Agric Res
https://doi.org/10.1007/s40003-021-00608-1

FULL-LENGTH RESEARCH ARTICLE

Estimation and Validation of Body Segment Parameters Using 3D Geometric Model of Human Body for Female Workers of Central India

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Received: 4 October 2020 / Accepted: 20 August 2021

Abstract Body segment parameters are required as input parameters to analyze the forces and moments acting on the joints. They can be used to design the farm tools, protective clothing, equipment, and workplaces. The study was planned to develop geometric models for female agricultural workers of Central India. Anthropometric data of 180 female agricultural workers aged between 25 and 45 years having weight of 45.74 ± (7.56) kg and height of 1510 ± (50) mm were collected to develop 14-segmental 3D geometrical models. The values of mean, maximum, minimum, standard deviation (SD) and 5th and 95th percentile anthropometric dimension were calculated. Based on geometric models, mass, density, volume, center of mass (COM) and moments of inertia of body segments were calculated. To test the validity of the model with other models for body segment parameters, an analysis was carried out using SAS 9.3 software with one-way analysis of variance. There was a significant difference ($p < 0.01$) between the study model and other models based on Dunnett's multiple comparisons post hoc test. From post hoc test analysis, it was observed that developed 14 segments geometric model can be used to determine body segment parameters (BSPs), *i.e.*, segment mass, volume, center of mass (COM) and radius of gyration (RG).

Keywords Segment mass · Center of mass · Moments of inertia · Segment length · Female agricultural workers

Introduction

In India, more than 250 million workers are involved in livestock rearing and agricultural activities [21]. In the present scenario of Indian agriculture, the contribution and role of female agricultural workers in crop production, post harvest processing, animal rearing and other domestic works are increasing. It is predicted that by 2020, 45% of total agricultural workers will be female workers [21]. The activities carried out by women workers either by traditional method or by using the technologies developed for male workers, have led to drudgery, discomfort and occupational health hazards to them. In order to reduce drudgery of women workers employed in agriculture, it is important to develop suitable machinery and workplace for them with applications of ergonomics and biomechanics.

In lower–middle income countries like India, most of agricultural operations were practiced using hand tools and machinery [15]. Repetitive use of non-ergonomic, locally designed tools and machinery in awkward posture leads to various occupational health issues such as, work-related exhaustion, operational difficulties, reduced performance and musculoskeletal disorders (MSDs).

Sometimes work-related MSDs happen widely in various work environments and are prevalent worldwide. Mostly, this is due to consideration of anthropometry of human body only and neglecting biomechanics during design of tools and machines. Proper development of agricultural tools and man-machine systems needs a detailed understanding of biomechanical principles of the

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Published online: 26 October 2021

human performance [1, 7]. MSDs affect the workers, company and economy by increasing disability, pain and health care costs as well as decreasing comfort and productivity. Hence, these unfavorable effects must be avoided by implementing ergonomic and biomechanic principles at work, which would be very helpful in reducing health problems related to work.

An estimation of geometric and inertial parameters of the body is necessary for biomechanical analysis of human movement. Body segment parameters can be estimated by different methods, including regression equations [13], geometric modelling [12, 23, 26], gamma radiation scanning [27], scaling methods [6], computerized tomography [14], inverse dynamics analyses, static force plate analysis, image analysis [25], DXA scan etc. Furthermore, imaging techniques like magnetic resonance imaging (MRI), computed tomography (CT), dual energy X-ray absorptiometry (DEXA) and gamma-ray scanning are costly methods as well as there is a risk of radiation exposure to subjects.

The body segment parameters (BSPs) like length, segment mass, center of mass (COM) and radius of gyration (RG) of body parts, are used in human factors, ergonomics and biomechanical modelling applications such as design of tools, protective clothing, equipments and workstations based on segment size and ranges of motion. While static models such as the 3D static strength prediction model are dependent on segment position, length, mass and COM inputs. Inverse dynamics models use mass, length, segment position, segment inertial properties and dynamic data in order to determine joint contact forces and moments. Body segment parameters can be used to generate a simple 3D geometric model in CAD environment. The model can be used in other areas, including spatial simulation of human behaviour, medicine (orthopedics, prosthetics design and orthotics), criminological science, etc.

As very limited data avaliable for body segment parameters of central Indian women workers, geometric models were developed in the study. The developed models of each body segment for mass, volume, density, center of mass and moment of inertia were compared with other methods suggested by different researchers [3, 9, 20, 24]. The results obtained from the study will be helpful for estimation of body segmentad parametrs of women workers research and development activities in agriculture and industrial sector.

Materials and Methods

Subjects

For the study, 180 healthy female agricultural workers from Bhopal District of Madhya Pradesh State were selected as subjects. They were in the age group of 25–45 years with an average height of 1510 (± 50) mm and mean body mass of 45.74 (± 7.56) kg. It was ensured that selected subjects were physically fit, with no illness history and willing to participate in the study [17]. Dwarf or giant subjects having musculoskeletal injuries were not selected for the study.

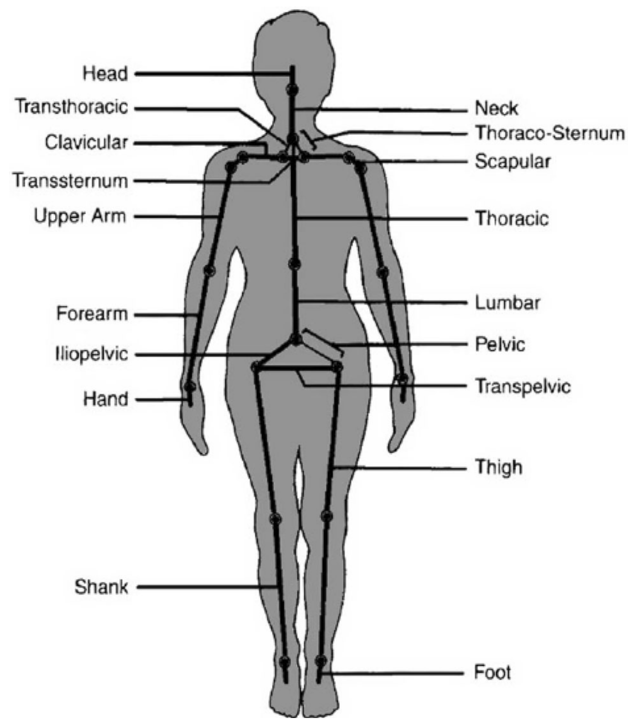

Fig. 1 Typical link-joint system (adapted from NASA/Webb, 1978)

