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Comparison of two approaches for calculation of the geometric and inertial characteristics of the human body of the Bulgarian population

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On the basis of a representative anthropological investigation of 5290 individuals (2435 males and 2855 females) of the Bulgarian population at the age of 30–40 years (YORDANOV et al. [1]) we proposed a 3D biomechanical model of human body of the average Bulgarian male and female and compared two different possible approaches to calculate analytically and to evaluate numerically the corresponding geometric and inertial characteristics of all the segments of the body. In the framework of the first approach, we calculated the positions of the centres of mass of the segments of human body as well as their inertial characteristics merely by using the initial original anthropometrical data, while in the second approach we adjusted the data by using the method based on regression equations. Wherever possible, we presented a comparison of our data with those available in the literature on other Caucasians and determined in which cases the use of which approach is more reliable.

Key words: *body segment parameters, anthropometry, centre of mass, moments of inertia*

1. Introduction

An estimation of geometric and inertial parameters of the body is necessary for biomechanical analysis of human movement. Body segment parameters can be estimated in a number of different methods, including regression equations (CLAUSER et al. [2], CHANDLER et al. [3]), geometric modelling (HANAVAN [4], JENSEN [5], HATZE [6], YEADON [7]), gamma radiation scanning (ZATSIORSKY and SELUYANOV [8], [9]), scaling methods (DAPENA [10], FORWOOD et al. [11], ZATSIORSKY et al. [12]), computerized tomography (HUANG and WU [13], RODRIGUE and GAGNON [14], WEI and JENSEN [15], ERDMANN [16]), magnetic resonance imaging (MUNGIOLE and MARTIN [17]), etc.

In order to be able to calculate analytically and to evaluate numerically the geometric and inertial parameters of all the segments of the body, one needs to define a particular and relatively simple model of the human body. In the current study, we presented such a simple 3D biomechanical model of the average Bulgarian male and female and compared two different possible approaches to determine the measures of the quantities mentioned above. Thus, in the framework of the approach (to be denoted further by A) we calculated the positions of the centres of mass of the segments as well as their inertial parameters merely by using the initial original anthropometrical data, while in the second approach (to be denoted further by B), we adjusted the geometrical data by using the method based on regression equations. Comparing the data obtained in this way with data available in literature on other Caucasians we demonstrated which approach is better for which characteristic of which particular segment. Let us note that for Bulgarian males and females there are no direct measurements of inertial parameters of the body segments. Therefore, the current study fills, at least partially, this gap and is a recipe for the determination of these parame-

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ters for a particular individual with an acceptable, for practical purposes, error.

2. Description of the model

The model consists of 16 segments: singular – head + neck, upper part of torso, middle part of torso, lower part of torso and double – thigh, shank, foot, upper arm, lower arm and hand, which are supposed to be shaped via relatively simple geometrical figures (see the figure). We assumed full body symmetry with respect to the sagittal plane, i.e. complete "left–right" symmetry. The geometrical models of segments and their characterizing parameters are given in table 1.

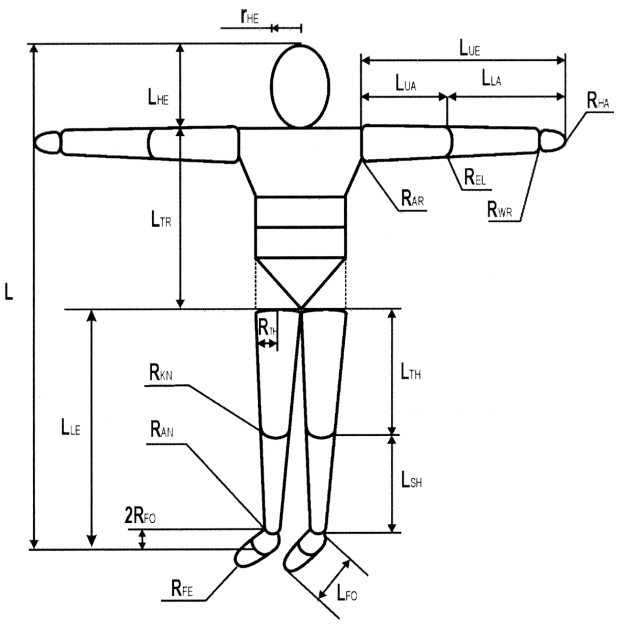
We made use of the average geometrical values, obtained in a representative anthropological investigation of 5290 individuals (2435 males and 2855 females) of the Bulgarian population at the age of 30–40 years by

