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Segmental Inertial Parameters of the Human Trunk as Determined from Computed Tomography

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Abstract—This study used computed tomography (CT) imaging to determine *in vivo* mass, center of mass (CM), and moments of inertia (Icm) about the CM of discrete segments of the human torso. Four subjects, two males and two females, underwent serial transverse CT scans that were collected at 1-cm intervals for the full length of the trunk. The pixel intensity values of transverse images were correlated to tissue densities, thereby allowing trunk section mass properties to be calculated. The percentage of body mass observed by vertebral levels ranged from 1.1% at T1 to 2.6% at L5. The masses of the upper, middle, and lower trunk segments as percentages of body mass were estimated to be 18.5, 12.2, and 10.7%, respectively. The whole trunk mass was estimated to comprise 41.6% of the total body mass. Transverse vertebral CM values were found to lie anterior to their respective vertebral centroids by up to 5.0 cm in the lower thoracic region. For the upper, middle, and lower trunk segments, the average CM positions were found to be 25.9, 62.5, and 86.9% of the distance from the superior to inferior ends of the trunk. The upper and middle trunk CMs corresponded to approximately 4.0 cm anterior to T7/T8 vertebral centroid levels and 1.0 cm anterior to L3/L4 vertebral centroid levels, respectively. For the whole trunk, the CM was 52.7% of the distance from the xiphoid process and approximately 2.0 cm anterior to L1/L2 vertebral centroid levels. Variations in CM and Icm values were observed between subject, but these were within the range of previous reports of body segment parameters. Differences from previous studies were attributable to variations in boundary definitions, measurement techniques, population groups, and body states (live versus cadaver) examined. The disparity between previous findings and the findings of this study emphasizes the need to better define the segmental properties of the trunk so that improved biomechanical representation of the body can be achieved.

Keywords—Body composition, Body segment parameters, Spine, Biomechanics.

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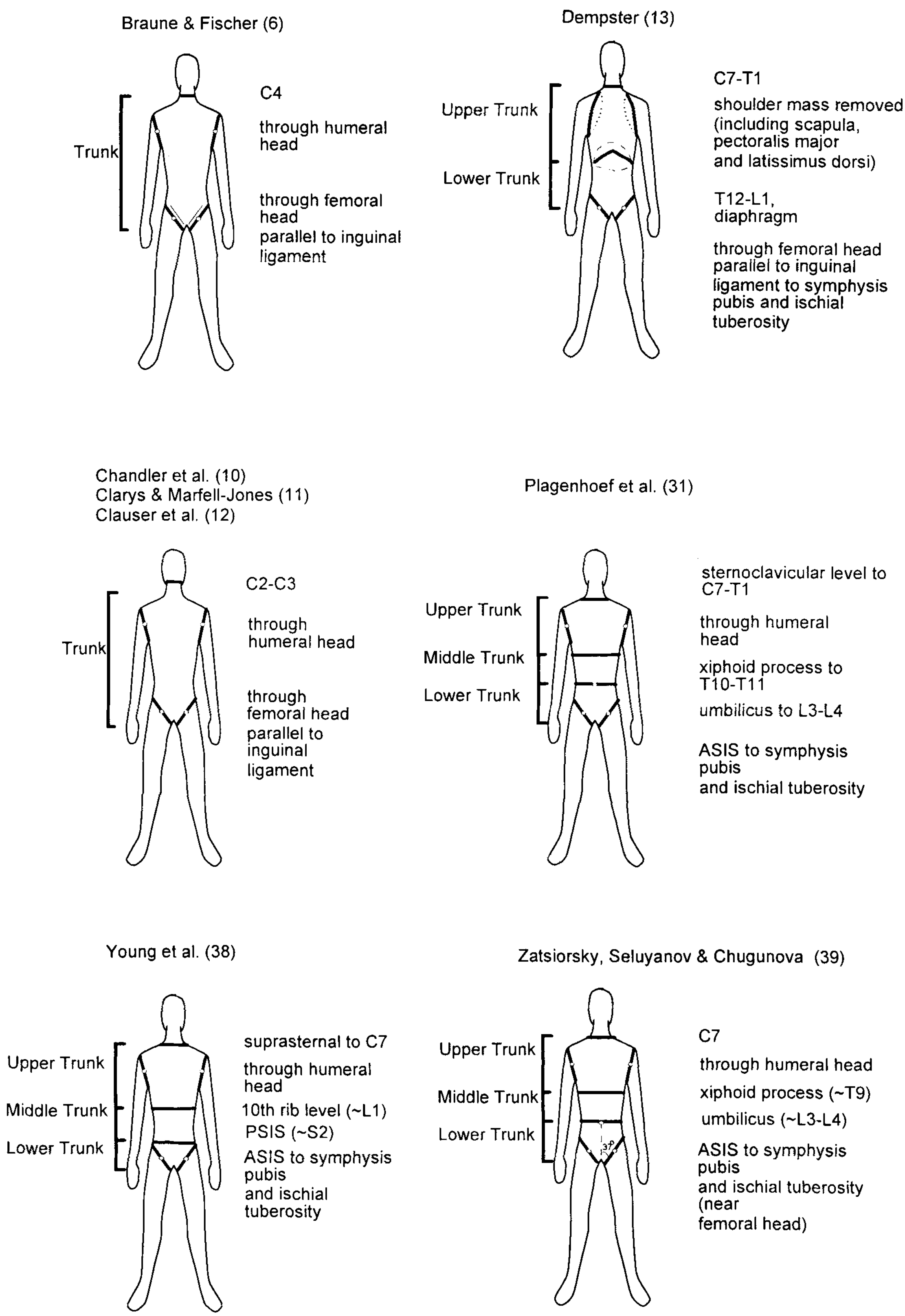
INTRODUCTION

A precise description of the segmental parameters, which includes mass, center of mass (CM), and moment of inertia (Icm) values, is necessary for biomechanical investigation with the use of linked-segment representations of the human body. This type of analysis has been used extensively in clinical, ergonomic, and sport research studies to identify the underlying mechanical determinants that facilitate and/or compromise mobility (29). Improving the specificity of segment parameter data for individual body type, gender, and age groups would reduce error in biomechanical modeling (21), this, however, has proved difficult to achieve. In particular, trunk segment parameters reported in the literature have varied considerably. For instance, the trunk mass as a percentage of body mass has been estimated to range from near 43% (39) to greater than 50% (22). Variation also exists in methods of reporting CM of the trunk. Typically, the CM position is reported in terms of proximal-distal location as a percentage of the distance between respective segment ends. Reported values for the trunk from its proximal end have ranged from 38% by Clauser *et al.* (12) to 53.1% by Chandler *et al.* (10). Inconstant definitions of trunk segment boundaries among investigations (Fig. 1) and differences among living and cadaveric states studied are some basic reasons for a lack of consensus in the reported literature. These disparities may introduce errors into static and dynamic analysis of the human body, hence, the need for refinement of segmental parameters (21).

