VALIDATION OF A DXA-BASED METHOD FOR OBTAINING INERTIA TENSORS: *'WHEN PIGS FLY'*

Marcel M. Rossi[1], Cyril J. Donnelly[1], Amar El-Sallam[1], James Dowling[2], Jeffrey A. Reinbolt[3] and Jacqueline Alderson[1]

School of Sport Science, Exercise and Health, The University of Western Australia, Perth, Australia[1]
Department of Kinesiology, McMaster University, Hamilton, Canada[2]
Mechanical, Aerospace, and Biomedical Engineering Department, University of Tennessee, Knoxville, U.S.A.[3]

This paper examines the accuracy of body segment inertia tensors estimated by combining information from dual-energy X-ray absorptiometry and a three-dimensional modelling technique proposed by Zatsiorsky et al. (1990) (DXA/Vol method). The inertia tensor of a frozen pig cadaver was estimated using the novel DXA/Vol method and traditional compound pendulum techniques. The pig cadaver was projected through the air and the experimental 'ground truth kinematics' were recorded. Simulated kinematics of the pig cadaver flight were generated using the inertia tensor derived from the DXA/Vol and compound pendulum methods and compared to the ground truth kinematics. Simulations based on the novel DXA/Vol method's inertia tensor tracked the experimentally recorded flight of the frozen pig cadaver with superior accuracy.

KEY WORDS: simulation; Zatsiorsky; modelling; airborne motion; flight.

INTRODUCTION: In sports such as gymnastics, skiing and diving, performance outcomes are determined by highly complex airborne movements. These intricate rotations result from the athletes' ability to change their mass distributions in space by moving their body segments whilst airborne. Computer simulations may help athletes and coaches understand how changes in body pose (i.e., joint kinematics) affect desired rotations and lead to technique-related decisions improving or optimising performance during these sports (Dapena, 1978; Yeadon, Atha, & Hales, 1990; Kwon, 2001). Three-dimensional (3D) mass distribution within each body segment, represented by a 3x3 matrix called an inertia tensor, also influences rotational airborne motion. This type of athlete anthropometry is highly specific to individuals within a given sport (Olds & Tomkinson, 2009). Therefore, the use of athlete-specific body segment inertia tensor values, along with other inertial properties of mass and 3D centre of mass position, may be critically important for the outcome accuracy of sport-based computer simulations and their efficacy for making technique recommendations to modify and enhance athlete performance. The compound pendulum method is an established gold standard for measuring body segment inertia tensors, but can only be used for *in-vitro* segments (Chandler, Clauser, McConville, Reynolds, & Young, 1975). Alternatively, the Gamma-Ray scanner (Zatsiorsky, Seluyanov & Chugunova, 1990) and more recently Dual-Energy X-Ray Absorptiometry (DXA) (Durkin, Dowling, & Andrews, 2002; Lee, Le, Fang, & Koh, 2009) have been used to estimate the inertial properties of body segments *in-vivo*. These technologies are only able to measure mass distribution over the scan planes (areal density), limiting their ability to measure body segment inertia tensors. Zatsiorsky et al. (1990) used areal density data collected from Gamma-Ray scans to create a volumetric template comprising of multiple parallelepipedal elements of uniform density to estimate 3D inertial properties. Though this method showed promise, the feasibility of Gamma-Ray scanning is poor, whereas areal density data from DXA is more readily available. Building on the volumetric model proposed by Zatsiorsky et al. (1990), the aim of this study was to evaluate whether an approach using areal density data obtained using DXA is able to provide accurate body segment inertia tensors.

METHODS: A cluster of 9 retro-reflective markers (10 mm diameter) were rigidly affixed to the dorsal surface of a solid-frozen pig cadaver. The pig cadaver was scanned with a Lunar Prodigy DXA scanner (GE Healthcare, Buckinghamshire, UK), and a custom Matlab script (v. 7.8.0, The Math Works, Inc., Natick, Massachusetts, USA) was used to output the mass distribution over the scanning surface, represented by a matrix of squared (0.20 x 0.20 cm) elements (El-Sallam et al., 2013; Rossi et al., 2013). A license agreement was arranged between The University of Western Australia and the General Electric Company Healthcare Division (GEHC) to gain access to raw data (mass areal density) files output by the scanner.

