Trunk density profile estimates from dual X-ray absorptiometry

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Abstract

Accurate body segment parameters are necessary to estimate joint loads when using biomechanical models. Geometric methods can provide individualized data for these models but the accuracy of the geometric methods depends on accurate segment density estimates. The trunk, which is important in many biomechanical models, has the largest variability in density along its length. Therefore, the objectives of this study were to: (1) develop a new method for modeling trunk density profiles based on dual X-ray absorptiometry (DXA) and (2) develop a trunk density function for college-aged females and males that can be used in geometric methods. To this end, the density profiles of 25 females and 24 males were determined by combining the measurements from a photogrammetric method and DXA readings. A discrete Fourier transformation was then used to develop the density functions for each sex. The individual density and average density profiles compare well with the literature. There were distinct differences between the profiles of two of participants (one female and one male), and the average for their sex. It is believed that the variations in these two participants’ density profiles were a result of the amount and distribution of fat they possessed. Further studies are needed to support this possibility. The new density functions eliminate the uniform density assumption associated with some geometric models thus providing more accurate trunk segment parameter estimates. In turn, more accurate moments and forces can be estimated for the kinetic analyses of certain human movements.

Keywords: Body segment parameters; DXA; Density; Geometric modeling

1. Introduction

Biomechanical modeling of the human body is required to evaluate the forces and moments acting across the joints. Models which represent the body segments as rigid bodies are based on cadaver, regression, imaging, or geometric methods. The geometric method combines a volume with a density function to obtain segment inertial estimates. The density variations depend upon the amount and the types of tissue within each section of the segment. To develop more accurate geometric models of the human body, we must first better understand how a segment’s density fluctuates. This is especially true for the trunk, the body section with the greatest fluctuation in the types and amount of tissue.

Magnetic resonance imagining (MRI) was one of the first imaging devices used to estimate trunk densities for modeling purposes (Pearsall et al., 1994). The tissues (fat, bone, muscle, etc.) within each MRI image from 26 males, 40.5 ± 14.4 years of age, were assigned a density value according to pixel intensity. The tissues were then digitized such that their volumes could be calculated. Assigned tissue densities were then combined with their respective volumes such that an average density for the upper, middle, and lower trunk could be estimated.

The density profile of the upper and lower trunk has also been estimated using computed tomography (Wei and Jensen, 1995). Fifty Chinese females between the ages of 18 and 23 were scanned while tissue volumes were determined using the method of Pearsall et al. (1994). However, the tissues were assigned a different set of density values than Pearsall et al. used. The authors reported a density range between 0.88 and 1.07 g/cm³ for the upper trunk and between 0.97 and 1.01 g/cm³ for the lower trunk.
Computed tomography was also used to examine the density of the upper and middle trunk sections of two males and two females with an average age of 61.0 ± 1.0 years (Pearsall et al., 1996). Although the trunk density profile was similar to that reported by Wei and Jensen (1995), the range for the upper trunk was markedly different (0.74–0.99 g/cm³).

A fourth trunk density study (Erdmann, 1997) used CT scanning on 15 males, 31.7 ± 4.7 years old. The study determined the volume of each tissue similar to the previous studies, but again, a different set of tissue densities was adopted. The study had the largest range in density profiles (from 0.8 to 1.1 g/cm³).

There is an agreement that non-uniform density profiles will afford geometric models more accuracy when estimating body segment parameters (Nigg, 1999). However, the magnitude to which non-uniform density profiles will increase the accuracy of a geometric model has not been fully examined. In fact, the only known study to compare variations in body segment parameter estimates between the same geometric model using non-uniform and uniform density functions was by Ackland et al. (1988). The study only found minor errors when assuming a uniform density for the upper leg segment. However, different results would be likely for the trunk section, which is both longer in length and has a much greater density variation. Regardless, there is a need to further refine models to account for their inconsistencies when used on different ages, genders and morphologies as found by Durkin and Dowling (2003). In turn, the errors in the inertial estimates due to the inconsistencies, both within and between models, result in significant differences in joint resultants from inverse dynamic methods (Andrews and Mish, 1996; Larivi`ere and Gagnon, 1999).