Table 1. Geometric approximations, parameters of the segments of the body, and densities of the different segments for males and females

	Males		Females		
Body segments	Anthropometric parameters[a] Model A [m]	Adjusted parameters of the model Model B [m]	Anthropometric parameters[a] Model A [m]	Adjusted parameters of the model Model B [m]	Density [kg/m^3][b]
1[c]	2	3	4	5	6
Head + neck (ellipsoid)	$R_{HE} = 0.156$ $r_{HE} = 0.078$	$R_{HE} = 0.156$ $r_{HE} = 0.078$	$R_{HE} = 0.146$ $r_{HE} = 0.074$	$R_{HE} = 0.154$ $r_{HE} = 0.080$	1087
Upper torso (reversed right elliptical cone)	L_{TR}=0.531 $L_1 = 0.177$ $R^* = 0.203$ $r^* = 0.148$ $R_1 = 0.150$ $r_1 = 0.110$	L_{TR}=0.531 $L_1 = 0.153$ $R^* = 0.203$ $r^* = 0.176$ $R_1 = 0.150$ $r_1 = 0.130$	L_{TR}=0.497 $L_1 = 0.166$ $R^* = 0.184$ $r^* = 0.133$ $R_1 = 0.138$ $r_1 = 0.100$	L_{TR}=0.497 $L_1 = 0.205$ $R^* = 0.200$ $r^* = 0.159$ $R_1 = 0.151$ $r_1 = 0.12$	953
Middle torso (elliptical cylinder)	$L_2 = 0.185$ $R_2 = 0.150$ $r_2 = 0.110$	$L_2 = 0.219$ $R_2 = 0.150$ $r_2 = 0.130$	$L_2 = 0.173$ $R_2 = 0.138$ $r_2 = 0.100$	$L_2 = 0.142$ $R_2 = 0.151$ $r_2 = 0.12$	953
Lower torso (elliptical cylinder + reversed elliptical cone)	$L_3 + L_4 = 0.169$ $R_3 = R_4 = 0.150$ $r_3 = r_4 = 0.110$	$L_3 + L_4 = 0.159$ $R_3 = R_4 = 0.150$ $r_3 = r_4 = 0.130$	$L_3 + L_4 = 0.158$ $R_3 = R_4 = 0.138$ $r_3 = r_4 = 0.100$	$L_3 + L_4 = 0.15$ $R_3 = R_4 = 0.151$ $r_3 = r_4 = 0.12$	953
Upper arm (frustum of cone)	$L_{UA} = 0.309$ $R_{AR} = 0.050$ $R_{EL} = 0.034$	$L_{UA} = 0.309$ $R_{AR} = 0.050$ $R_{EL} = 0.044$	$L_{UA} = 0.286$ $R_{AR} = 0.047$ $R_{EL} = 0.030$	$L_{UA} = 0.286$ $R_{AR} = 0.050$ $R_{EL} = 0.034$	1053
Lower arm (frustum of cone)	$L_{LA} = 0.247$ $R_{EL} = 0.034$ $R_{WR} = 0.030$	$L_{LA} = 0.247$ $R_{EL} = 0.044$ $R_{WR} = 0.030$	$L_{LA} = 0.219$ $R_{EL} = 0.034$ $R_{WR} = 0.030$	$L_{LA} = 0.219$ $R_{EL} = 0.034$ $R_{WR} = 0.030$	1100
Hand (sphere)	$R_{HA} = 0.044$	$R_{HA} = 0.047$	$R_{HA} = 0.039$	$R_{HA} = 0.039$	1137
Thigh (frustum of cone)	$L_{TH} = 0.510$[d] $R_{TH} = 0.091$ $R_{KN} = 0.049$	$L_{TH} = 0.510$ $R_{TH} = 0.095$ $R_{KN} = 0.055$	$L_{TH} = 0.479$[d] $R_{TH} = 0.095$ $R_{KN} = 0.046$	$L_{TH} = 0.479$ $R_{TH} = 0.098$ $R_{KN} = 0.050$	1062
Shank (frustum of cone)	$L_{SH} = 0.372$ $R_{KN} = 0.049$ $R_{AN} = 0.036$	$L_{SH} = 0.372$ $R_{KN} = 0.055$ $R_{AN} = 0.04$	$L_{SH} = 0.346$ $R_{KN} = 0.046$ $R_{AN} = 0.036$	$L_{SH} = 0.346$ $R_{KN} = 0.050$ $R_{AN} = 0.04$	1088
Foot (frustum of cone)	$L_{FO} = 0.263$ $R_{FO} = 0.046$ $R_{FE} = 0.018$	$L_{FO} = 0.263$ $R_{FO} = 0.046$ $R_{FE} = 0.018$	$L_{FO} = 0.239$ $R_{FO} = 0.040$ $R_{FE} = 0.018$	$L_{FO} = 0.239$ $R_{FO} = 0.040$ $R_{FE} = 0.018$	1092