Detailed analyses of segmental properties of the trunk by vertebral level have been limited. Parks (27), in an unpublished dissertation, conducted one of the first detailed examinations of trunk mass distribution by dissecting one cadaver; however, this information has not been widely adopted. The most thorough cadaver investigations were conducted by Liu and Wickstrom (26), who dissected a total of eight cadavers that had been frozen and transversely sectioned the cadavers' trunks into a series of slices corresponding to vertebral levels. The CM of each



Braune & Fischer (6)
Trunk
C4
through humeral head
through femoral head parallel to inguinal ligament
Dempster (13)
Upper Trunk
Lower Trunk
C7-T1
shoulder mass removed (including scapula, pectoralis major and latissimus dorsi)
T12-L1, diaphragm
through femoral head parallel to inguinal ligament to symphysis pubis and ischial tuberosity
Chandler et al. (10)
Clarys & Marfell-Jones (11)
Clauser et al. (12)
Trunk
C2-C3
through humeral head
through femoral head parallel to inguinal ligament
Plagenhoef et al. (31)
Upper Trunk
Middle Trunk
Lower Trunk
sternoclavicular level to C7-T1
through humeral head
xiphoid process to T10-T11
umbilicus to L3-L4
ASIS to symphysis pubis and ischial tuberosity
Young et al. (38)
Upper Trunk
Middle Trunk
Lower Trunk
suprasternal to C7
through humeral head
10th rib level (~L1)
PSIS (~S2)
ASIS to symphysis pubis and ischial tuberosity
Zatsiorsky, Seluyanov & Chugunova (39)
Upper Trunk
Middle Trunk
Lower Trunk
C7
through humeral head
xiphoid process (~T9)
umbilicus (~L3-L4)
ASIS to symphysis pubis and ischial tuberosity (near femoral head)

FIGURE 1.

slice was then determined relative to the vertebral body by a knife-edge balancing technique, and the Icm was resolved by using a torsion pendulum device. A recent detailed investigation of the trunk by Duval-Beaupère and Robain (14) studied 10 male and 4 female live young adults by using a gamma-ray scanner in conjunction with lateral X-rays to identify mass corresponding to specific vertebral levels.

Given the dearth of specific information on discrete segmental properties of the trunk region, additional study is required. Therefore, the primary purpose of this study was to calculate *in vivo* the mass, CM, and Icm within the anatomical reference system for individual vertebral levels and for the regions of the thorax, abdomen, and pelvis by using computed tomography (CT). A sample of subjects of different body types was assessed, and the segment estimates were compared with those of previous reports. Other aspects of the data are discussed in detail, including the assessment intersubject variability, the effect of different measurement techniques, and the relation between spinal curvature and CM position.

METHODS

Four adults, two men and two women, comprised the subject sample. Individual and group mean measures of age, height, mass, and body mass indices are presented in Table 1. Subject 1 (male) and Subject 4 (female) were representative of average population dimensions, whereas Subject 2 (female) and Subject 3 (male) were closer to the 85th percentile for stature and body mass index for age and gender groups (9). All subjects were referred for medical reasons to the CT unit of Kingston General Hospital, Kingston, Ontario, Canada, and agreed to participate in the study. The pathologic conditions of the subjects were judged to not affect the results of this study. Data are presented in terms of averages of four subjects and individually.

Subjects were in a supine position with the upper limbs in anatomical position during CT scanning. CT images were obtained on a CT/T Continuum scanner (CT Hi Light Advantage Whole Body CT Scan, GE, Mississauga, Ontario, Canada) with the use of a 512 × 512 pixel display monitor with a window size for 8 bit images. The window was centered around a CT number −027 for optimal contrast between muscle and adipose tissues. Transverse CT images of the trunk were collected at 1-cm intervals from the superior surface of the symphysis pubis to the level of the upper border of the body of the first thoracic vertebrae (T1). Each transverse scan had a field of view diameter of 40 cm. The CT images initially were preserved on transparency film. With back-projection lighting, the film images were viewed with a gray-scale video camera. Video images were transferred using a video control card for presentation on a high-resolution microcomputer monitor. The resolution of the video control card was 256 × 256 pixels and was capable of differentiating between 256 pixel intensity levels. Subsequent data acquisition and analysis were performed on PC/MS-DOS microcomputer.

The CT images were analyzed in three stages: digitizing of transverse profiles of the trunk perimeter; tissue density/pixel intensity calibration; and calculation of volume, mass, and density of the transverse trunk images. All images were analyzed by one individual on a computer with an enhance image control card (Imagewise/PC, Micromint Inc, Vernon, CT, USA). The 256 × 256 pixel image (at 0.16 cm/pixel) was displayed on the computer monitor with a graphics mouse interface for image measurements. The anatomical level within the trunk represented by a CT image was determined.

Each CT image had a common reference origin at the bottom of the field of view, which permitted subsequent cross-referencing and grouping of transverse images to form discrete trunk segments. The coordinate system for the scan picture consisted of *x*, *y*, and *z* axes representing the transverse, anteroposterior, and longitudinal directions, respectively. Profiles of the trunk viewed in each transverse section were digitized from the video digital image. The profiles were digitized along the perimeter of the object boundary. Upper limb regions lateral to the glenohumeral joint and lower limb regions lateral to the hip joint were excluded. CT transverse images obtained were 1 cm thick; therefore, volumes for digitized profiles were calculated by multiplying measured areas by the thickness.

TABLE 1. Description of the subject sample: gender, age, height, and mass.

Subject	Gender	Age (years)	Height (cm)	Percentile*	Mass (kg)	Percentile*	Body Mass Index (kg/m^2)	Percentile*
1	Male	46	170.2	40	75.9	45	26.2	50
2	Female	65	175.2	95	68.5	70	22.3	85
3	Male	68	185.3	90	76.4	45	22.3	90
4	Female	65	152.4	35	62.3	50	26.8	40
Average		61.0	170.8		70.8		24.4	
(SD)		(1.0)	(13.8)		(6.7)		(2.4)	

*Percentile ranking by gender based on Canada Fitness Survey, 1983.

The accuracy of linear measures was calculated to be within 0.5 cm, as determined from calibration shapes. In addition, circumferential and area measures were made from 10 repeated samples of three transverse trunk sections, one each from the upper, middle, and lower trunk regions. Reproducibility was observed with standard errors of 0.2 cm and 2.7 cm^2, respectively, corresponding to 0.5% of linear and 2% of area measurements. The latter error was larger primarily as a result of differences in edge discrimination.

From the CT images, it was possible to determine tissue densities, as demonstrated by Huang and Suarez (19) and Reid (32). Pixel intensity is related to the calculated Hounsfield unit or CT number, which, in turn, correspond to the electron density, a function of both the density and composition of the tissues being examined (7). All pixel values for each slice were transformed to equivalent density values by using a method similar to that described by Reid (32).

By sampling various pixel intensities at bone, muscle, and adipose sites within each CT image, and comparing them with empirical tissue density values, a quartic pixel intensity/density relation was calculated by the least-squares regression analysis (Fig. 2). This regression allowed the gray scale to correspond to the CT number code bar present on each film transparency. The nonlinear image properties may have been introduced as a result of the sequential transfer of images (i.e., from CT to film, film to analog video, analog video to digital images) and as possible consequence of the window size of the CT scanner, a feature that limits the full range of observable attenuation values for the tissues in question (4). Local mass density values were determined from pixel intensity measures, which corresponded to the CT number according to the function:

$$p_{ijk} \doteq C_0 + C_1(g_{ijk})^4 \tag{1}$$

where p_{ijk} is the density at pixel $_{ijk}$, g_{ijk} is the intensity value at pixel $_{ijk}$, and C_0 and C_1 are regression constants.