There is uncertainty as to whether variations in the density pattern among the studies are a result of inter-individual characteristics or a study’s methodology (e.g. differences in trunk boundary definitions). Understanding the individual characteristics that affect the trunk density profile may lead to a better understanding of the factors causing variations in body segment parameters, i.e. mass, center of mass location and moment of inertia. The purposes of this study were to: (1) develop a new method for estimating density profiles and (2) develop a new set of density profiles to be used in geometric models and in turn, explore variations in density profiles between individuals of similar age and the same gender but with different morphological characteristics.

2. Methods

2.1. Participants

A total of 25 females and 25 males were recruited from the student body of Queen’s University in Kingston, Ont., Canada. Anthropometric characteristics of the participants can be found in Table 1.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI (kg/m²)</th>
<th>Fat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Min</td>
<td>18.0</td>
<td>154.5</td>
<td>51.9</td>
<td>19.9</td>
</tr>
<tr>
<td>Max</td>
<td>33.0</td>
<td>181.5</td>
<td>67.1</td>
<td>26.1</td>
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<tr>
<td>Mean</td>
<td>22.2</td>
<td>165.1</td>
<td>59.3</td>
<td>21.8</td>
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<tr>
<td>SD</td>
<td>4.0</td>
<td>6.0</td>
<td>4.0</td>
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</tr>
<tr>
<td>Males</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>18.0</td>
<td>174.2</td>
<td>58.7</td>
<td>18.6</td>
</tr>
<tr>
<td>Max</td>
<td>35.0</td>
<td>201.1</td>
<td>102.9</td>
<td>32.5</td>
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<td>5.9</td>
<td>11.2</td>
<td>3.0</td>
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Percent fat estimates were measured from DXA.

2.2. DXA scanning

Prior to testing, participants read and signed a consent form approved by the Institution’s Ethics Board. Participants were asked to lie supine on the scan table with their arms abducted to the point where there was a clear separation between the arms and the trunk. A whole body dual X-ray absorptiometry (DXA) scan was performed using a Hologic™ QDR Delphi-A fan beam machine. The scan took approximately 3 min and exposed the participant to an amount of radiation that is equivalent to a trans-continental flight. According to the American Cancer Society, this exposure equates to approximately 6 mrem compared to the average annual natural background exposure of 300 mrem.

2.3. Photographic procedures

Immediately following the DXA scan, height and weight measures were recorded using traditional methods. Trunk length and the xiphoïd, omphalion, and anterior superior iliac spine distance from the proximal trunk boundary (C7–T1 intervertebral disk) were measured using an anthropometer.

The photographic procedures that followed were similar to those of Jensen (1978). First, two reflective markers (1 cm²) were placed at the level of the joint centers such that one could be seen from the front and the other from the side. The markers were placed at the level of the C7–T1 intervertebral disk, acromion process, and anterior superior iliac spine.

Two digital cameras (1536 pixels high × 1024 pixels wide) were placed orthogonal to each other, 6 m from the center of the participant. The field of view was approximately 2 m high × 1.5 m wide, resulting in a resolution of approximately 1.3 × 1.4 mm/pixel, respectively. One camera was positioned to capture the right side of the participant (sagittal plane) and the other to capture the front view (frontal plane). One camera was triggered using a timer while the other was triggered manually resulting in simultaneous front and side images of the participant. Included in both front and side images were horizontal and vertical meter sticks used to convert image size to life size units of measure. The meter sticks for each camera were placed at the same horizontal distance from the camera as the center of the body.