[a] Data according to [1] and [18].
[b] Data according to [22].
[c] Column number.
[d] Length of the thigh is the distance between the anthropometric landmarks *iliospinale–tibiale*.

YORDANOV et al. [1], and constructed a geometrical model which represents the "average" male or female of the Bulgarian population. The data collected by YORDANOV [1] were to a small extent supplemented with the data published by TOSHEV [18]. It turns out that the height and the mass of the average male are 1.71 m and 77.7 kg, respectively. The corresponding data for the average woman are 1.58 m and 65.3 kg.



Simplified segment biomechanical model of a human body

The explanation of the way we determined the numerical values of the geometrical parameters, chose the anthropometric landmarks, modelled the segments, etc., for all segments was already described by NIKOLOVA et al. [19], [20], to which we refer the reader interested in details. In table 1, a summary of all that information is presented.

In a current study of approach A, we simply used this original experimental data (see in table 1, column 2 for males and column 4 for females) to calculate the volume and the inertial characteristics of all the segments of the average Bulgarian man and woman, including the positions of the centres of the masses of different segments as well as their principal moments of inertia.

In approach B, we adjusted the geometrical parameters measured in such a way that our simple geometrical figures approximated at best the volume (and, therefore the mass) characteristic of the different segments of the body derived via the regression equations formulated by ZATSIORSKY and SELUYANOV [8], [9]. More explicitly, we calculated the expected mass of a given segment using an appropriate regression equation and then its volume and we looked for such an adjustment of the initial geometric characteristics which would lead to the best reproduction of that volume within the geometric approximation of the segment via a simple geometrical figure. Of course, by doing so, we tried to keep the adjusted parameters within 10% relative error with respect to their original values. The adjusted values, obtained in the way described above, are given in table 1. For males and females the data is given in columns three and five, respectively. Since for males the regression coefficients calculated by ZATSIORSKY and SELUYANOV [8], [9] are based on the measurements of 100 males, whereas those given by SHAN and BOHN [21] are based on 25 Caucasian males, we used for males the coefficients derived in [8], [9]. In the case of females, however, the corresponding regression equations derived in [8], [9] are based on data for a small group of athletes. Therefore in the case of females, we used the regression equation reported in [21].