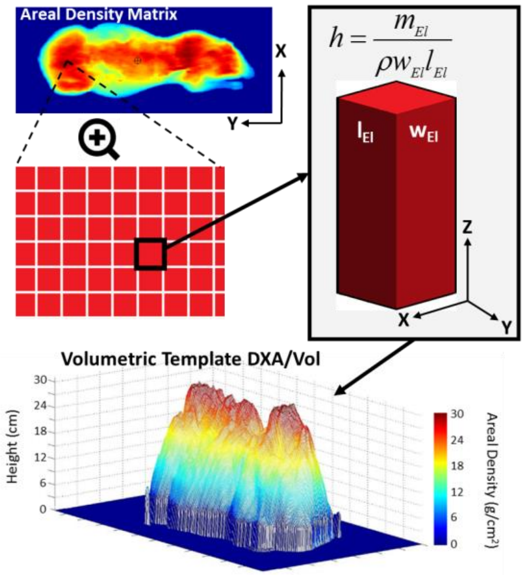

Figure 1: Calculation of the DXA/Vol volumetric template

Estimation of the mass distribution within the pig cadaver's volume was performed by creating a volumetric template as proposed by Zatsiorsky et al. (1990), which assumes the body as a collection of parallelepipeds (one for each squared element) of uniform density (ρ=1g/cm^3), whose height (h) was computed as shown in Fig. 1. The inertia tensor of the pig cadaver was then computed by combining the mass, centre of mass and principal moments of inertia from a sum of each parallelepiped. For the purposes of this manuscript, this will be referred to as the DXA/Vol method.

In addition, the inertia tensor of the pig cadaver was also estimated through a modified compound pendulum (CP) method (Rossi et al., 2016). A rigid rectangular frame (0.6 m x 0.6 m x 0.8 m) was suspended above the ground in six different orientations (two non-parallel axes for each anatomical plane). Oscillations of the rectangular frame with and without the pig cadaver firmly affixed to the rigid rectangular frame were recorded in each of the six orientations using a 24-camera VICON Motion Analysis System (240 Hz). Custom Matlab functions enabled the calculation of; (i) the moment of inertia about the axis of rotation for each oscillation trial and (ii) the inertia tensor of the pig cadaver.

The pig cadaver was manually projected through the calibrated volume of the laboratory. Marker positions were recorded from the first frame of full release to the frame prior to ground contact (flight time=0.426 sec). Two pig models were created in OpenSim (v. 3.3, simt-k.org, Stanford, CA) using the inertia tensors estimated from the DXA/Vol and CP methods. The airborne experimental ground truth kinematics of the pig cadaver were calculated from the 3D marker trajectories and with the inverse kinematic (IK) tool in OpenSim. The Application Programming Interface (API) and the Forward Dynamics tool in OpenSim were used to validate the inertia tensors estimated using the DXA/Vol and CP methods. Briefly, the tool generates dynamic simulations of a model's motion through the numerical integration of the Newton-Euler differential equations, which define the dynamics of the model. For each pig cadaver model, the experimentally derived kinematics were used to define the initial states of the

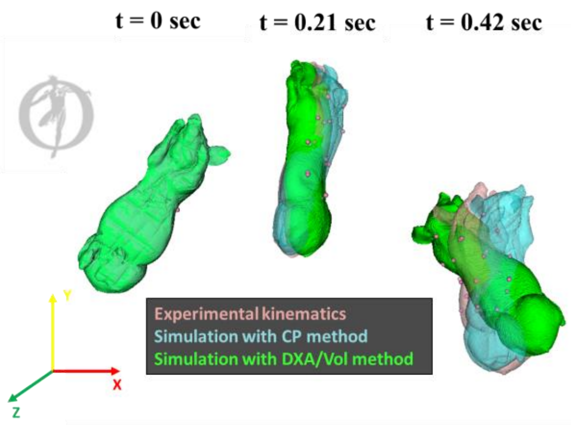

Figure 2: Experimental and simulated kinematics for the two estimation methods.

model to generate the forward dynamics simulations of the airborne motions. In total 427 simulations, with 427 different starting points along the simulation flight path were performed for each of the cadaveric pig models. To assess model accuracy, discrepancies between the experimentally recorded kinematics of the cadaveric pig flight, and the simulated flight of each pig model were calculated, and expressed as deviation angles (degrees) between the angular velocity vectors. The distribution of the root mean squared deviation angles for each of the simulated pig flight trials were presented as boxplots (10^{th} to 90^{th} percentile).

RESULTS: The inertia tensors estimated from the DXA/Vol and CP methods were re-expressed with respect to their principal moments of inertia (eigenvalues I_X, I_Y and I_Z) and principal axes of inertia (eigenvectors $\boldsymbol{I_X}$, $\boldsymbol{I_Y}$ and $\boldsymbol{I_Z}$) in the sagittal (X), longitudinal (Y) and transverse (Z) axes for numerical comparison (Table 1). The principal moments of inertia are presented as an absolute value ($kg{\cdot}m^2$) and normalised by their corresponding I_X. The orientation of each principal axis of inertia estimated with the DXA/Vol method were expressed by deviation angles from the CP $\boldsymbol{I_X}$, $\boldsymbol{I_Y}$ and $\boldsymbol{I_Z}$ (angles α, β and γ, respectively, in degrees). The root mean squared deviation angles between the DXA/Vol simulation and the experimentally recorded flight of the pig cadaver model ranged between 6.3^o and 13.9^o (10th to 90th percentile), with a median of 7.9^o). The deviation angles between the CP simulation and the experimentally recorded flight of the pig cadaver model ranged between 7.6^o and 16.4^o (10th to 90th percentile), with a median of 10.3^o.