2.4. Data reduction—volume

Once all data were collected, the front and side digital images were imported into the ‘Slicer’ program (McIlwain, 1998) to outline the trunk section as defined in Fig. 1. At the distal end, the trunk was separated from the legs, starting with a horizontal line from the perineum to one-third the thickness of the leg. The line then extended diagonally up through the anterior superior iliac spine. The definition for the lower trunk boundary

Table 1

Anthropometric statistics for the 25 female and 25 male participants

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<td>5.9</td>
<td>11.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>
where the variables are defined in Fig. 2 and the angles are measured in ellipse was also used.

\[
V = \frac{1}{2} \pi ab \sin \theta
\]

\[
2.5. Data reduction—DXA and trunk density determination

Once the calibration equation was developed, the high tissue attenuation values from the DXA scan were converted to mass per unit area and then multiplied by the area of each attenuation value to obtain mass. Each attenuation value represented an area of 0.81 cm², this area is machine dependent and corresponded to a width of 0.62 cm and a length of 1.30 cm. This predetermined length matched the 1.30 cm thickness used to section the trunk volume above.

The ability to use raw tissue attenuation from a fan beam DXA (namely the HologicTM Delphi machine) has been assessed (Wicke, 2006). It was found that mass, center of mass location, and moments of inertia could be accurately estimated (i.e. all within approximately 1.5%), regardless of the object’s position or location on the scan table.

The mass sections for the trunk were then mapped onto their corresponding volume sections. To do so, the axilla, perineum, and shoulders were used as points of reference. The trunk–shoulder and trunk-leg boundaries of the DXA data were determined from the width measurements taken from the digitization in the volume procedure. The mass for a transverse section was calculated by summing each of the mass values across that section. Finally, the density for each 1.3 cm section was determined by dividing the mass by the volume.

2.6. Data reduction—density profiles

Once the density profiles were obtained, a discrete Fourier transformation (DFT) was used to develop an individual density function for each participant. To determine the number of coefficients that would best represent the raw data, a residual analysis of the functions was performed (Winter, 1990). Once the best function for each participant was determined, an average function for both females and males was developed.

2.7. Statistical procedures

Descriptive statistics (including z-scores) for the RMS error of each individual curve were determined using SPSS™ (Chicago, IL). Descriptive statistics were also performed for the RMS error of the average female and male functions. In the case of any outliers, the anthropometric characteristics of the individual(s) would be compared to the rest of the participants. In essence, this exploratory method could help determine whether density profile variation could possibly be due to variations in tissue distribution within each gender.

3. Results

Table 1 shows the minimum and maximum values, average and standard deviation for the age, height, weight, body mass index (BMI) (weight x height²), and percent body fat (measured from DXA) of the participants. During the DXA scanning process, one of the male participant’s raw data file was corrupted and therefore could not be used in the study.

Residual analysis revealed that for every case a fourth order Fourier series function best represented the raw density curve. The descriptive statistics for these individual functions of the 49 participants for females and males, separately, are shown in Table 2.

Eqs. (2) and (3) are the average female and male functions, respectively, where \( f(x) \) and \( m(x) \) is the trunk density (g/cm³) and \( x \) is the trunk length normalized from 0 to 1, corresponding to the trunk’s proximal and
distal ends, respectively.

\[ f(x) = 0.9207 - 0.0306 \cos(2\pi x) \\
- 0.0170 \sin(2\pi x) + 0.0666 \cos(4\pi x) \\
- 0.0147 \sin(4\pi x) + 0.0018 \cos(6\pi x) \\
+ 0.0449 \sin(6\pi x) + 0.0200 \cos(8\pi x) \\
+ 0.0163 \sin(8\pi x), \] 

\[ m(x) = 0.9250 - 0.0090 \cos(2\pi x) \\
- 0.0438 \sin(2\pi x) + 0.0553 \cos(4\pi x) \\
- 0.0370 \sin(4\pi x) + 0.0197 \cos(6\pi x) \\
+ 0.0427 \sin(6\pi x) + 0.0175 \cos(8\pi x) \\
+ 0.0070 \sin(8\pi x). \] 

The \( z \)-scores (\( > 2.0 \)) indicated that two participants' RMS errors were outlying values (i.e. individual function compared to average function), one female and one male. These two participants had a higher BMI and percent body fat than the average, and in the case of the male, his BMI and percent body fat were the highest across all males. Fig. 3 depicts the average female and male density curves along with the two outliers. The female outlier showed a similar density pattern in the upper trunk as the average female curve, but her curve for the lower trunk was notably different. For the male outlier, the overall curve was more flat than the average male curve.

