Computer and Mathematical Modelling of the Female Human Body: Determination of Mass-inertial Characteristics in Basic Body Positions

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Abstract: The aim of the current article is: 1) to present 16-segmental biomechanical model of the *female* human body generated within a SolidWorks medium. 2) to determine the mass-inertial characteristics of the human body of the average Bulgarian female on the basis of the model. These parameters are needed in order to design wearable or rehabilitation robots and devices properly; 3) to verify the model via comparing its results for the segments of the body with analytical results from our previous investigation of these segments; 4) to predict the inertial properties of a human body in various body positions. The comparison performed between our model results and data reported in literature gives us confidence that this model could be reliably used to calculate these characteristics at random postures of the body.

1 INTRODUCTION

The knowledge of the geometric and mass-inertial characteristics (volume, mass, center of mass, moments of inertia) of human body segments, as well as those of the total body, is needed for analyses of the human motion – of the specific segments of it, or of a given person. This topic has been subject of intensive simulations and mathematical modeling, see,e.g., classical positions on a system theory (Zadeh and Desoer, 1963); human gait analysis (Jensen, 2009); theory-based simulation applied to the physical objects (Respondek, 2010); modeling of the dynamics and energetics of impact in crutch walking (Carpentier et al., 2010); biomechanical optimization to interpret dancers' pose selection (Allen et al., 2011); studies of vibration response of idiopathic scoliosis patients via investigating a proper 3-dimentional finite-element model (Li et al., 2011); the investigation of inertial properties of athletes performing pure somersaults (Mikl, 2014). Obviously, the knowledge of the geometric and mass-inertial characteristics is equally important for the both genders – for males as well as for females. Unfortunately, the overwhelming amount of data available in literature, due to a variety of different reason, concerns males. Next, even when such measurements have been performed, almost all available data is about the different segments, not for the body as a whole. Therefore, an approach aiming to fill in that gap is highly desirable. A 3D model of the female body and its computer realization within the SolidWorks media is presented is the current work. The model allows, in principal, the determination of the mass-inertial parameters of the female body in any posture of the body that is of interest. In order to make some systematization in studying of the mass-inertial parameters of the humans in position related to their everyday activities, leisure, sport, work, etc., the basic positions have been classified long ago (Santschi et al. 1963; Chandler et al., 1975; Hanavan, 1964). In the current article we will present data for these characteristics for the average Bulgarian women in four of these basic positions.

As far as antropometric and mass inertial data for females are concerned, initially, using stereophotogrammetry, the regression equations on the base of a sample of 46 adult women were developed (Young, 1983). Then, on the basis of gamma-scanner method, the mass-inertial parameters of 15 female athletes have been investigated (Zatsiorsky and Seluyanov, 1983). Over that period of time based on the so-called elliptical zone method, the body segment parameters of 15 college-age females have been estimated and classified into endo,

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meso- and ecto-morphs (Finch, 1985). The mass-inertial charchterstics of 80 Japanese women have been investiagted and the diff erence in segment mass proportions with the sample of 215 men has been discussed (Ae et al., 1991). On the basis of measurements of 25 young German females, the regression equations for estimating length, mass and moments of inertia of the segments have been derived (Shan and Bohn, 2003). One of the most contemporary used method is the one dual energy x-ray absorptiometry. Based on it, the differences in estimation of mass, center of mass location and radius of gyration of 5 segments between 4 human populations were estimated (Durkin and Dowling, 2003). Finally, in Yordanov et al., 2006 the anthropometrical data from a detailed representative anthropological investigation of the Bulgarian population have been gathered. The study contains data of total of 2854 females at the age 31-40 years. This study will be our major source of anthropometric data when modeling the body of the average Bulgarian female.