Measurement of Anthropometric Dimensions of the Subjects

Based on previous studies [19, 23], 30 anthropometric dimensions of 180 female workers were measured to develop geometric models of head + neck, torso, thigh, shank, foot, upper arm, lower arm and hand. The terminologies of anthropometric dimension given by NASA [2] were used for this study; Fig. 1 and Table 1 show the typical link-joint system and definition of human body links given by NASA [2]. The same was used to determine joint locations. The straight-line distance between adjacent joint centers was the link length. Unfortunately, anthropometric measurements do not run from joint to joint but usually between externally discernible landmarks, such as bony protrusions on the skeleton. As per the previous researchers [18, 22], there is a high correlation between the measured anthropometric dimensions and measured link length. So, the measured anthropometric dimension was considered as link length. A Harpenden anthropometer,

Table 1 Body segments with geometric shape assigned in present study

Body segments	Geometric shape	Definition of body link [2]
Head + neck	Ellipsoid	The straight line between the occipital condyle/C1 and C7/T1 vertebral interspace joint centers
Torso	Elliptical cylinder	The straight-line distance from the occipital condyle/C1 interspace joint center to the midpoint of a line passing through the right and left hip joint centers
Upper arm	Frustum of cone	The straight line between the gleno-humeral and elbow joint centers of rotation
Lower arm	Frustum of cone	The straight line between the elbow and wrist joint centers of rotation
Thigh	Frustum of cone	The straight line between the hip and knee joint centers of rotation
Shank	Frustum of cone	The straight line between the knee and ankle joint centers of rotation
Hand	Sphere	The straight line between the wrist joint center of rotation and the center of mass of the hand
Foot	Sphere	The straight line between the ankle joint center and the center of mass of the foot

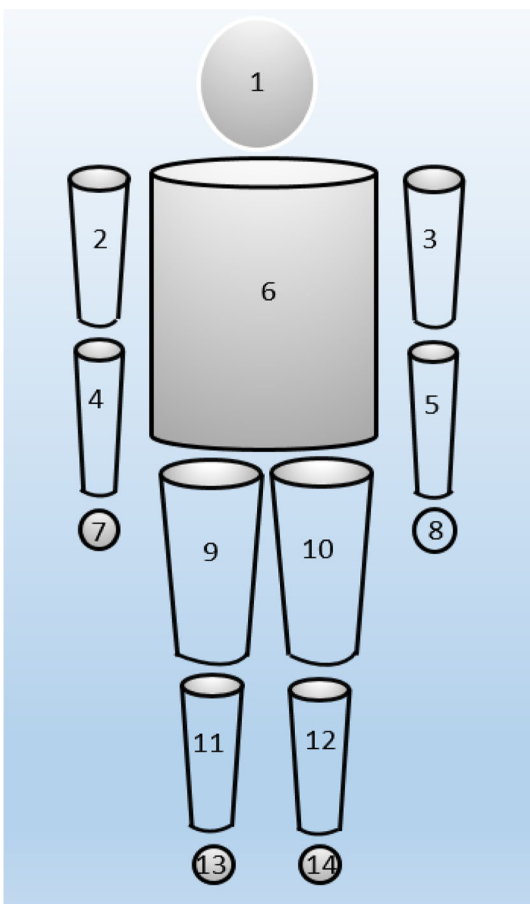

Fig. 2 3D geometric model of human body

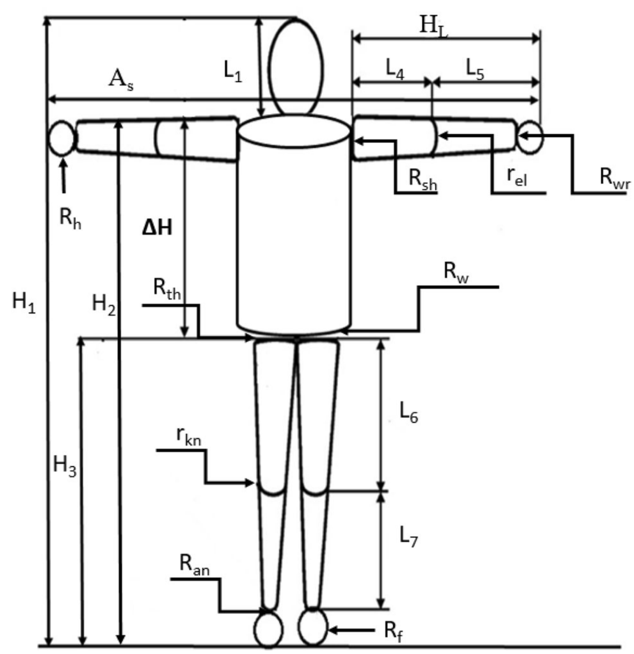

Fig. 3 Notations used for 14 segmental models of human body. L_1 = Total height-acromial height, H_1 = height of subject, H_2 = acromial height, H_3 = trochanteric height, L_4 = upper arm length, L_5 = forearm length, L_6 = thigh length, L_7 = length of shank, R_{sh} = radius at shoulder, r_{el} = radius at elbow height, R_{wr} = radius at wrist, R_{th} = radius of thigh, r_{kn} = radius of knee, R_{an} = radius of ankle, R_w = radius of waist, R_f = radius of foot, R_h = radius of hand, A_s = Arm span, H_L = arm reach from wall-wall to acromion distance

Harpenden stadiometer, Harpenden sitting height table, a steel rule of 1 m long, Vernier's caliper of 0.1 mm precision and measuring ribbon of 1.5 m length were used to measure the anthropometric dimensions of the selected subjects.