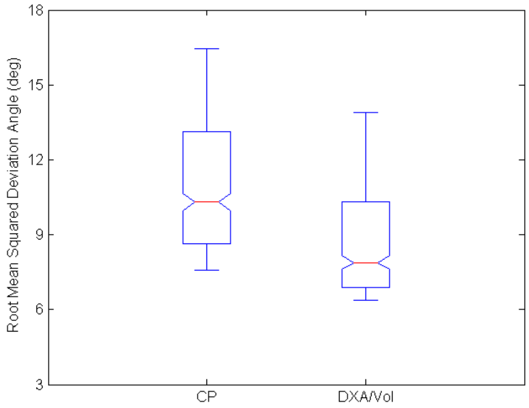

Figure 3: Boxplot distribution for root mean squared deviation angles.

Table 1: Principal moments and axes of inertia for the pig cadaver.

	CP Method	DXA/Vol Method
I_X ($kg{\cdot}m^2$) (I_X/I_X)	0.97 (1.00)	0.86 (1.00)
$\boldsymbol{I_X}$ (α, β, γ) (deg)	-	(15.2, 87.5, 105.0)
I_Y ($kg{\cdot}m^2$) (I_Y/I_X)	0.15 (0.15)	0.10 (0.12)
$\boldsymbol{I_Y}$ (α, β, γ) (deg)	-	(90.2, 9.0, 81.0)
I_Z ($kg{\cdot}m^2$) (I_Z/I_X)	0.97 (1.00)	0.86 (1.00)
$\boldsymbol{I_Z}$ (α, β, γ) (deg)	-	(105.2, 81.4, 162.4)

DISCUSSION:

The aim of this study was to assess whether 3D, athlete-specific inertia tensors can be accurately estimated by combining areal density measures from DXA with the 3D volumetric modelling technique proposed by Zatsiorsky et al. (1990). Findings showed that the DXA/Vol method estimated inertial tensors comparable to those from the compound pendulum method, while producing simulations that more accurately tracked the experimentally recorded flight of a pig cadaver. These results show the DXA/Vol method can calculate realistic inertial tensor estimates that are more accurate than common compound pendulum approaches.

Smaller principal moments of inertia values were found for DXA/Vol in comparison with the CP values. For the normalised principal moments of inertia, the only difference was observed in the longitudinal ($\boldsymbol{I_Y}$) axis (20% lower). With the finite parallelepipedal elements distributed more closely to the longitudinal axis ($\boldsymbol{I_Y}$), calculation of I_Y is more dependent on the estimated height of the parallelepipeds. The density of each parallelepipedal element is assumed to be uniform, which is an acknowledged limitation to this method, and would have contributed to the large between-method discrepancies for the I_Y. Conversely, no differences were observed in the I_X and I_Z estimates, which is likely due the parallelepipeds being distributed more distantly from their respective sagittal ($\boldsymbol{I_X}$) and transverse ($\boldsymbol{I_Z}$) axes. Therefore, calculation of I_X and I_Z are more dependent on each parallelepiped mass and position over the DXA scanning surface, which is a measure with established accuracy (Durkin et al., 2002).

Despite the observed differences in inertia tensor parameters between methods, the dynamic validation approach of this research showed the DXA/Vol method generated the most accurate simulations of the pig cadaver flight (fig. 3). These results are important as they not only take into consideration the magnitude of principal moments of inertia but also the orientation of the principal axes of inertia. Despite the addressed I_Y artifact, the DXA/Vol $\boldsymbol{I_X}$, $\boldsymbol{I_Y}$ and $\boldsymbol{I_Z}$ orientations appear to be sufficient to assure greater simulation accuracy than the compound-pendulum-based inertia tensor estimates alone. This study is the first to demonstrate that DXA values combined with a volumetric modelling technique can be used to estimate inertia tensors for irregular-shaped, non-uniform-density specimens with superior accuracy to more commonly used compound pendulum methods.

CONCLUSION: The combination of areal density data from DXA with a volumetric modelling technique described by Zatsiorsky et al. (1990) is an accurate *in-vivo* method for estimating body segment inertia tensors. As DXA is a safe, cheap and widely accessible medical imaging technology, the DXA/Vol method has the potential to become a new standard for obtaining body segment inertial properties for musculoskeletal modelling (athletic and pathological populations) and simulations of airborne movements.

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