The density values used for bone, muscle and adipose were 1.50, 1.06, and 0.94 g/cc, respectively. Minimum pixel intensity values were assigned to the lung region having a density value of 0.25 g/cc. The empirical density values used are representative of *in vivo* estimates reported in the literature (15,19,24,33,37). Coefficients of determination ranging from 0.90 to 0.95 for the constructed regression equations suggested that the density profiles of the CT images were interpreted accurately. The regression constants were determined for each image.

The trunk was divided into several segments on the basis of the reconstruction of transverse scans. The segments defined represented distinct anatomical regions of the trunk (Fig. 3). The vertebral trunk segments from T1 to L5 inclusively consisted of the horizontal trunk sections, and each contained a complete vertebral body. Segment boundaries were established through the intervertebral disc union between vertebral bodies. The upper (thorax), middle (abdomen), and lower (pelvis) trunk segments consisted of vertebral levels T1 to T12, L1 to L5, and S1 to S5, respectively. In addition, the whole trunk was defined from vertebral levels T1 to S5. The trunk boundaries excluded the neck and upper limbs superiorly and the lower limb portions of the thighs inferiorly.

The parameters estimated for each segment included volume (V), mass (M), density (p), center of volume (CV), and CM. Furthermore, the Icm through the CM of each segment was determined about the three anatomical axes. The calculation of these parameters is outlined in studies by Huang and Suarez (19) and Reid (32).

RESULTS

Comparison by vertebral level revealed variations among subjects in segment properties, but, in general, the volume of each vertebral segment tended to increase in the caudal direction, corresponding to similar increases in segmental mass for all subjects. On average, mass increased from 2.7 to 6.3% of trunk mass, or 1.1 to 2.6% of body mass (Table 2; Fig. 4). Among subjects, the mass and volume values of each level were very consistent in the mid-thoracic region; however, in the lower segments, male subjects tended to have a greater mass and volume. As a result of the lung space in the thorax, the resultant densities (g/cc) were lowest in the upper vertebral levels; densities were 0.99, 0.74, and 1.02 at T1, T6, and T12,

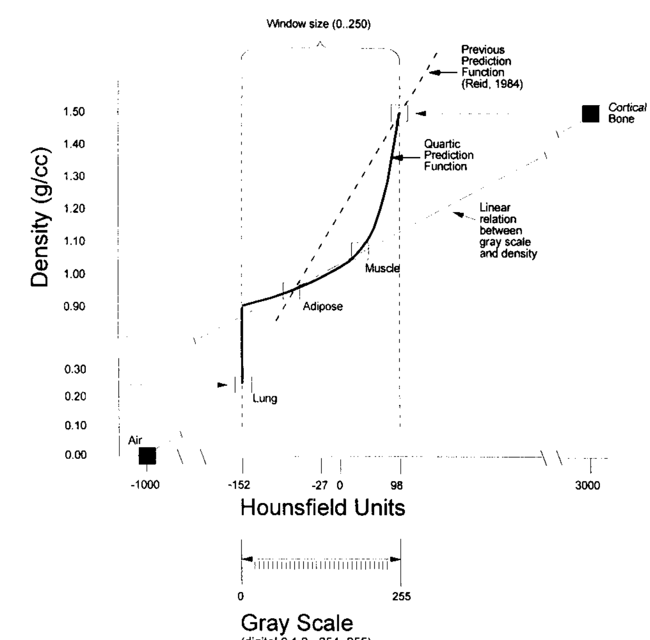


FIGURE 2.

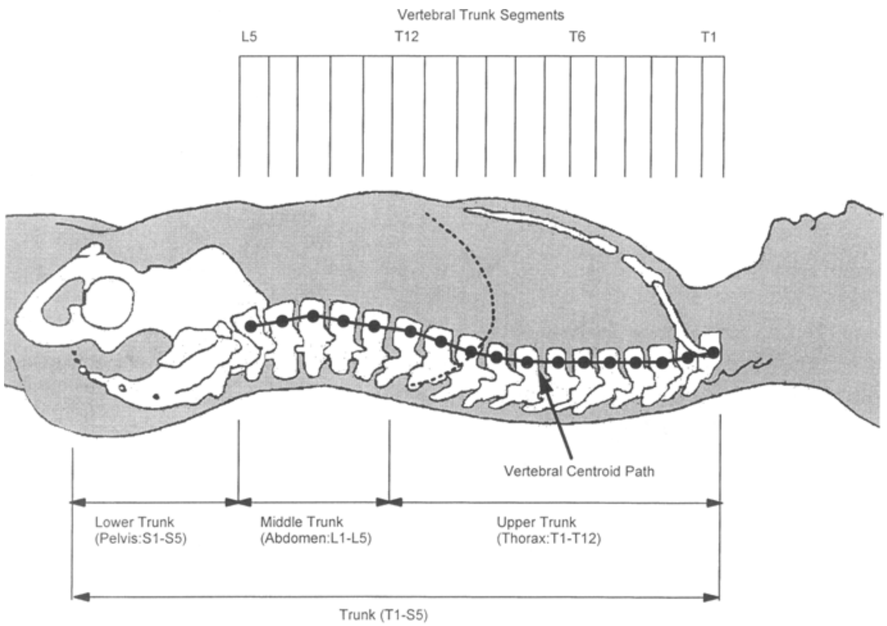


FIGURE 3.

respectively. In the lumbar vertebral levels, density values ranged between 1.00 and 1.04 g/cc. In the sacral region (pelvis), the density was estimated to be approximately 1.07 g/cc. The density profiles by vertebral level were similar among subjects for the lower vertebral regions but varied for intermediate regions; for example, at the T10 level density values ranged from 1.15 to 0.65 g/cc. The leaner subjects (Subjects 2 and 3) tended to have the higher density values.

For the larger segments of the trunk, the masses of the thorax, abdomen, and pelvis as percentages of the whole trunk mass were 44.8, 29.5, and 25.7%, respectively (Table 3; Fig. 5). Alternatively, as a percentage of total body mass, the thorax, abdomen, and pelvis masses were found to account for 18.5, 12.2, and 10.7%, respectively. For all subjects, the total trunk was estimated to contain 41.4% of the total body mass, and values ranged from 36.7 to 45.0%. A variable density in the trunk was observed. Although the thorax contained the largest portion of trunk volume and mass, it was identified on average to have the lowest density of 0.87 g/cc compared with densities of 1.02 and 1.07 g/cc for the abdomen and pelvic segments, respectively. Overall, the density of the whole trunk was 0.96 g/cc.

In the sagittal plane, the calculated positions of the segmental CM and CV by vertebral levels were found to

TABLE 2. Average mass, volume, and density estimates of vertebral trunk segments.