Table 2 The mean values and the standard deviations (S.D.) of the measured anthropometric parameters of the human body segments required to create the model of the Central Indian female workers

Segment	Anthropometric parameters (mm)	Mean	SD	Min	Max	5^{th}	95^{th}
Weight	Body mass (kg)	45.74	7.56	28.00	76.00	34.06	58.17
Head + neck	Total height	1510.40	50.01	1383.00	1660.00	1433.14	1592.66
	Head length	183.30	6.67	163.00	200.00	172.99	194.28
	Head breadth	138.58	5.04	125.00	155.00	130.79	146.87
	Menton to top distance	200.27	10.21	171.00	246.00	184.49	217.06
Torso	Acromial height	1260.74	47.61	1120.00	1410.00	1187.19	1339.05
	Trochanteric height	799.81	39.16	667.00	911.00	739.31	864.22
	Chest breadth	237.83	25.38	185.00	317.00	198.61	279.58
	Waist breadth	227.18	28.06	170.00	322.00	183.83	273.34
	Chest circumference	807.87	75.24	650.00	1120.00	691.62	931.63
	Waist circumference	698.66	89.96	535.00	1030.00	559.68	846.64
	Biacromial breadth	276.88	18.81	220.00	368.00	247.82	307.83
Upper arm	Elbow height	960.12	39.43	848.00	1098.00	899.20	1024.99
	Shoulder circumference	348.46	12.11	300.00	430.00	328.54	368.38
	Elbow circumference	226.15	17.58	200.00	260.00	197.24	255.07
Lower arm	Forearm length	423.83	19.72	377.00	467.00	393.36	456.27
	Wrist circumference	146.64	6.91	125.00	165.00	135.97	158.00
	Arm reach from wall	759.05	34.10	682.00	849.00	706.37	815.14
	Wall to acromion distance	94.60	12.53	67.00	130.00	75.24	115.22
Hand	Hand length	171.48	8.21	151.00	191.00	158.79	184.99
	Hand breadth	74.48	4.33	63.00	93.00	67.80	81.60
	Hand thickness	24.85	1.99	20.00	32.00	21.78	28.11
Thigh	Buttock popliteal length	454.47	24.02	389.00	532.00	417.35	493.99
	Thigh Circumference	449.73	47.18	330.00	600.00	376.83	527.34
Shank	Knee height sitting	388.87	23.53	312.00	450.00	352.52	427.57
	Calf circumference	283.83	23.41	240.00	360.00	247.66	322.34
	Ankle Circumference	220.00	18.26	190.00	270.00	189.97	250.03
Foot	Foot length	230.45	11.18	203.00	254.00	213.17	248.84
	Foot breadth	87.47	5.15	76.00	103.00	79.51	95.94
	Medial malleolus height	73.19	5.31	55.00	85.00	64.99	81.92

The purpose of the study was briefed to the female farmworkers for better cooperation from the subjects and obtain more accurate anthropometric data. Two observers conducted all measurements. The dimensions of the body were measured from the right side to ensure scientific uniformity.

Estimation of Geometrical Parameters

The simplified 3D model of the human body used in the study, which consists of 14 segments viz., head + neck, torso, thigh, shank, foot, upper arm, lower arm and hand and their shape were assumed to be of relatively simple geometrical bodies (Fig. 2). The geometrical segmental models of human body and their corresponding notations are explained in Fig. 3. For simplicity, it is assumed that full body symmetry with respect to the sagittal plane, *i.e.*, complete "left–right" symmetry [16, 19, 22]. The 3D geometric model of the human body was developed in Creo software (Company: PTC, version: Pro elements) using the dimensions given in Table 2.

The following assumptions were considered to module the human body:

1) The human body can be represented by a set of rigid bodies with simple geometric shapes.
2) The human body is not consistent in density; due to cavities of tissue, water content, bone component and fat tissues.

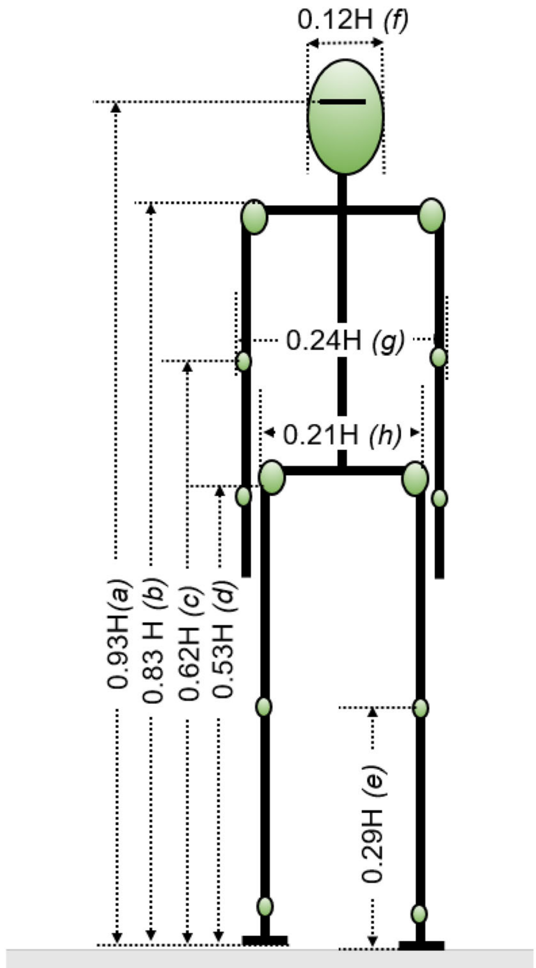

Fig. 4 Segmental proportions as a function of stature (H) for different percentile female agricultural workers of central India in standing posture (a: eye height, b: acromial height, c: olecranon height, d: trochanteric height, e: knee height, f: head length, g: elbow–elbow breadth, h: hip breadth)

3) Mass repartition remains unchanged, and the volume of muscles is constant regardless of the body position.
4) Body is assumed to be symmetrical to the sagittal plane and divided into eight segments, i.e., head with neck, trunk, upper arm, forearm, hand, thigh, shank and foot as given by [23].
5) The center of mass (COM) is the same as the center of gravity (COG).
6) The limbs move about fixed pivot points when the body position changes.