3. Calculation of inertial parameters of the human body

3.1. Approach A

As explained above, in this approach we calculated the masses of all the segments directly from the volumes of these segments determined based on the anthropometric measurements reported in [1] and the analytical equations for the volumes of the relatively simple geometrical figures approximating the segments. The densities are taken according to BJORNSTRUP [22] (see column six in table 1). Note that by approximating a segment to a given geometrical figure, a given error in reproducing its mass is immediately generated. The results for the masses of the segments derived in this way for males and females are given in column six of table 2 and in column three of table 3, correspondingly.

3.2. Approach B

For males persons, as already explained in section 2, we used the regression equations derived in [8], [9] based on the investigation of their body segment pa-

Table 2. Mass [kg] of the entire body and its segments for males

Segment	DRILLIS, CONTINI (see Ref. [25])	CLAUSER et al. (see Ref. [2])	CHANDLER et al. (see Ref. [3]) [a]	ZATSIORSKY, SELUYANOV (see Ref. [8], [9])	Approach A	Approach B
1[b]	2	3	4	5	6	7
Entire body	73.40	65.60	65.10	73.00	62.26	77.70
Head + neck	–	–	–	5.02	4.32	5.07
Torso	–	33.31	34.00	31.78	27.98	34.36
Upper arm	2.62	1.73	1.87	1.98	1.82	2.13
Lower arm	1.32	1.05	1.10	1.78	0.88	1.25
Hand	0.44	0.43	0.39	0.48	0.40	0.46
Thigh	6.95	6.75	6.89	10.36	8.59	11.06
Shank	3.09	2.84	2.68	3.16	2.31	3.29
Foot	0.99	0.96	0.83	1.00	0.98	1.02

[a] The mean values from the left- and right-hand sides of the body.
[b] Column number.

Table 3. Mass [kg] of the entire body and its segments for females

Segment	Mass		
	ZATSIORSKY (see Ref. [23])	Approach A	Approach B
1[a]	2	3	4
Entire body	61.90	52.35	65.30
Head + neck	4.20	3.64	4.48
Torso	26.39	21.77	30.27
Upper arm	1.58	1.43	1.66
Lower arm	0.86	0.78	0.77
Hand	0.35	0.28	0.24
Thigh	9.16	8.26	9.01
Shank	3.00	2.00	2.91
Foot	0.88	0.72	0.67

[a] Column number.

rameters of 100 living males by scanning them with a gamma-radiation beam. Taking into account that the total mass of the average Bulgarian man is $M = 77.7$ kg, the body height $L = 171$ cm and that any segment is represented by the regression equation of the following type

$$M_S\,[\mathrm{kg}] = A_1 + A_2 M\,[\mathrm{kg}] + A_3 L\,[\mathrm{cm}], \qquad (1)$$

where $M = 77.7$ kg, $L = 171$ cm, we derived the masses of all the segments (column seven of table 2). In the same table, the data for the masses of the segments for other Caucasian males, obtained by different authors, are also presented.

The average Bulgarian woman is characterized by the mass $M = 65.3$ kg and the body height $L = 158$ cm. Using the regression equations derived in [21] of the type of equation (1), we obtained the data for female masses of the entire body and its segments (see table 3) and compared them with the data of ZATSIORSKY [23].

In tables 4 and 5, the results for the moments of inertia obtained via approaches A and B for males and females, respectively, are compared for any of the segment of the model, with the experimental results available from the literature for other Caucasians. For each segment, a system of axes was defined with its origin at the centre of mass of the segment and x, y and z being the frontal, sagittal, and longitudinal axes of the given segment, correspondingly.

Note that because of the $x \leftrightarrow y$ symmetry in modelling the upper arm, lower arm, hand, thigh, shank and foot, i.e., for all the segments except for the torso, the principal moments of inertia I_{XX} and I_{YY} are equal.