Level	Mass (g)	Trunk Mass (%)	Body Mass (%)	Volume (cc)	TV (%)	Density (g/cc)
T1	810.9 (348.0)	2.7 (1.0)	1.1 (0.5)	810.9 (332.5)	2.6 (0.9)	0.99 (0.06)
T2	779.5 (316.3)	2.6 (0.9)	1.1 (0.4)	867.1 (357.5)	2.8 (0.9)	0.91 (0.06)
T3	975.8 (133.2)	3.3 (0.2)	1.4 (0.2)	1125.7 (134.8)	3.7 (0.2)	0.84 (0.07)
T4	919.6 (107.2)	3.1 (0.2)	1.3 (0.1)	1180.3 (119.8)	3.9 (0.2)	0.78 (0.09)
T5	944.6 (116.8)	3.2 (0.3)	1.3 (0.2)	1230.6 (110.6)	4.0 (0.2)	0.77 (0.10)
T6	932.0 (26.4)	3.2 (0.3)	1.3 (0.1)	1264.2 (113.7)	4.1 (0.3)	0.74 (0.07)
T7	976.2 (48.8)	3.4 (0.3)	1.4 (0.1)	1283.1 (112.6)	4.2 (0.2)	0.77 (0.08)
T8	1049.3 (83.4)	3.6 (0.4)	1.5 (0.1)	1274.9 (139.0)	4.2 (0.2)	0.83 (0.11)
T9	1095.5 (170.7)	3.8 (0.7)	1.6 (0.2)	1256.1 (155.4)	4.1 (0.2)	0.89 (0.17)
T10	1419.1 (481.0)	4.8 (1.5)	2.0 (0.6)	1575.1 (325.7)	5.1 (0.8)	0.90 (0.21)
T11	1479.3 (331.0)	5.0 (0.9)	2.1 (0.3)	1561.7 (317.2)	5.1 (0.8)	0.96 (0.11)
T12	1767.0 (406.3)	6.0 (1.0)	2.5 (0.4)	1742.0 (431.3)	5.6 (0.9)	1.02 (0.02)
L1	1677.2 (380.7)	5.7 (0.9)	2.4 (0.4)	1694.3 (402.3)	5.5 (0.8)	1.00 (0.10)
L2	1688.7 (347.4)	5.7 (0.8)	2.4 (0.3)	1663.5 (358.8)	5.4 (0.7)	1.02 (0.03)
L3	1669.7 (319.9)	5.7 (0.7)	2.3 (0.3)	1616.6 (312.9)	5.2 (0.6)	1.03 (0.01)
L4	1799.1 (127.4)	6.2 (0.8)	2.6 (0.2)	1778.6 (140.8)	5.9 (0.8)	1.01 (0.01)
L5	1823.8 (69.9)	6.3 (0.8)	2.6 (0.3)	1756.2 (57.0)	5.8 (0.8)	1.04 (0.02)

Mass also is expressed as a percentage of trunk mass and body mass, and volume is expressed in terms of total trunk volume.

coincide, except in the mid-thoracic region, where the CV tended to be anterior to CM, up to a maximum of 0.7 cm at T4. Along the transverse axis, the CM was situated in close proximity to the CV except for the mid-thoracic regions, where the CM tended to be up to 0.6 cm farther to the right.

The average positions of the vertebral centroids (VC) and their corresponding CM are presented in Table 4. The profile of the VC was observed to reflect the normal primary (thoracic and sacral) and secondary (lumbar) curvatures of the spinal column in the sagittal plane when plotted with respect to the y and z (longitudinal) axes (Fig. 6). Comparisons of profiles among subjects showed variations in the extent of curvature in the thoracic and lumbar regions. In general, the profile of the CM positions followed a curvilinear path in the sagittal plane that was not coincident with the VC profile. The CM positions were not found to correspond to the VC profile, except at the upper thoracic and lower lumbar regions. Despite intersubject VC profile differences, the CM consistently was anterior to its respective VC at most levels. The CM-VC displacement was greatest in the mid-spine, ranging from 0.8 cm at T1, to 4.6 cm at T9, to 0.4 cm at L5.

The CM and CV for the upper, middle, and lower segments of the trunk were determined within the three anatomical planes and relative to adjacent vertebral levels (Table 4). The CM and CV longitudinal positions are described as percentages of segment length from the superior end. Minimal differences were noted between CM and CV positions for these segments. On average, the CM position of the upper (thorax) segments was approximately 4.0 cm anterior to the T7/T8 vertebral centroid, or 25.9 and

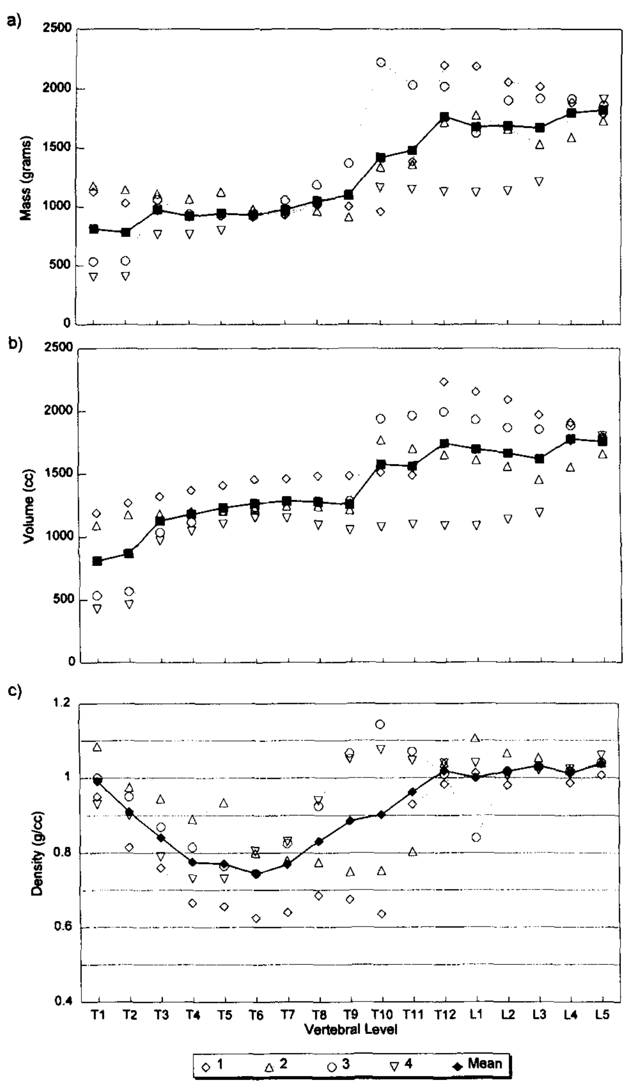


FIGURE 4.

TABLE 3. Segment parameters for the whole trunk and subregions (upper, middle, mid-lower, and lower).

Trunk Mass	29435.7 (2722.6)		
% TM	100.0 —		
% BM	41.4 (2.1)		
Volume	30798.1 (3515.6)		
% TV	100.0 —		
Density	0.96 (0.04)		
	x	*y*	*z*
CM	0.1 (0.3)	0.6 (0.6)	27.4 (1.7)
Icm	7.1 (1.8)	8.2 (1.9)	3.1 (0.4)
CM % TL	0.2 (0.6)	1.1 (1.1)	52.7 (1.1)
CM % SL			
Upper Mass	13148.9 (1574.9)		
% TM	44.6 (2.1)		
%BM	18.5 (1.3)		
Volume	15171.5 (2166.2)		
% TV	49.1 (1.6)		
Density	0.87 (0.07)		
	x	*y*	*z*
CM	0.2 (0.5)	0.5 (0.7)	13.4 (0.6)
Icm	1.2 (0.3)	1.7 (0.3)	1.5 (0.3)
CM % TL	0.5 (0.9)	0.9 (1.3)	25.9 (1.3)
CM % SL	0.9 (2.0)	2.0 (2.7)	54.5 (2.4)
Middle Mass	8801.2 (1219.2)		
% TM	29.8 (2.4)		
% BM	12.2 (0.6)		
Volume	8651.5 (1347.1)		
% TV	28.0 (2.2)		
Density	1.02 (0.03)		
	x	*y*	*z*
CM	−0.0 (0.4)	1.3 (0.8)	32.5 (2.3)
Icm	0.6 (0.3)	0.7 (0.2)	0.8 (0.2)
CM % TL	−0.0 (0.7)	2.5 (1.5)	62.5 (0.9)
CM % SL	−0.4 (2.8)	8.9 (5.1)	56.3 (6.1)
Lower Mass	7485.6 (716.3)		
% TM	25.6 (2.8)		
% BM	10.7 (1.4)		
Volume	6975.2 (651.4)		
% TV	22.9 (2.6)		
Density	1.07 (0.01)		
	x	*y*	*z*
CM	0.0 (0.2)	−0.3 (0.5)	45.2 (3.7)
Icm	0.3 (0.1)	0.7 (0.3)	0.8 (0.3)
CM % TL	0.0 (0.4)	−0.6 (0.9)	86.9 (1.9)
CM % SL	0.7 (1.8)	−2.1 (4.0)	59.7 (10.6)

BM, body mass; TL, trunk length; TM, trunk mass; SL, segment length.