Certainly, the generation of 3D model of the human body in a CAD media needs knowledge of anthropometry and biomechanics. One should, effectively resolve specific problems related to: a) correct body decomposition; b) the selection of necessary anthropometric landmarks; c) the choice of the geometrical bodies with which the corresponding segments of the body shall be modeled; d) the genuine model generation within a proper CAD system (e.g. SolidWorks); e) The verification of the so generated model via comparison with analytical results in order to show that computer generated model provides reliable data quantities.

Let us emphasize, that understanding the mass-inertial parameters of the body is of importance for proper design of vehicles, wheelchairs, exoskeletons, rehabilitation devices, ergonomics, sports, orthotics and prosthetics design, etc. We hope that our model will be helpful in these areas.

The aim of this study is to develop a mathematical model of woman able to predict the inertial properties of the human body in any fixed body position and to use this model to develop a design guide for some of the problems mentioned above. For the specific realization of the model in the current study we will rely on data for the Bulgariam women. However, our approach is, of course general and can be applied to any other set of data for other women. In the current study we will perform a comparsions of our results for the average Bulgarian women with data available in literature for other Caucasian women.

2 MODEL AND METHOD

We utilize a mathematical model of the human body initially proposed in (Nikolova and Toshev, 2007). Out there, this model has been used to determine the geometric and mass-inertial parameters of the different segments of the body. Here, in order to avoid any repetition of these details, we refer the interested reader for further specifics to (Nikolova and Toshev, 2007). We are going to present only some brief comments in order to introduce the very basic facts for the model used in the current study - see Fig. 1.

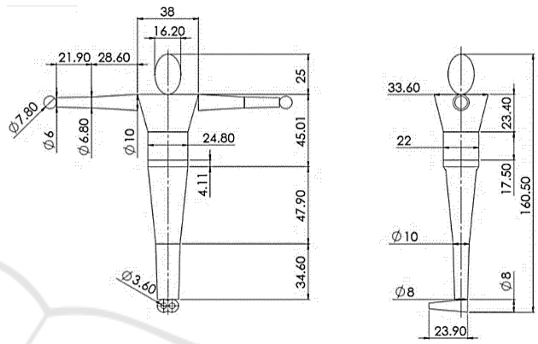

Figure 1: 16-segemental model of the female human body and the corresponding dimensions [cm].

In the current work the model consists of 16 segments: head + neck, upper, middle and lower part of torso, thigh, shank, foot, upper arm, forearm and hand, assumed to be relatively simple geometrical bodies. We accepted full body symmetry with respect to the sagittal plane, i.e., complete ‘‘left–right’’ symmetry. The decomposition of the body segments is made according to anthropometric points used in (Zatsiorsky, 2002).

The anthropometrical data needed is taken from the detailed representative anthropological investigation of the Bulgarian population (Yordanov et al., 2006). We recall that 2854 females at the age 31-40 years have been measured. For any segment and any quantity measured, we take the average values established in this investigation and design a model that represents the so defined "average" Bulgarian woman. As it illustrated in Fig. 1, the segments are modeled by means of geometrical bodies similar to those in (Hanavan, 1964), but with the following modifications:

(1) the torso is decomposed in three instead of two parts;

(2) the upper part of the torso is approximated by means of a right reverted elliptical cone, while it is an elliptical cylinder in (Hanavan, 1964);

(3) we specify both middle and lower torso according to (Zatsiorsky, 2002), modeled as an elliptical cylinder and an elliptical cylinder + reverted elliptical cone, respectively. Let us recall that in (Hanavan, 1964), these two segments are grouped together and modelled as an elliptical cylinder.

All segments of both the lower and upper extremities are assumed to be cone frustums and the hand is modeled as a sphere.

After determining the geometrical parameters of the segments, one can analytically obtain all the other characteristics of interest, such as volume, mass and moments of inertia.

Once the mass-inertial parameters of the segments are determined, one can also study the corresponding characteristics of the total body assuming the body to be in a given position of interest. To realize this goal, we have performed a generation of the model in CAD system – SolidWorks. We have *verified* the computer realization by comparing the results it achieved for the mass -inertial parameters of the segments of the body with the ones reported in (Nikolova and Toshev, 2007).