4. Conclusions and discussion

In the framework of the presented simple 3D biomechanical model of the human body that represents the "average" Bulgarian male and female, we compared two different approaches for evaluation of the inertial characteristics of any segment of the body. In the framework of approach A, we calculated the positions of the centres of mass of the segments as well as their inertial parameters merely by using the initial original anthropometrical data, while in approach B, we adjusted these data by using the method based on regression equations. The inspection of the results obtained in such a way (see tables 4 and 5) reveales that approach A can be applied successfully in the estimation of the moments of inertia of males for head + neck, upper torso, upper arm, thigh and shank, while approach B is more reliable for the estimation of the middle and lower torso, lower arm, hand and foot. For females approach A can be used for calculating the moments of inertia of the middle torso, upper arm, lower arm, thigh, shank and the foot. Approach B is useful for the estimation of the head + neck,

Table 4. Moments of inertia [kg·cm^2] of the body segments through their respective centre of mass for males

Segment	ZATSIORSKY (see Ref. [23])			Approach A			Approach B		
	I_{XX}	I_{YY}	I_{ZZ}	I_{XX}	I_{YY}	I_{ZZ}	I_{XX}	I_{YY}	I_{ZZ}
Head + neck	293.9	272.1	202.4	262.9	262.9	105.2	308.3	308.3	123.3
Upper torso	705.2	1725.6	1454.5	838.8	1296.5	1505.7	983.1	1233.3	1763.7
Middle torso	819.1	1280.8	1203.1	537.1	774.7	790.5	1001.3	1180.3	1259.4
Lower torso	525.0	656.8	592.4	224.8	380.2	472.5	579.5	704.5	1074.4
Upper arm	114.4	127.3	38.9	148.3	148.3	17.1	220.8	220.8	25.1
Lower arm	60.2	64.7	12.6	46.5	46.5	4.51	54.7	54.7	8.5
Hand	8.7	13.2	5.3	3.1	3.1	3.1	4.0	4.0	4.0
Thigh	1999.4	1997.8	413.4	1814.9	1814.9	241.3	1564.0	1564.0	307.7
Shank	371.0	385.0	64.6	271.2	271.2	21.7	231.9	231.9	34.0
Foot	40.0	44.4	10.3	49.8	49.8	6.58	46.7	46.7	6.6

Table 5. Moments of inertia [kg·cm^2] of the body segments through their respective centre of mass for females

Segment	SHAN, BOHN (see Ref. [21])			Approach A			Approach B		
	I_{XX}	I_{YY}	I_{ZZ}	I_{XX}	I_{YY}	I_{ZZ}	I_{XX}	I_{YY}	I_{ZZ}
Head + neck	251.3	212.9	119.4	195.0	195.0	79.7	269.8	269.8	114.7
Upper torso	1331.6	2223.4	1766.8	541.5	841.1	957.7	1279.8	1722.4	1961.8
Middle torso	269.6	489.4	533.1	356.9	518.6	518.9	407.1	568.9	716.4
Lower torso	464.9	660.7	692.5	144.2	248.8	309.2	342.2	491.4	662.4
Upper arm	88.6	87.0	19.6	97.9	97.9	11.4	123.5	123.5	15.8
Lower arm	29.9	31.8	4.2	32.9	32.9	4.0	34.6	34.6	4.0
Hand	3.1	2.5	1.2	1.7	1.7	1.7	1.4	1.4	1.4
Thigh	1111.1	1118.2	299.8	1516.5	1516.5	245.6	1714.7	1714.7	290.5
Shank	256.2	298.8	68.9	204.8	204.8	17.2	119.4	119.4	24.8
Foot	12.1	12.3	2.2	31.5	31.5	3.7	35.8	35.8	3.7

upper and lower torso, and the hand. Let us note that while using approach B for the Bulgarian population we have demonstrated the applicability of the regression equations derived in Refs. [8], [9] and [21] to Russians and Germans, correspondingly, and thus we did verify those equations.

In order to further reduce the differences between our results obtained within approach A and those available in literature, we plan, following KWON [24], to improve the geometrical modelling of the segments by using geometrical figures such as stadium solids, elliptical solids and semi-ellipsoids that are closer to the real shape of some of the segments of the human body. Unfortunately, currently we do not have a sufficient number of measured anthropometric parameters to accomplish that goal and the performance of additional measurements is planned and ongoing.

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