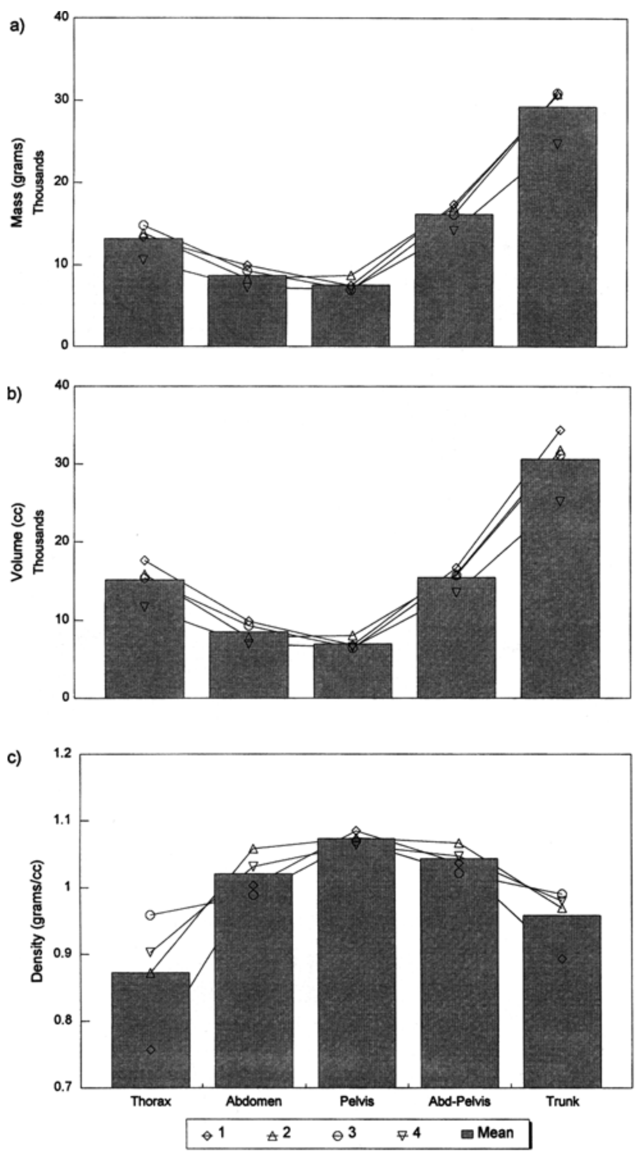


FIGURE 5.

54.5% of trunk and thorax lengths, respectively. For the middle (abdomen) segment, the average CM position was approximately 1.0 cm anterior to the L3/L4 vertebral centroids, or 62.5 and 56.3% of the trunk and abdomen lengths, respectively. For the lower (pelvic) segment, the average CM position was 86.9 and 59.7% of the trunk and pelvis lengths, respectively. Differences among subjects in CM percentage locations in the longitudinal direction were noted for the middle and lower segments. The transverse CM positions for these segments were within 1.0 cm of the coincident VC positions.

The CM and CV for the whole trunk also were determined within the three anatomical planes and relative to adjacent vertebral levels. Minimal intersubject differences were seen, and the average position of the CM was 52.7% of the cephalic to caudal longitudinal distance of the trunk, which corresponded to approximately 2 cm anterior to the L1/L2 vertebral centroid levels; the average position of CV, in contrast, was 50.0% of the cephalic to caudal distance of the trunk length, which corresponded to 2 cm anterior to the T12/L1 vertebral centroid levels.

The segmental Icms of the trunk were calculated about their respective CM in the sagittal, frontal, and transverse planes. The Icm of vertebral trunk segments tended to increase in the caudal direction (Table 5). About the transverse axis, the average Icm increased in the caudal direction from 20 kg $\times$ cm^2 at T1 to 70 kg $\times$ cm^2 at T12 then decreased to 55 kg $\times$ cm^2 at L5. Icm values about the anteroposterior axis were observed to range from 67 kg $\times$ cm^2 at T1 to 122 kg $\times$ cm^2 at L5, whereas, about the longitudinal axis, Icm values ranged from 87 kg $\times$ cm^2 at T1 to 177 kg $\times$ cm^2 at L5.

The Icm values about the three anatomical axes through the CM of the larger trunk segments are presented in Table 6. For the upper, middle, and lower trunk segments, the average Icm values ranged from 1,200 to 1,700 kg $\times$ cm^2, 600 to 800 kg $\times$ cm^2, and 300 to 800 kg $\times$ cm^2. For the trunk, Icm values derived from CV positions about the transverse and anteroposterior axes were slightly greater than were Icm values estimated about the CM. The average Icm values for the trunk about the transverse, anteroposterior, and longitudinal axes through the CM were 7,100, 8,200, and 3,100 kg $\times$ cm^2, respectively, and average Icm values through the CV were 7,400, 8,400, and 3,100 kg $\times$ cm^2, respectively.

DISCUSSION

The measures derived from this CT analysis represent one of the few detailed segment parameter investigations

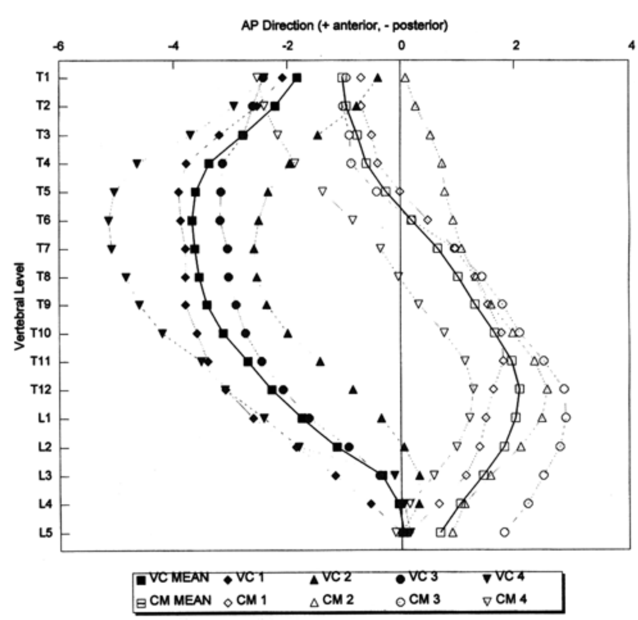


FIGURE 6.