The human body was divided in different segments based on anthropometric dimension. Segments were modeled in the forms of geometrical shapes. The shape of head + neck part was assumed as ellipsoid; thigh, shank, upper arm and lower arm as frustum of cone; and foot and hand were approximated as sphere. The variation in geometry of torso was reported by several authors. Hanvan

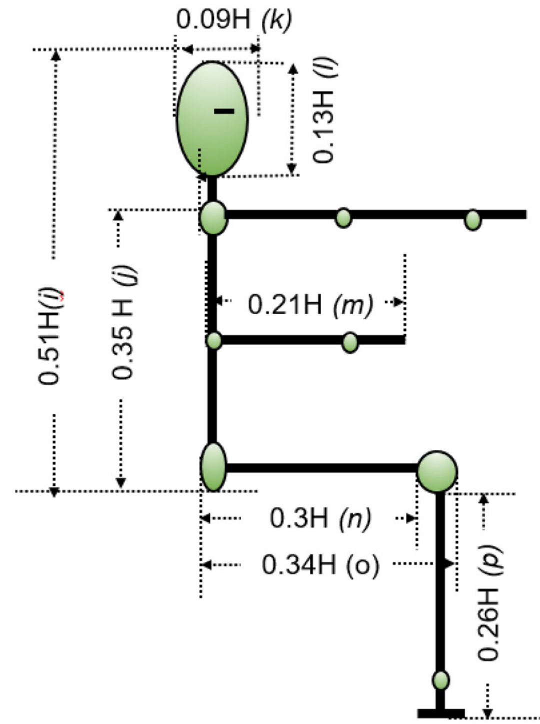

Fig. 5 Segmental proportions as a function of stature (H) for different percentile female agricultural workers of central India in sitting posture. (i: sitting height, j: acromion height (sitting), k: head breadth l: menton to top of the head, m: elbow grip length, n: buttock popliteal length, o: buttock knee length, p: popliteal height sitting)

[12] initially reported that the upper and lower torso are of right elliptical cylinders shape. Later on Merill [22] classified torso in upper, middle and lower torso with geometry of right reverted elliptical cone, elliptical cylinder and elliptical cylinder + reverted elliptical cone, respectively. In this study, torso has been considered as single part of elliptical cylinder geometry.

Furthermore, 16 particular body dimensions were chosen to illustrate the differences of segmental proportions of 50th percentile female agricultural workers in both standing and sitting postures. Totally, eight body dimensions measured in standing posture viz., eye height, acromial height, olecranon height, trochanteric height, knee height, head length, elbow-elbow breadth, and hip breadth were selected for measurement of segmental proportion (Fig. 4). In addition, another set of eight body dimensions were measured in sitting posture, viz., height, acromion height, head breadth, menton to top of the head, elbow grip length, buttock popliteal length, buttock knee length, and popliteal height (Fig. 5).

Links and Joints

It is important to note that approximation of segments by geometric models significantly reduces the number of independent parameters. According to Kroemer [18], only a small number of geometric dimensions directly coincide with them. Therefore, it is important to know the geometrical parameters used and their relation to actually measured dimensions. The body segments with geometric shape assigned are given in Table 2.

Volume of Body Segments

The volume of different body segments was estimated using the following formulae of geometric model. Head + neck part was assumed to be ellipsoid is shape, and its volume (V_n) can be estimated by

$$V_n = \frac{4}{3} * \boldsymbol{\pi} * \mathbf{L_1} * \mathbf{L_2} * \mathbf{L_3}$$

where $L_1 = H_1\text{-}H_2$ = total height-acromial height, mm., L_2 = head length, mm, L_3 = head breadth, mm.

Torso was considered as single part of elliptical cylinder geometry, so volume of torso (V_n) can be estimated by

$$V_n = \pi * R_w * B_1 * \Delta H$$

where $R_{w\,=}$ radius of waist, mm. $B_1 = \frac{1}{2}$ * breadth of waist, mm, ΔH, mm = $H_2\text{-}H_3$ = acromial height-trochanteric height.

The volume of upper arm (V_3), lower arm (V_4), thigh (V_5) and shank (V_6) were approximated by shape of frustum of cone and represented by generalized Eq. (3). While calculating the volume of upper arm, "R" represented the radius at shoulder (R_{sh}) and "r" represented radius at elbow (r_{el}). In case of lower arm, "R" and "r" were used to denote radius at wrist (R_{wr}) and elbow (r_{el}), respectively. Similarly, for calculation of volume of thigh, radius of thigh (R_{th}) and knee (r_{kn}) were considered as "R" and "r". For calculation of volume of shank, "R" represents radius of ankle (R_{an}) and "r" represents radius of knee (r_{kn}). All these notations are shown in Fig. 3.

$$V_n = \frac{1}{3} * \boldsymbol{\pi} * \mathbf{L_n}\left[\mathbf{R^2} + \mathbf{R} * \mathbf{r} + \mathbf{r^2}\right]$$

where, n = 3, 4, 5 and 6., L = length of the corresponding segment, mm

Since the hand and foot were approximated as a sphere,

$$\textit{The volume of hand} = V_n = \frac{4}{3} * \boldsymbol{\pi} * \mathbf{R_h^3}$$

where R_h = radius of hand which was calculated based on hand dimensions such as thickness, length and breadth, mm

$$\textit{The volume of foot} = V_n = \frac{4}{3} * \boldsymbol{\pi} * \mathbf{R_f^3}$$

where R_f = radius of foot which was calculated based on foot dimensions such as length, breadth and medial malleolus height, mm.

Density of Segment

Each body segment has a unique combination of bones, muscles, fats and other tissues. The density of the whole body is not uniform. The density of distal segments is greater than that of proximal segments because of their higher bone proportion. The human body consists of many types of tissues having different densities. Contini [4] developed an expression for body density in kg/l as a function of the ponderal index (PI),

$$\textit{Body density} = 0.69 + 0.9 * PI$$

$$\mathbf{PI} = \frac{\boldsymbol{Height}}{\boldsymbol{weight}^{1/3}}$$

where body height is in m and weight in kg.

Based on Eq. (6), whole-body density of 180 female agricultural workers was calculated. Winter [26] predicted the trends for six limb segments, i.e., upper arm, lower arm, thigh, shank, hand and foot as a function of whole-body density and from that density for each body segment was determined.

Mass of Segments

The mass of each segment was calculated using basic formula of density as given below.

$$\textbf{Density}\left(\mathbf{kg/m^3}\right) = \frac{\boldsymbol{Mass}(\boldsymbol{kg})}{\boldsymbol{Volume}(\boldsymbol{m})^3}$$

Center of Mass of Each Segment

The center of mass (COM) of a body part is weighted average of the mass distribution of the body. The numerical equation for a particular geometry was used to calculate the COM of a particular body segment. The most of expressions needed for COM can be derived in a relatively straight forward manner. For head + neck part, the COM was estimated using Eq. (9) and the COM of upper arm, lower arm, thigh and shank was modeled as a frustum of cone and calculated using the formula (10). The COM was measured from the upper cross-section of the segment. The torso was considered as single part of elliptical cylinder geometry, so the COM was calculated using Eq. (11). The COM of foot and hand was centroid of sphere, i.e., half of diameter. The notations used for calculations of COM are the same which are used to calculate volumes of segments and unit of all dimensions in mm.

$$COM^{(H+N)} = \frac{\textbf{Major/Minoraxis}}{2} \tag{9}$$

$$COM^{(UA,LA,TH\&SH)} = \frac{L}{4} * \left\{ \frac{\mathbf{R}^2 + 2 * \mathbf{R} * \mathbf{r} + 3\mathbf{r}^2}{\mathbf{R}^{2+}\mathbf{R} * \mathbf{r} + \mathbf{r}^2} \right\} \quad (10)$$

$$COM^{(TR)} = \frac{\Delta \mathbf{H}}{2} \quad (11)$$

where H + N = head + neck, UA = upper arm, LA = lower arm, TH = thigh, SH = shank.