The basic positions of the body have been classified long ago in the literature – see, e.g., (Santschi et al. 1963; Chandler et al., 1975; Hanavan, 1964; NASA, 2000). One usually considers eight principal body positions. Unfortunately, the data from the above studies is only for men while for women they are either missing or are very few and not enough for reasonable statistically verifiable estimations. In the following sections we will try to enrich the literature with data for four of these positions for the *female* human body:

1) the so-called standing position – see Fig. 2, which will provide us a basis of comparison,

2) the sitting with forearms down position – see Fig. 3,

3) the standing with arms over head – see Fig. 4, and

4) the standing position with maximal horizontal span of upper extremities – see Fig. 5.

3 DETERMINATION OF MASS-INERTIAL CHARACTERISTICS IN DIFFERENT BODY POSITIONS

As stated above, we consider the "standing position", "sitting position", "standing with arms over head position" and the "standing position with maximal horizontal span of upper extremities". For each position, a system of axes with an origin at the center of mass is defined. The axes coincide with the approximate body axes: the frontal (y), the sagittal (z), and the longitudinal (x) ones.

3.1 Standing Position

Data for males in such a position are well known – see, e.g., (Santschi et al. 1963; Chandler et al., 1975; Hanavan, 1964; NASA, 2000). In the "standing position" the individual stands erect with head oriented in the so-called Frankfort plane and with arms hanging naturally at the sides. Data for the mass-inertial parameters of the female human body in standing positions we are aware of is presented in Table 1. This table contain data for the center of mass in the corresponding posture of the body measured from the anthropometric point *vertex* of the head (the "x" coordinate) and from the sagittal plane through the middle of the body when in standing position.

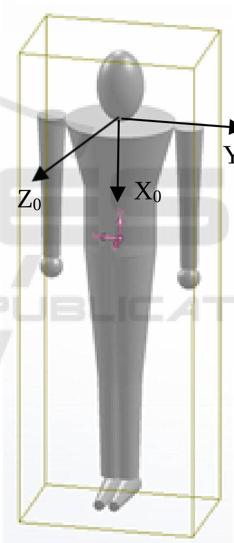

Figure 2: Standing position.

Table 1 also provides a comparison with the data we have obtained for the average Bulgarian female in this position with the corresponding data taken from the literature. Table 1 contains the data for the average height and mass of person in the corresponding study compared with the investigations of (Abraham et al., 1979) and (Young, 1983).

The inspection shows a reasonably good agreement between our results and those previously reported in the literature.

Table 1: Standing position.

	Young			**Abraham et al.**	**Our data**
	Min	Max	Mean		
I_{XX} [kg.cm^2]	5.8	24.0	11.6	-	6.7
I_{YY} [kg.cm^2]	49.1	135.0	85.0		78.3
I_{ZZ} [kg.cm^2]	53.0	135.0	91.9	-	81.9
Stature [cm]	161.20			162.60	160.51
Mass [kg]	63.90			64.64	60.65
Center of mass [cm]	-			-	67.3

3.2 Sitting, with Forearms Down

In the “sitting, with forearms down” position the segments of the body are as in “standing position”, except that the forearms are parallel to X-axis and the wrist axes are also parallel to X-axis, see. Fig. 3.

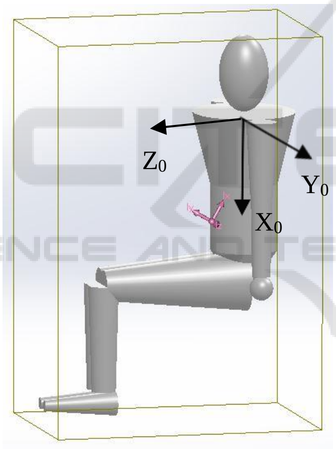

Figure 3: Sitting, forearms down.