TABLE 4. Average positions of VC and CM for vertebral trunk segments.

	VC			CM		CM − VC	
Level	z	x	y	x	y	x	y
T1	1.0 (0.0)	1.0 (1.4)	−1.8 (0.8)	0.5 (0.8)	−1.0 (1.0)	−0.5 (0.9)	0.8 (0.7)
T2	2.5 (0.5)	0.7 (1.3)	−2.2 (0.8)	0.3 (1.0)	−1.0 (1.0)	−0.4 (0.7)	1.3 (0.5)
T3	4.0 (1.0)	0.6 (1.0)	−2.8 (0.8)	0.4 (0.6)	−0.8 (1.0)	−0.2 (0.7)	2.0 (0.4)
T4	6.0 (1.0)	0.1 (0.8)	−3.4 (1.0)	0.2 (0.7)	−0.6 (0.9)	0.1 (0.7)	2.8 (0.4)
T5	8.0 (1.0)	−0.3 (1.0)	−3.6 (1.0)	0.1 (0.9)	−0.3 (0.8)	0.4 (0.5)	3.4 (0.5)
T6	10.0 (1.0)	−0.1 (0.8)	−3.7 (1.0)	0.5 (0.9)	0.2 (0.6)	0.6 (0.3)	3.9 (0.5)
T7	12.0 (1.0)	−0.2 (0.7)	−3.6 (0.9)	0.3 (0.9)	0.7 (0.6)	0.5 (0.4)	4.3 (0.5)
T8	14.0 (1.0)	−0.0 (0.9)	−3.5 (0.9)	−0.1 (0.6)	1.0 (0.6)	−0.1 (0.7)	4.6 (0.5)
T9	16.0 (1.0)	−0.1 (0.8)	−3.5 (1.0)	−0.2 (0.7)	1.3 (0.6)	−0.1 (0.7)	4.6 (0.5)
T10	18.0 (1.0)	0.1 (0.4)	−3.2 (0.9)	−0.0 (0.3)	1.6 (0.5)	−0.2 (0.4)	4.6 (0.5)
T11	20.5 (1.1)	0.1 (0.4)	−2.7 (0.8)	−0.3 (0.4)	1.9 (0.5)	−0.5 (0.6)	4.4 (0.7)
T12	23.0 (1.4)	−0.1 (0.5)	−2.3 (0.9)	−0.7 (0.7)	2.1 (0.7)	−0.6 (0.9)	4.1 (0.8)
L1	25.8 (1.8)	0.1 (0.8)	−1.7 (0.9)	−0.4 (0.6)	2.0 (0.7)	−0.4 (0.8)	3.5 (0.9)
L2	28.5 (2.2)	0.0 (0.7)	−1.1 (0.8)	−0.4 (0.4)	1.8 (0.7)	−0.4 (0.6)	2.7 (0.8)
L3	31.3 (2.6)	−0.0 (0.6)	−0.3 (0.5)	−0.1 (0.5)	1.4 (0.7)	−0.1 (0.6)	1.8 (0.9)
L4	34.0 (3.0)	0.1 (0.3)	−0.0 (0.3)	−0.2 (0.4)	1.0 (0.8)	−0.2 (0.6)	1.1 (0.8)
L5	37.0 (3.0)	0.0 (0.0)	0.0 (0.1)	−0.1 (0.6)	0.6 (0.7)	−0.1 (0.6)	0.4 (0.9)

Relative displacement between CM-VC presented (transverse, anteroposterior, and longitudinal directions equivalent to *x, y,* and *z* axes).

undertaken of the human trunk. Favorable comparison with previous reports was found. For instance, a significant relation ($r^2 = 0.83$; $p < 0.005$) between the mass estimates for the 17 vertebral levels with previous measures by Liu and Wickstrom (26) was observed. However, the mass values were not similar to those found by Duval-Beaupère and Robain (14), whose study used combined gamma-ray scans and sagittal X-ray measures. The discrepancy with the latter study occurred within the upper thoracic region, particularly at the T3 level. At this level, Duval-Beaupère and Robain (14) presented a substantial fluctuation in mean mass values from 2.3 kg at T2 to 6.1 kg at T3 then down to 1.4 kg at T4. This sudden and discontinuous increase in mass may have been caused by the partial inclusion of mass of the shoulder and upper limb region, which was avoided in this study and in that by Liu and Wickstrom (26). In addition to the above-mentioned similarities, density profiles for vertebral levels (Fig. 4) were similar to those reported by Wei and Jensen (35) in a study of 50 females in which CT was to identify body segment density variation.

For the larger segments of the trunk, the mass and density values reported from previous studies where found to vary substantially (Table 6). These differences may be attributed to variation in measurement techniques as well as to discrepancies in boundary definitions. Accordingly, it should not be surprising that comparisons among studies are difficult. Several of the segment mass percentages reported previously compared favorably with our findings (26,27,30,39). In general, cadaver-based studies tended to overestimate the mass of the whole trunk in comparison with living subject analysis, the mass estimates of which ranged from 44.2 to 52.4% (10–13). These differences may be attributed to changes in tissue composition after death and to the preservation techniques used. The main difference between the cadaver and the living body may be the change in thoracic density, specifically that of the lung tissue. Reported density values of *in vitro* lung tissue are 0.581 g/cc (33), 0.563 g/cc (15), and 1.050 g/cc (37), whereas *in vivo* measures are 0.254 g/cc during expiration (24). Therefore, the *in vivo* state is markedly less dense than *in vitro*. In addition, in the cadaver the accumulation of blood and the displacement of abdominal contents cephalically may increase thoracic density.

TABLE 5. Average Icm estimates for vertebral trunk segments.

	Icm (kg × cm^2)		
Level	x	y	z
T1	20.2 (10.5)	67.0 (27.8)	87.2 (37.8)
T2	23.5 (12.6)	67.3 (30.0)	90.7 (42.6)
T3	31.4 (8.6)	83.7 (11.3)	115.1 (19.5)
T4	33.5 (9.1)	83.0 (10.7)	116.5 (19.7)
T5	35.1 (8.8)	80.2 (9.9)	115.3 (18.7)
T6	38.5 (6.9)	78.0 (5.8)	116.5 (12.7)
T7	40.8 (8.3)	74.3 (3.3)	115.2 (11.2)
T8	44.0 (10.5)	72.5 (7.7)	116.5 (17.7)
T9	46.6 (12.0)	71.8 (12.4)	118.4 (24.0)
T10	60.8 (15.9)	89.0 (26.9)	149.8 (42.2)
T11	61.5 (16.3)	90.5 (23.0)	152.0 (39.1)
T12	60.3 (26.3)	110.5 (35.0)	180.8 (61.0)
L1	64.0 (22.1)	111.3 (32.2)	175.3 (53.6)
L2	59.1 (20.3)	109.1 (27.4)	168.2 (47.2)
L3	54.1 (17.0)	106.6 (23.8)	160.8 (40.6)
L4	52.0 (16.6)	112.3 (17.6)	164.3 (34.3)
L5	54.6 (15.7)	121.9 (20.9)	176.5 (35.3)

Transverse, anteroposterior, and longitudinal directions are equivalent to *x, y,* and *z* axes.

TABLE 6. Comparison of trunk segment parameters values from past studies to the results of this study.

