwon, 1996). The objectivity and accessibility of the measured whole-body mass was considered beneficial for the accuracy assessment conducted in this investigation. As suggested by Yeadon (1990), the level of agreement between simulations performed using the predicted BSIP and actual performances may provide insight into the appropriateness of other predicted inertia parameters in the future.

A mean absolute error of 2.10% was obtained using direct measurements, which was comparable to that previously achieved by Yeadon (1990; 2.03%) using direct measurements from three subjects. A higher mean error was achieved using the presented whole-body image-based approach (2.87%) compared with the direct measurements, which suggests that the accurate inertia modeling of whole-body mass ideally requires the use of measurements taken directly from the subject.

However, the slightly lower mean error achieved using the direct compared with image-based measurements was counterbalanced by the substantially longer subject contact time required (direct: 30 min; image: 5 min). Furthermore, the direct method was not found to provide a consistently improved whole-body mass replication for every subject relative to the image-based approach.

A video-based and direct measurement approach for predicting BSIP using Hatze's (1980) inertia model were previously compared by Baca (1996). Although the video-based approach was benefited by its ease of application and rapid availability, the accuracy of the approach in reproducing actual BSIP was not assessed. In contrast to Baca (1996), this study confirmed that image-based measures can be combined with inertia modeling to reproduce actual BSIP with an accuracy comparable to that achieved using direct measurements. The developed approach was benefited by the achievement of a high level of accuracy in whole-body mass replication using only 95 measurements, which was a notably reduced data set than required by Baca (1996; 220 measurements). The benefits of a reduced measurement set are a shorter processing time integrated with a potentially reduced measurement error across the whole-body profile. Further insight into the sensitivity of the predicted BSIP to the direct measurement error may be alleviated by detailed measurer and digitizer reliability assessments in future investigations.

Limitations in inertia modeling associated with changes in lung volume during the measurement of subjects have previously been highlighted (Yeadon, 1990). Subjects were asked to maintain tidal breathing during direct measurement and image capture to minimize mass discrepancies incurred with possible lung volume alterations. Alongside potential errors associated with anthropometric measurement, the success of the image-based and direct measurement approaches was potentially limited by the homogenous segment density assumption of Yeadon's (1990) model. Future analyses may benefit from integrating component inertia models (e.g., Gittoes & Kerwin, 2006), which consider soft and rigid tissue densities, with the image-based approach to produce improved BSIP replications

The presented image-based approach was limited by the need to obtain model-specific three-dimensional anthropometric measurements e.g., limb perimeters. The sensitivity analysis, however, suggested that the use of combined 2-D widths and depths was successful owing to the improved whole-body mass replication achieved compared with alternative approaches using only widths and only depths. The image-based approach was also potentially limited by the level of resolution that could be achieved in reproducing extremity measurements with a whole-body field of view. Anthropometric measurements were subsequently derived using higher resolution extremity images combined with the whole-body image. Although, a slightly reduced mean absolute error (0.32%) was achieved, the improvement was not consistent across all subjects. Without a substantial and consistent improvement in the whole-body mass replication, the rationale for the inclusion of the extremity images into the image analyses may be weakened because of the additional image collection and digitizing time required.

The presented image-based approach provides a successful alternative to direct measurement for obtaining anthropometric measurements required for customized inertia modeling. The image-based approach is potentially beneficial for indirectly deriving comprehensive anthropometric measurements from large samples of subjects or elite athletic performers for whom time-consuming data collections may be undesirable.

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