Inertial Characteristics

The moment of inertia of a body segment was determined from the segment mass, proximal radii, distal radii and the segment geometry. The default visual 3D segments were treated as geometric objects which have inertial characteristics based on their shape. The radius of gyration of head + neck, trunk, upper arm, forearm, hand, thigh, shank and foot was calculated from values of moment of inertia. Based upon the literature [12, 20, 23], the moment of inertia of ellipsoid, right elliptical cylinder, frustum of cone and sphere was estimated as follows:

The moment of inertia of head + neck (ellipsoid geometry) with mass (M_1) and semi-axes L_1, L_2 and L_3, which are given in Sect. 2.6.

$$I_{XX} = \frac{\mathbf{M}1}{5}$$

$$I_{YY} = \frac{\mathbf{M}1}{5}\left[\mathbf{L}_1^2 + \mathbf{L}_3^2\right]$$

$$I_{ZZ} = \frac{\mathbf{M}1}{5}\left[\mathbf{L}_1^2 + \mathbf{L}_2^2\right]$$

The moment of inertia of torso (right elliptical geometry) with mass (M_2) and radius r_w and height ΔH as given in Sect. 2.6.

$$\mathbf{I_{xx}} = \mathbf{I_{yy}} = \frac{M_2}{4}\left[\mathbf{r}_\mathbf{w}^2 + \frac{\Delta H}{3}\right.$$

$$I_{ZZ} = \frac{1}{2} * \mathbf{M_2} * \mathbf{r}_\mathbf{w}^2$$

The mathematical model for frustum of cone given by [12] used for calculation of moment of inertia as given in Eqs. (17) and (18).

$$I_{XX} = I_{YY} = \frac{\boldsymbol{a}_1\boldsymbol{a}_2\boldsymbol{M}_i^2}{\partial * \boldsymbol{L}_i} + b_1 b_2 M_i L_i^2$$

$$I_{zz} = \frac{2\boldsymbol{a}_1\boldsymbol{a}_2\boldsymbol{M}_i^2}{\partial * \boldsymbol{L}_i}$$

where $a_1 = \frac{9}{20\pi}$

$$a_2 = \frac{1 + x + x^2 + x^3 + x^4}{\sigma^2}$$

$$\sigma = 1 + X + X^2$$

$$X = \frac{R_{distal}}{R_{proximal}} \quad for\ R_{distal} < R_{proximal}$$

$$b_1 = \frac{3}{80}$$

$$b_2 = \frac{1 + 4x + 10x^2 + 4x^3 + x^4}{\sigma^2}$$

$$\partial = \frac{3M_i}{L_i * \left(R_{Proximal+}^2 R_{distal} R_{proximal+} R_{distal}^2\right) * \pi} \quad i = 3,\ 4,\ 6\ and\ 7$$

M_3, M_4, M_6 and M_7 = segment mass of upper arm, lower arm, thigh and shank, respectively, unit in kg .

L_4, L_5, L_6 and L_7 = segment length of upper arm, lower arm, thigh and shank, respectively, unit in mm.

The moment of inertia of a hand and foot (sphere geometry) with radius R_h, R_f and mass M_5,M_8, respectively, given below

$$I_{XX} = I_{YY} = I_{zz} = \frac{2}{5} * M_5 * R_h^2$$

$$I_{XX} = I_{YY} = I_{ZZ} = \frac{2}{5} * M_5 * R_h^2$$

Validation of Model and Data Analysis

For comparison of estimated body segment parameters (BSPs) of geometric models developed by [3, 9, 12, 13, 24, 26] were used. These six models were selected because these models were most commonly used by researchers and represent a variety of analytical techniques and samples [1, 10]. In general, these approaches have strong agreements with more precise techniques. For example, Damavandi [5] stated that body segments parameters obtained from geometrical models used by [8, 12, 20] had good agreement with force plate method. Furthermore, Durkin [10] reported that BSP of lower leg from [8, 12, 19] had good agreement with BSP value obtained from dual-energy X-ray absorptiometry (DEXA) scanner.

To test the validity of the developed model, with other models for body segment parameters, an analysis was carried out in SAS 9.3 software using one-way analysis of variance (ANOVA). Furthermore, in cases where significant differences ($p < 0.01$) were observed between the studied model and others model, Dunnett's multiple comparisons post hoc test was conducted. If the proposed method provides BSP values within the range of the other techniques, it can indicate its validity to calculate the desired parameters, even after significant differences are observed between the methods.

Table 3 Volume of the body segments (10^{-3} m^3) for female farm workers

Volume($10^{-3}m^3$)					
Sr. No	Segment	Dempster 1955, Winter 2009	Caluser,1969	Dumas, 2007	Present study, 2020
1	Head + neck	3.34	3.39	3.06	4.40
2	Trunk	24.71	24.63	20.63	18.29
3	Upper arm	1.20	1.29	1.05	1.99
4	Forearm	0.65	0.72	0.64	0.70
5	Hand	0.23	0.31	0.23	0.22
6	Thigh	4.31	4.90	6.68	4.90
7	Shank	1.93	1.97	2.06	1.96
8	Foot	0.59	0.69	0.46	0.35