Upper Trunk	Gender	Mass (% BM)	Density (g/cc)	CM %	Icm (kg × cm²) x	y	z	Measurement Technique
Dempster (1955)	M	11.0	0.92	62.7	1150.0			Cadaveric
Parks (1959)	M	18.6		45.0				Cadaveric
Liu and Wickstrom (1973)	M	19.6						Cadaveric
Plagenhoef *et al.* (1983)	M	20.1		56.7				Water immersion
	F	17.0		56.3				
Young *et al.* (1983)	F	26.3			2140.6	2790.2	1858.8	Photographic
Zatsiorsky *et al.* (1990)	M	16.0		50.7	1725.6	705.2	1454.5	Gamma-ray
	F	15.5		50.5	1082.8	490.3	1005.0	
Duval-Beaupere and Robain (1987)	M	29.4						Gamma-ray and X-ray
	F	27.0						
Jensen and Fletcher (1994)	M	14.5			840.0			Photographic
	F	14.6			740.0			
Pearsall *et al.* (1994)	M	13.0	0.82	51.5	830.0	1600.0	1800.0	MRI
This study	M/F	18.5	0.87	54.5	1250.0	1650.0	1500.0	CT
Middle Trunk	**Gender**	**Mass**	**Density**	**CM**	**Icm (kg × cm²) x**	**y**	**z**	
Parks (1959)	M	13.2		56.0				Cadaveric
Liu and Wickstrom (1973)	M	14.5						Cadaveric
Plagenhoef *et al.* (1983)	M	13.1		46.0				Water immersion
	F	12.2		46.0				
Young *et al.* (1983)	F	4.1			119.7	179.0	273.3	Photographic
Zatsiorsky *et al.* (1990)	M	16.4		45.0	1280.8	819.1	1203.1	Gamma-ray
	F	14.7		45.1	717.3	480.2	658.7	
Duval-Beaupere and Robain (1987)	M	12.2						Gamma-ray and X-ray
	F	12.6						
Pearsall *et al.* (1994)	M	16.0	1.01	49.0	1000.0	1700.0	1700.0	MRI
This study	M/F	12.2	1.02	56.3	550.0	750.0	850.0	CT
Lower Trunk	**Gender**	**Mass**	**Density**	**CM**	**Icm (kg × cm²) x**	**y**	**z**	
Dempster (1955)	M	26.4	1.01	59.9	4340.0			Cadaveric
Parks (1959)	M	13.6		59.9				Cadaveric
Plagenhoef *et al.* (1983)	M	13.7		5.0				Water immersion
	F	16.0		5.0				
Young *et al.* (1983)	F	14.6			727.3	901.2	1241.6	Photographic
Zatsiorsky *et al.* (1990)	M	11.2		35.4	656.8	525.0	592.4	Gamma-ray
	F	12.5		34.8	477.3	411.0	503.0	
Jensen and Fletcher (1994)	M	37.0			5350.0			Photographic
	F	30.6			2530.0			
Pearsall *et al.* (1994)	M	13.3	1.02	44.7	1100.0	1800.0	1800.0	MRI
This study	M/F	10.7	1.07	59.7	300.0	750.0	800.0	CT
Trunk	**Gender**	**Mass**	**Density**	**CM**	**Icm (kg × cm²) x**	**y**	**z**	
Harless (1860)	M	44.2		44.8				Cadaveric
Braune and Fischer (1889)	M	46.1		60.1				Cadaveric
Dempster (1955)	M	49.7	1.03		18400.0			Cadaveric
Kulwicki (1962)					15159.2	15159.2	4393.2	Cadaveric
Whitsett (1963)					12610.1	13559.2	3118.6	Cadaveric
Clauser *et al.* (1969)	M	50.7	1.03	38.0				Cadaveric
Chandler *et al.* (1975)	M	52.4	0.85		16193.7	10876.3	3785.1	Cadaveric
Plagenhoef *et al.* (1983)	M	46.9						Water immersion
	F	45.2						
Young *et al.* (1983)	F	45.0			8700.0	9500.0	3400.0	Photographic
Zatsiorsky *et al.* (1990)	M	43.6						Gamma-ray
	F	42.7						
Reid (1984)	M/F	52.8	1.16	50.6				CT
Clarys and Marfell-Jones (1986)	M	47.0						Cadaveric
	F	45.3						

TABLE 6. Continued.

Upper Trunk	Gender	Mass (% BM)	Density (g/cc)	CM %	Icm (kg × cm²) x	y	z	Measurement Technique
Jensen and Fletcher (1994)	M	51.5						Photographic
	F	46.2						
Pearsall *et al.* (1994)	M	42.2	0.94	53.0	21000.0	23000.0	5400.0	MRI
This study	M/F	41.4	0.96	52.7	7100.0	8200.0	3100.0	CT

Volumetric techniques tended to overestimate the mass of the whole trunk in comparison with other current *in vivo* findings (22,31,38). These values were approximately 3–10% greater than were those reported by these *in vivo* measures. These discrepancies may be attributed to the use of segment density values derived from cadaver studies, such as that by Dempster (13), the values of which were greater than were those estimated from the living. Therefore, the volumetric technique may be improved by incorporating density profiles representative of the living (35).

Differences in trunk density and trunk mass as a percentage of body mass were observed between the previous CT study by Reid (32) and these results. The former study reported values of 1.16 g/cc and 52.8%, respectively, compared with our findings of 0.96 g/cc and 41.6%, respectively. These discrepancies may be assigned to the modified density/pixel intensity function used in the analysis of the CT images. In the Reid study (32), bone and adipose regions were used to calibrate the density estimation function, whereas the more recent function accounts for muscle tissue regions as well. This modification improved the sensitivity to tissue density identification and accommodated for the CT window size distortions (Fig. 2). The latter function tended to overestimate the density of muscle tissues; as a result, the overall trunk density and mass percentages would be greater.

A range of masses for the trunk segments was observed among subjects. These findings concur with those of a previous report identifying substantial variation between lean and obese males (30) and suggest that prediction functions must consider more than body stature and body mass to be sensitive to individual characteristics. Therefore, to better estimate the segmental properties of the trunk, other specific anthroporometric measures must be considered (30,39). It is essential that researchers apply body segment parameters derived from populations specific to their subject groups.

With regard to CM measures, most vertebral CMs were positioned anterior to their respective vertebral centroids in both the mid-thoracic and sacral regions. These trends were significantly similar ($r^2 = 0.66$; $p < 0.005$) to those reported for the cadaver study of Liu and Wickstrom (26) and to those reported for the gamma-ray scanner study of Duval-Beaupère and Robain (14) ($r^2 = 0.77$; $p < 0.005$). However, the latter study's magnitudes were substantially smaller because the CM positions were reported relative to the anterior edge of the vertebrae and not the vertebral centroid. If an approximate distance from the anterior edge to vertebral centroid were considered (*e.g.*, 1.5–2.0 cm), the CM-VC profiles would correspond better in magnitude to Liu and Wickstrom (26) results and to these findings.

Because the mass distribution was not centered about the vertebral column, the gravitationally induced flexion moments generated by superior loads would tend to collapse the spine in the upright position. These findings are similar to those reported by using lateral radiographs (3) and those reported by using a force plate and Moiré topographic technique (28). These studies found that the body's line of gravity passed through cephalic and caudal vertebral bodies and was anterior to the remaining vertebral column. Furthermore, the demonstration by electromyographic studies (2) that phasic back muscle activity is involved during the normal upright stance suggests that the surrounding ligament and joint structures alone are unable to maintain structural stability. Other mechanisms, such as extension moments provided by intra-abdominal pressure (18), tension produced in the thoracolumbar fascia (34), and indirect support from the pelvis and muscular pelvic floor may aid stability.