4. Discussion

The first goal of this study was to develop a new method for estimating trunk density profiles. The two primary advantages of this method are that participants are not exposed to large amounts of radiation compared to computed tomography and that the cost of obtaining density profiles is small relative to MRI. However, several limitations to this method exist. First, the DXA scan was performed with the participant in the supine position while volume estimates were obtained from images of the participant while standing. As a result, the tissues within the trunk may not have been perfectly aligned when mapping the two sets of data to obtain the density functions. A second limitation is the unavoidable errors in the estimates of the volume (photogrammetric method) and mass per unit area (DXA scan). Volume estimates from the photogrammetric method were found to have average errors of less than 5% and mass per unit area from DXA of less than 1% (Wicke, 2006). A third limitation was in the mapping of the two data sets. Volume estimates were combined with the mass per unit area to obtain density. Although care was taken to ensure that two data sets were

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Individual functions</th>
<th>Average functions</th>
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</thead>
<tbody>
<tr>
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<td>Females</td>
<td>Males</td>
</tr>
<tr>
<td>Mean</td>
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<td>0.024</td>
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<td>0.005</td>
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<tr>
<td>Minimum</td>
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<td>0.016</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.042</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison between the trunk density function of the two individuals with \( z \)-scores greater than 2.0 (\( z > 2.0 \)) and the average function for each gender. Location of the xiphoid, omphalion, and iliac crest are also shown for females (F) and males (M).
well aligned, it is likely that the mapping was not exact and introduced some error. Unfortunately, the magnitude of this error cannot be determined. Still, the new method produced density profiles similar to those from previous studies (discussed in further detail below) but without the radiation and costs of CT scanning or MRI, respectively.

The second goal of this study was to develop trunk density functions for male and female university-aged students that can be used in geometric models and to explore whether gender or morphological factors may have an influence on these functions. The latter portion of this goal will be discussed first. According to the World Health Organization, a BMI below 18.5 kg/m$^2$ is considered underweight and a value above 30 kg/m$^2$ is considered obese. None of the participants in the study were underweight and only one male was obese.

The $z$-scores for the RMS error between the females’ individual and average function showed only a single outlier. The single female outlier (who had an RMS error greater than 2.0) had a density that was similar to the average female for the upper trunk section (Fig. 3). In the lower section, the curves diverged with the average female density becoming greater than that of the outlying female’s function. This divergence in the lower trunk section may very well have been a result of the gynoid body type of this participant; none of the other females had this body type. A gynoid body accumulates body fat around the hips and buttocks. The greater fat percentage reduces that section’s overall density.

Comparing the obese male’s density function to that of the average function across all males, the former was more flat (Fig. 3), meaning there was less axial density change. In the upper trunk region, where the density drops, due to the presence of the lungs, an increased amount of fat would increase the density. In the lower trunk region, where the density is higher, due to bone (pelvis) and muscle tissue, a larger fat percentage would decrease the overall density. This same variation in the lower trunk density between the average and outlying female was also observed.

The trunk density profiles of the two genders appear to be similar in nature with slight variations in magnitude. In the upper trunk region, the females have a slightly greater density which may be due, in part, to a larger amount of fatty tissue (i.e. breasts), reducing the influence of the lungs. In the mid-trunk region, the female densities reach a peak of approximately 1.05 g/cm$^3$, whereas the male’s peak is only 1.01 g/cm$^3$. Males tend to deposit fat in the abdominal region likely contributing to the lower peak found in the male density function. Finally, in the lower trunk, where women tend to deposit fat, the females have densities that are less than those of their male counterparts.