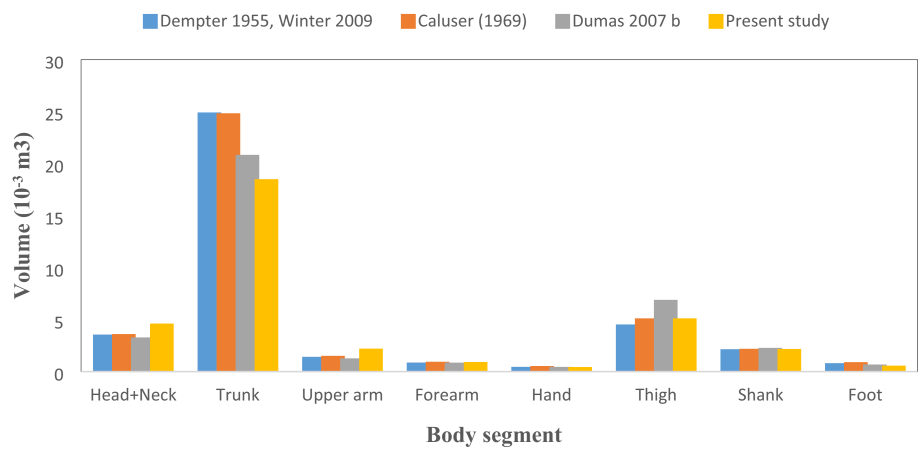

Fig. 6 A comparison between the volume of segments obtained from the present study geometric models and other estimation models for female workers

Table 4 Post hoc Dunnett's test results for body segment volume (m^3) obtained from the present study geometric model and the other techniques for the entire sample

Model	Body segments							
	Head + neck	Trunk	Upper arm	Forearm	Hand	Thigh	Shank	Foot
Dempster (1955)	0.069^{NS}	6.14^{*}	-0.47^{*}	-0.008^{NS}	0.037^{NS}	-0.011^{NS}	0.12^{NS}	0.139^{*}
Clauser (1969)	-0.039^{NS}	3.58^{NS}	–	0.011^{NS}	0.078^{*}	0.11^{NS}	0.059^{NS}	0.166^{*}
Dumas 2007 b	-0.076^{NS}	1.79^{NS}	-0.53^{*}	0.029^{NS}	0.048^{*}	1.51^{*}	0.24^{NS}	0.048^{NS}

Statistical Significance (*$p < 0.05$)

Results and Discussion

Anthropometric Data and Segment Proportion of Female Agricultural Workers

The descriptive statistics, viz., mean, standard deviation (SD), minimum, maximum and percentile values (5th and 95th), of anthropometric data of selected female agricultural workers are calculated and given in Table 2. The mean weight and height of the subjects were 45.74 ± 7.53 kg and 1510 ± 50 mm, respectively. There was a difference of 160 mm between 5 and 95th percentile values of stature of selected female workers. The stature is an important dimension for its relevancy in determining several other body dimensions. However, the 5th and 95th percentile values of stature of female agricultural workers were 1433 and 1593 mm, which suggest that the design parameter should not exceed the range. The segmental proportions of the body dimensions were found in accordance with the proportions observed by other researchers.

Table 5 Density of the body segments for female agricultural workers

Density, kg/m³					
Sr. No	Segment	Dempter,1955; Winter 2009	Clauser (1969)	Dumas 2007 b	Present study, 2020
1	Head + Neck	1110	1071	1000	1050
2	Trunk	920	1023	1000	1150
3	Upper arm	1070	–	1000	1085
4	Forearm	1130	1099	1000	1120
5	Hand	1170	1108	1000	1140
6	Thigh	1050	1045	1000	1060
7	Shank	1090	1085	1000	1085
8	Foot	1090	1085	1000	1100

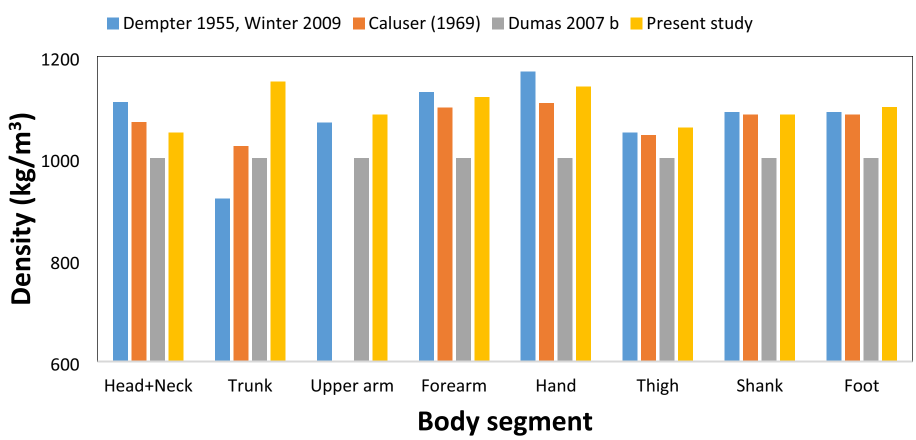

Fig. 7 A comparison between the density of body segments obtained from the present study geometric models and other estimation models for female workers

Table 6 Relative location of the center of mass (% of segment length) of the body segments from the proximal end of the segment

COM (% of segment length)							
Sr. No	Segment	Dempster 1955, Winter 2009	Clauser, 1969	De leva, 1996	Zatsiorsky, 2002	Dumas, 2007	Present study,2020
1	Head + neck	43.3	46.4	48.41	48.4	55.9	50.0
2	Trunk	–	38[c]	49.64[d]	43.5	39.33	50.0
3	Upper arm	43.6	21.3	57.54	56	50	43.0
4	Forearm	43	39	45.59	57.4	41.1	43.0
5	Hand	49.4	–	74.74	65	76.8	50.0
6	Thigh	43.3	37.2	36.12	46.1	37.7	42.6
7	Shank	43.3	37.1	43.52	40.3	40.4	45.8
8	Foot	42.9	44.9	40.14	59.9	38.2	50.0

c,d = sum of thorax, abdomen, pelvis

Volume, Density and Mass of Body Segments

The volume of all body segments was calculated using Eqs. (1) - (5). Table 3 and Fig. 6 show volume of all segment based on geometry and their comparison with the experimental data given in the literature [3]. The result of post hoc Dunnett's test indicated that there was a significant ($p < 0.05$) in volume of upper arm estimated in the study with other techniques (Table 4). For head + neck, for arm and shank the differences was 3 percent and no