In the frontal plane, the positions of the vertebral CMs relative to the VCs, from the level of the first thoracic to the fifth lumbar vertebrae, essentially were coincident. These results concur with previous findings by Liu and Wickstrom (26). In both studies, the VC and CM locations varied slightly to the right of the trunk's geometric midline. Such findings are not unusual in that, for both sexes, there usually is a slight lateral curvature of the spine to one side. A definitive explanation as to why these curvatures exist has yet to be determined (8), although some possible explanations suggest that lateralized human functions, such as handedness, may be a contributing factor (16). In this study, the CM of consecutive vertebral segments appeared to mimic the VC in the frontal plane, thereby, suggesting a potential relationship between lateral curvatures of the spine and mass distribution within the trunk segment.

With regard to Icm, values derived for the vertebral trunk segments were found to correspond to findings presented by Liu and Wickstrom (26). For vertebral trunk segments from T1 to L5, the mean Icm values about the three anatomical axes (*i.e.*, transverse, anteroposterior, longitudinal) correlated significantly ($p < 0.005$; $df = 15$) with their reported values, having r^2 values of 0.47, 0.66, and 0.69, respectively. The high agreement seen for Icms about the longitudinal axis was reaffirmed by the finding of no significant difference between mean values, as determined by Student's t-test ($p < 0.05$). Anteroposterior axis values were similar, except those of T1 to T6 vertebral segments, inclusive, for which our findings were significantly greater ($p < 0.05$) than were Liu and Wickstrom's results (26). Transverse axis measures were similar, except those of vertebral segments T1 to T9 and L3 to L5, inclusive, for which our findings were significantly smaller ($p < 0.05$) than were those presented in Liu and Wickstrom's study (26). The discrepancy of anteroposterior and transverse Icm values may be attributed to the fundamental difference in how these values were obtained by the two studies; that is, Liu and Wickstrom (26) used a torsion pendulum to measure inertial properties of frozen cadaveric trunk sections, whereas, in this study analysis of CT images of living subjects was used.

Minimal differences were observed in whole trunk CVs and their respective CMs, despite the obvious visual asymmetric anteroposterior deposition of subcutaneous adipose tissues about the trunk in the transverse plane, as viewed from the CT scans. General regulatory mechanism may be at work to balance the mass deposition of subcutaneous adipose stores about each vertebral segment. Furthermore, for the upper, middle, and lower trunk segments, the CV and CM positions were similar, thereby suggesting that indirect methods, such as photogrammetry (22,38) and water submersion (31), may be used accurately to determine individual trunk segment parameters. However, a discrepancy between CM and CV estimates was noted for the whole trunk, such that the CV position was approximately one vertebral level more cephalic in the trunk than was the CM. This difference may be attributed to the great variability in density that cannot be accounted for by a uniform density assumption inherent to the volumetric technique (1). For instance, the average densities of the thorax, abdomen, and pelvic segments were estimated to be 0.87, 1.02, and 1.07 g/cc, respectively; therefore, CM estimates should tend to be more caudally located.

The agreement of these results with those of previous trunk segment parameter studies varied. For vertebral segments, CM and Icm values have compared favorably with previous detailed cadaver studies (26), lending support to these findings. However, for the larger trunk segments, CM and Icm values were found to vary considerably, underscoring the lack of consensus in trunk segment parameters, both among previous reports and with these results. For instance, the CM of the trunk has been reported to be from 38.0 (12) to 60.1% (17) of the distance along the trunk length from the superior end. More recent studies (10,32) were better related to our average CM estimate of 52.7%. The abdomen and pelvis segment parameters, however, were seen to be particularly sensitive to orientation relative to the measurement coordinate system. For instance, the CM for the pelvis in the longitudinal direction ranged from 5.0 (31) to 64.0% (27) compared with our average of 59.7% (from the superior end). Additional dissimilarities in Icm estimates were evident; for example, the Icm of the trunk about the transverse axis ranged from 18,400.0 kg*cm^2 (13) to our average of 7,100.0 kg*cm^2.

The disparity in trunk segment parameters is a consequence of several factors, such as differing population groups (*e.g.*, gender, age, fitness, body type), measurement techniques, and boundary definitions. The difference between cadaveric and living samples adds further to the discord. The CM measures expressed as a percentage of segment length appear to be particularly sensitive for the shorter trunk segments, such as the abdomen and pelvis. The variation within this study for the percent location of the CM for the middle and lower segments may have been affected by the extent of curvature within the lower spine and the amount of pelvic tilt, both of which would change the lumbar-sacral height and, therefore, the percent location of the significant's length. The lack of uniform trunk segment predictors represents a fundamental problem that must be addressed for accurate biomechanical modeling of the human body to be achieved.

Although this study provides insight into the mass distribution and inertial properties of the trunk, several unanswered questions remain. It is not readily apparent whether measurements taken from the supine positions assumed by the subject can be generalized to the upright positions. Furthermore, the degree to which the normal primary and secondary curvatures of the spine were reduced or enhanced by the supine position of the subjects could not be determined given the mode of data collection in this study. In addition, the extent to which the mobile visceral contents of the abdominal cavity were displaced in the supine position, particularly toward the thorax, was not evident. It is reasonable to suggest that discrepancies in spinal posture and mass distribution measures may be observed when different postures relative to the gravitation field are assumed; however, the significance of such discrepancies remains to be determined. A simple test to assess the effects of spinal curvature on visceral position would be to measure patients in the supine and prone positions.

A definitive understanding of the distribution of the mass support within the trunk has yet to be resolved; that is, the proportion and relative position of mass are not clear. A simplified assumption may define the mass adjacent to a vertebral level as its point of support; however, this does not accurately describe the anatomy of this region, in which highly mobile viscera enveloped by mesentery tend, during upright stance, to hand like sacs at an oblique angle from the posterior abdominal wall. More likely, the mass of the free abdominal contents is supported from superior vertebral levels, as well as from below from the iliac fossae, and indirectly from the pelvic floor. Improvements in biomechanical models, therefore, should attempt to render a more realistic trunk loading distribution, such that the mechanical behavior of the spine can be better presented.

It is apparent from this study that a consensus on the trunk segment properties does not exist. Part of the dissension is a product of disparate segment boundary definitions of the trunk, but disagreement also may be attributed to differences in the measurement sample, for example, whether it is based on cadavers or living subjects. Moreover, variation in population samples in age, gender, fitness level, and even race and body type (21) may affect predicted mass properties. Furthermore, describing the trunk in a linked-segment format may be inappropriate, given that the trunk is a composite of many articulating skeletal components and tissue mass regions that cannot be discretely separated as easily as can the appendicular segments. Because the trunk is a composite structure, its mass support is distributed and not necessarily sustained by the vertebral column alone. In addition, the mass properties of the trunk are not constant. In essence, the segment properties of the trunk are dynamic: They can change with orientation in space and with the phases of inspiration and expiration.

Substantial variability is common in the biomechanical properties of the human body, and this variability consistently is seen both intrastudy and interstudy. Therefore, the biomechanics research community must choose either to accept the use of approximate values of segment properties or to use subject-specific measures and/or noninvasively acquired measures to improve the accuracy of predicting mechanical behavior of the body.

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