The average density profiles of the male and female functions are plotted along with other functions from previous studies (Fig. 4). Also included in the figure are the average locations of the xiphoid, omphalion, and superior iliac crest for the females and males of this study. Although the general characteristics of each function appear to be similar, there are discrepancies in the locations of the local minima and maxima as well as their magnitudes. In the upper trunk region, the lowest density value occurs, on average, at 20% of the trunk length. Erdmann (1997) and Wei and Jensen (1995) have the highest density values (approximately 0.9 g/cm$^3$) at this point, though the location along the trunk is slightly inferior in the Erdmann study.

![Fig. 4](image-url) Trunk density profiles developed from various studies. The male and female profiles were derived from this study. The Erdmann profile was estimated from a hand-drawn profile. Location of the female (F) and male (M) xiphoid, omphalion, and iliac crest obtained from the participants in this study are also shown.
The magnitude of the density value for this study and the Pearsall et al. (1996) studies averaged round 0.8 g/cm³.

The mid-trunk local maximum also varies. In the trunk density function developed by Erdmann (1997) this maximum was reported to occur well before its occurrence in the other three studies. The magnitude of this maximum is similar across all studies with values ranging from 1.0 to 1.05 g/cm³. The lower trunk region appears to have the greatest variance between the different studies. The Pearsall et al. (1996) density values terminated at the L5 vertebrae but had a similar profile to Erdmann up to this point. At the lower end of this trunk section, Erdmann’s profile increases, up to a value of 1.1 g/cm³, whereas the Wei function remains relatively constant around 1.01 g/cm³. At the level of the umbilicus, the two density functions (male and female) of this study drop to approximately 0.90 g/cm³ and slowly increase to density values near that of Wei and Jensen (1995).

The general nature of the trunk density function appears similar across the various studies. However, variances among the research protocols are likely responsible for some of the variations seen. Differences in trunk boundary definitions, methods for density estimates and the characteristics of the participants tested are the key contributors. Isolating the characteristics of the participants from variations in trunk definitions and methods for density estimates provides insight into the interaction between inter-individual differences caused by morphology and gender.

One remedy to help isolate trunk density variations according to individual morphological characteristics is to adopt a universal trunk definition, thus eliminating some of the variance due to differences in methodology. Fig. 1 illustrates where the most common trunk boundaries among the research exist but with a new lower trunk boundary that includes the entire pelvis. Adopting this new trunk boundary definition may result in a greater consistency between studies and therefore allow for better comparisons between them.

The trunk segment has the greatest intra-individual variation and inter-individual differences compared with any other segment. It is known that characteristics such as morphology and gender have some influence on these two entities. This study has provided some insight into the relationship between individual characteristics and trunk density profiles. More specifically, a possible link between body fat distribution and inter-individual differences in trunk densities has been shown.

Geometric models have traditionally adopted a single density value for the trunk. However, its density is by no means uniform. With the advent of imaging techniques, estimates of the trunk density profile have been developed. Implementing a non-uniform density function into a geometric model will improve the body segment parameter estimates. This magnitude of improvement would need to be assessed by comparing a geometric model using both non-uniform and uniform density function to some gold standard method for estimating body segment parameters. More importantly the influence of the estimated body segment parameters from the two functions on the forces and moments generated during various movement patterns (e.g. walking, lifting, etc.) need to be examined. In a sensitivity analysis of lifting tasks, Desjardins et al. (1998) found that segment masses had the greatest influence on upper body model accuracy for estimating moments about the L5/S1 joint and that geometric models of the trunk need to consider the inter-individual variability in trunk morphology (Larivière and Gagnon, 1999). Thus, a geometric trunk model with a non-uniform density function will likely provide more accurate force and moment estimates of lifting and other tasks.

Conflict of interest

There are no known financial and personal relationships with other people or organizations that could inappropriately influence the outcome of this study.

Acknowledgments

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References