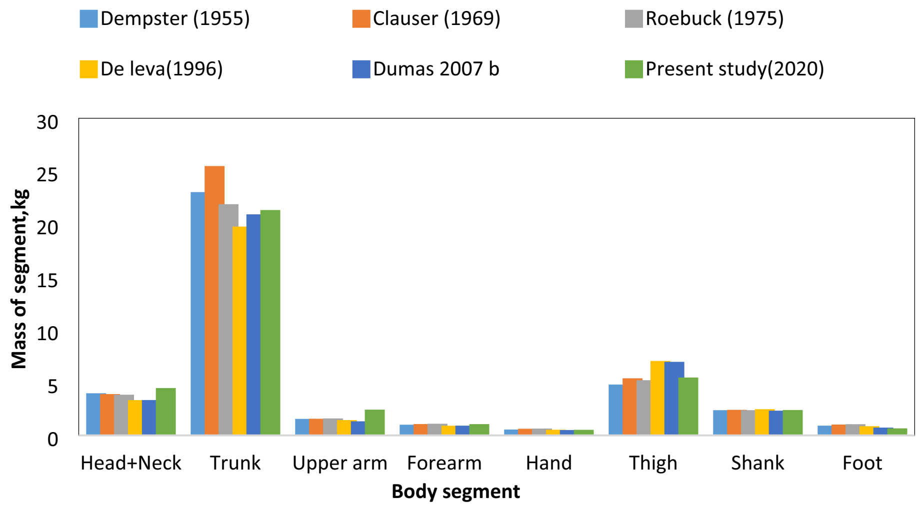

Fig. 8 A comparison between the segment mass results obtained from the present study geometric models and other estimation models for female workers

Table 7 Post hoc Dunnett's test results for body segment masses (kg) obtained from the present study geometric model and the other techniques for the entire sample

Model	Body Segments							
	Head + neck	Trunk	Upper arm	Forearm	Hand	Thigh	Shank	Foot
Dempster (1955)	0.277 NS	1.026 NS	− 0.539*	− 0.00280 NS	0.049 NS	− 0.063 NS	0.143 NS	0.148 NS
Clauser (1969)	0.027 NS	1.108 NS	− 0.607*	− 0.00180 NS	0.080*	0.047 NS	0.064 NS	0.175 NS
Roebuck (1975)	0.126 NS	− 0.128 NS	− 0.541*	0.04900 NS	0.107*	0.239 NS	0.210 NS	0.225 NS
De leva (1996)	− 0.185 NS	− 1.920 NS	− 0.643*	− 0.06220 NS	0.033 NS	1.366 NS	0.210 NS	0.092 NS
Dumas 2007 b	− 0.243 NS	− 2.550 NS	− 0.697*	− 0.06830 NS	0.009 NS	0.848 NS	0.015 NS	− 0.005 NS

Statistical Significance (*$p < 0.05$)

Table 8 Mass of the segments of the body (kg) for female agricultural workers

Mass of segment, kg (% of total body mass)							
Sr. No	Segment	Dempster, 1955	Clauser, 1969	Roebuck, 1975	De leva, 1996	Dumas, 2007	Present Study
1	Head + Neck	8.1[a]	7.3	7.8	6.68	6.7	6.18
2	Trunk	49.7	50.7[c]	47.2[d]	42.57	45.1	45.99
3	Upper arm	2.8	2.6	2.9	2.55	2.3	4.71
4	Forearm	1.6	1.6	1.8	1.38	1.4	1.72
5	Hand	0.6	0.7	0.8	0.56	0.5	0.54
6	Thigh	9.9	10.3	10.8	14.78	14.6	11.36
7	Shank	4.6	4.3	4.6	4.81	4.5	4.64
8	Foot	1.4	1.5	1.7	1.29	1	0.84

a = mass without neck

c, d = sum of thorax, abdomen, pelvis

significant differences were observed in body segment masses, therefore, the models developed by Clauser [3] can be used to calculate volume of Indian female farm workers except upper arm.

The density for whole body was calculated using Eqs. (6) and (7). Once whole-body density was determined, the density for each segment using method described by Winter [26]. Table 5 and Fig. 7 show density of all

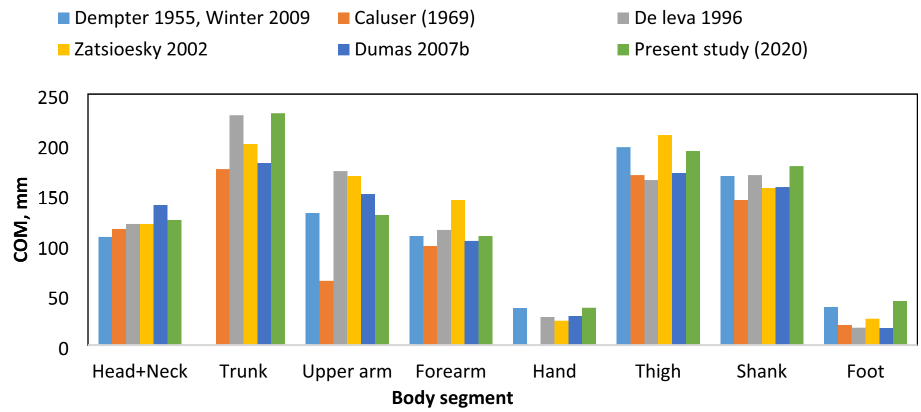

Fig. 9 A comparison between center of mass results obtained from the present study geometric models and other estimation models for female workers

Table 9 Post hoc Dunnett's test results for Centre of mass (mm) obtained from the present study geometric model and the other techniques for the entire sample

Model	Body Segments							
	head + neck	Trunk	Upper arm	Forearm	Hand	Thigh	Shank	Foot
Dempster (1955)	− 17.515*	–	2.425NS	− 3.130NS	− 0.633NS	− 1.414NS	− 10.23NS	− 6.5977*
Clauser (1969)	− 8.992NS	− 56.578*	− 65.070*	− 12.609*	–	− 27.998	− 31.16*	− 4.7788*
De leva(1996)	− 5.673 NS	1.152NS	44.121*	3.139 NS	17.2886*	− 31.869	− 7.979NS	− 9.2465*
Zatsiorsky 2002	− 3.616 NS	− 28.687*	39.201*	3.034NS	10.6300*	11.401	− 1.795NS	8.0620*
Dumas 2007 b	14.585*	− 48.238*	21.953*	− 7.516 NS	18.9960*	− 25.062	− 18.913*	− 11.07*

Statistical Significance (*$p < 0.05$)

segments based on geometry and comparison with the experimental data available in literature of Clauser [3]. As model of density was not significant, because data of density for others model were not available for each person, so no further post hoc test was conducted. Based on the volume and density given in Table 3 and 4, respectively, the mass of each body segment was calculated using Eq. (8) which is presented in (Table 6) and Fig. 8. Table 7 shows post hoc Dunnett's test results for body segment mass. It was observed that model [3, 9, 20] shows not significant results for Head + neck, Trunk, forearm, thigh, shank and foot and can be used to calculate masses.