Table 2: Sitting, forearms down.

Characteristic	**Our data**
I_{XX} [kg.cm^2]	13.0
I_{YY} [kg.cm^2]	56.8
I_{ZZ} [kg.cm^2]	59.5
Center of mass [cm]	60.7

Table 2 contains data for moments of inertia and center of mass [cm] of model of the body in the corresponding position.

3.3 Standing, Arms over Head Position

In the “Standing, arms over head” position, legs, torso, and head same as “Standing position”; upper extremities raised over head, parallel to X axis; wrist axes parallel to Y-axis; hands slightly clenched (see. Fig. 4). Table 3 contains data for moments of inertia and center of mass of model of the body in the corresponding position.

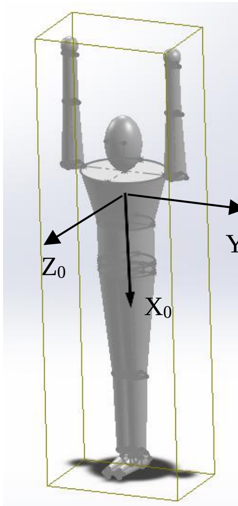

Figure 4: Standing, arms over head.

Table 3: Standing, arms over head.

Characteristic	**Our data**
I_{XX} [kg.cm^2]	67.1
I_{YY} [kg.cm^2]	99.8
I_{ZZ} [kg.cm^2]	103.3
Center of mass [cm]	63.0

3.4 Standing Position with Maximal Horizontal Span of Upper Extremities

The position shown on Fig. 5 is not one of the basic ones described in (Santschi et al. 1963; Chandler et al., 1975; Hanavan, 1964; NASA, 2000). It has been studied from (Hanavan, 1964), but only for men.

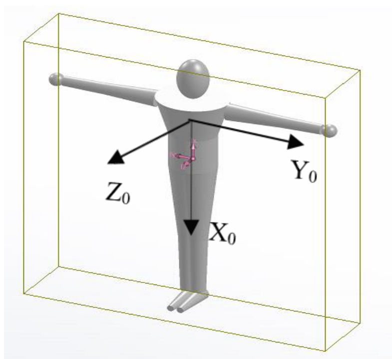

Figure 5: Standing position with maximal horizontal span of upper extremities.

We investigate it and think it would be useful in sports like figure skating etc. Table 4 contains data for moments of inertia and center of mass of model of the body in the corresponding position. The comparison of this data with the data from Table 1 shows that Ixx increases 10 times in position with maximal horizontal span of upper extremities in comparison with the standard standing position. The last implies that when skater suddenly contracts his upper limbs towards the body the angular speed of rotation will diminish also about 10 times from the initial angular speed. This is the scientific foundation for the effect, which the skaters are customarily using in figure skating nowadays and one enjoys on TV.

Table 4: Standing position with maximal horizontal span of upper extremities.

Characteristic	Our data
I_{XX} [kg.cm^2]	67.1
I_{YY} [kg.cm^2]	99.8
I_{ZZ} [kg.cm^2]	103.3
Center of mass [cm]	65.6

4 CONCLUSIONS

In the current paper a 16-segment biomechanical model of the human body of women is proposed and its 3D model realization in SolidWorks environment is performed. The specific geometrical realization reflects the “average” Bulgarian woman. Using the model, data for the mass-inertial characteristics of the body in its four basic positions have been obtained and compared, wherever possible, with those reported in the literature. Let us note that the model is suitable for the performance of static, kinematic and dynamic analysis. A modification of the model so that it can represent a specific individual is easily achievable by using the individual anthropometric dimensions for that particular person. The comparison performed between our model results and data reported in literature gives us confidence that this model could be reliably used to calculate the mass inertial characteristics at *any* specific posture of the body.

The model is applicable in rehabilitation robotics, computer simulations, medicine, sports, ergonomics, criminology and other areas.

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