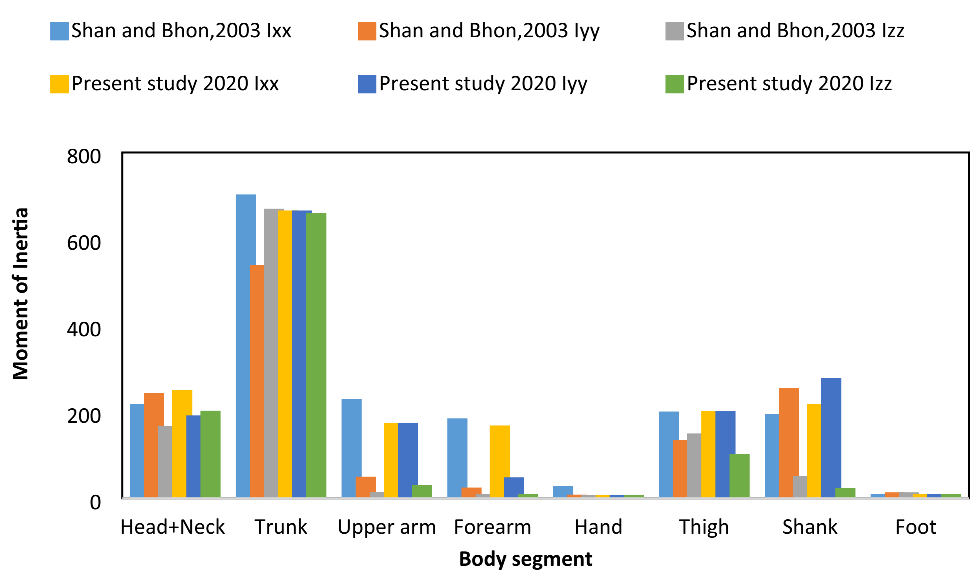

Fig. 10 A comparison between moment of inertia (kg-cm$^{2)}$ results obtained from the present study geometric models and other estimation models for female workers

Table 10 Post hoc Dunnett's test results for radius of gyration (mm) obtained from the present study geometric model and the other techniques for the entire sample

Model	Head + Neck			Trunk			Upper arm		
	R_{xx}	R_{yy}	R_{zz}	R_{xx}	R_{yy}	R_{zz}	R_{xx}	R_{yy}	R_{zz}
De leva 1996	-31.3^*	-62.4^*	-70.7^*	110.9^*	148.2^*	128.5^*	-7.0^{NS}	-35.2^{NS}	18.9^{NS}
Dumas 2007 b	-30.1^*	-67.6^*	-61.1^*	253.6^*	280.5^*	183.5^*	12.8^{NS}	-26.4^{NS}	61.2^*

Model	Forearm			Hand			Thigh		
	R_{xx}	R_{yy}	R_{zz}	R_{xx}	R_{yy}	R_{zz}	R_{xx}	R_{yy}	R_{zz}
De leva 1996	-7.81^*	-47.7^*	42.19^*	9.94^*	1.35^*	15.50^*	35.8	-52.0^*	153.2^*
Dumas 2007 b	-4.62^*	-9.5^*	2.72^*	23.3^*	8.21^*	19.76^*	12.3	-39.9^*	131.9^*

Model	Shank			Foot		
	R_{xx}	R_{yy}	R_{zz}	R_{xx}	R_{yy}	R_{zz}
De leva 1996	-3.01^{NS}	-63.4^*	65.5^*	-15.8^*	-3.32^*	-1.53^{NS}
Dumas 2007 b	3.15^{NS}	-60.4*	70.3^*	-6.80*	16.4^*	16.4^*

Statistical significance (*$p < 0.05$)

However, for upper arm all models were significantly different ($p < 0.05$). The critical difference for mass varies from (− 0.53 to − 0.69) kg for all models. The relative mass (%, according to the mass of the whole body) of head + neck, trunk, upper arm, forearm, hand, thigh, shank and foot for female agricultural workers of central India was 9.18%, 45.99%, 4.71%, 1.72%, 0.54%, 11.36%, 4.64% and 0.84%, respectively.

Location of Centre of Mass

The COM (the ratio of distance from the proximal end of the segment and the length of the segment) of all the segments of the body was calculated using Eqs. 9–11. Table 8 and Fig. 9 show a fairly good agreement between study model and the experimental results. Post hoc Dunnett's test (Table 9) revealed that the relative location of COM (i.e., COM location/SL) of thigh and shank obtained using the study geometric model was lower than other model. Similarly, the relative COM location of head + neck, forearm and shank was nearly equal to [9]. The critical range for COM for head + neck, forearm and shank was − 5.67 mm, 3.1 mm, − 7.9 mm for De leva model. The COM location for Head + neck and forearm based on proposed method was 5.87% and 4.27% higher as compared to model given by De Leva [20].

Moment of Inertia

For calculation of inertia data for the extremities, the regression equations used by the authors [3, 12] were used. All equations were presented in the work of Erdmann [11]. The procedure for obtaining the mass of body parts and position of the COM are given in detail in Sect. 2.8 and 2.9. Figure 10 presents the results of radius of gyration found for the torso and for all other body segments for female agricultural workers which was derived by using Eqs. (12) to (20). The units of post hoc Dunnett's test for radius of gyration are tabulated in Table 10. From analysis, it was observed that there was a significant difference ($p < 0.05$) for all body segments models except upper arm.

Conclusions

The objective of this study was to estimate and validate 14-segment geometric model for female agricultural workers of central India. The model can be used to determine body segment mass, volumes, density, center of mass location and moment of inertia. With respect to mass values for all segments except upper arm, no statistical difference was found. The values obtained from the developed geometric model were found to be comparable to those of the other researchers [3, 9]. With respect to volume, density and center of mass of upper arm and foot segments, considerable variation was observed between the study and models of other researchers. Furthermore, segmentation differences were observed between [9] for radius of gyration value for all segments ($p < 0.05$) and may be due to assumption of constant density. Difference between results of the study and those reported in the literature can be improved by using geometric model shape close to the real shape of human body segments.

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