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3D Model of the Human Body Generated within Pro/Engineer™ Environment

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1. Introduction

Knowledge of geometric (lengths, widths, circumferences, angles) and mass-inertial characteristics of the segments of the human body is of key importance in human motion analysis. Under "motion analysis" we understand not only the analysis of human walk characteristics and parameters (i.e. the application of action forces, the imposture of walk limitations, mass center position, body trajectory, body particular segments etc.) but also the set of modern problems of realistic computer animation and numerical simulation of motion.

Human motion analysis is of specific importance for areas such as simulation of the human behavior in space and in sports, design of impact protective transport systems, criminology, ergonomics, etc.

Motion data can also be used in anthropomorphic robotics and medicine (orthopedics, traumatology, orthotics and prosthesis design).

Besides the analysis of natural motion, the study of the joint functioning of human segments and orthopedic device also proves to be important for prosthetic design and orthotics, whereas an orthopedic device should have an appropriate geometry and suitable mass distribution.

Body parameters can be estimated in a number of different ways, including regression equations (Chandler et al. [1]), Clauser et al. [2]), body segment modeling as series of geometric solids (Hanavan [3], Hatze [4]), employment of medical imaging techniques /computerized tomography, magnetic resonance imaging/ (Mungiole, Martin [5]) etc.

Note however that the 3D models designed by using imaging techniques are not mobile, i.e., they do not change their shape in the course of time. Yet, considering a number of kinematical and dynamic biomechanical problems, mobility proves to be necessary. There are many approaches for the design of a solid model, providing indispensable joint movements. Models suggested in biomechanical literature often have 14, 15 and 16 segments based on left-right symmetry.

2. A simplified geometrical model of the human body

Our approach is based on a simplified 3D model of the human body that consists of 16 segments, assumed as relatively simple geometrical figures. We suppose full body symmetry with respect to the main plane, i.e. a complete “left-right” symmetry. The model is developed on the basis of a detailed representative anthropological investigation of the Bulgarian population (partially published in Yordanov et al. [6]) performed during the period 1989-1993. A total of 5289 individuals (2435 males and 2854 females) have been studied. We take the average values found and design a model representing an “average” male person with height 1.71 m, and mass 77.7 kg. Some model data, not available in Yordanov et al. [6] are taken from Toshev [7]. Table 1 presents the relevant body decomposition, the geometrical models of the individual segments, densities and masses.

Table 1. Geometrical parameters of body segments, body segment simplified models and segment densities and masses

Body segments	Model	Model parameters, m	Density*, kg/m^{3}	Mass**, kg
Head + Neck	Elliptical sphere	$R_{HE} = 0.156$ $r_{HE} = 0.078$	1087	5.0699
Upper torso	Reverted right elliptical cone	$L_1 = 0.153$ $R^* = 0.203$ $r^* = 0.176$ $R_1 = 0.150$ $r_1 = 0.130$	953	12.4317
Middle torso	Elliptical cylinder	$L_2 = 0.220$ $R_2 = 0.150$ $R_2 = 0.130$	953	12.8518
Lower torso	Elliptical cylinder + reverted elliptical cone	$L_3 = 0.146$ $R_3 = R_4 = 0.150$ $r_3 = r_4 = 0.130$ $L_4 = 0.013$	953	8.7429
Upper arm	Frustum of cone	$L_{UA} = 0.309$ $R_{SH} = 0.050$ $R_{EL} = 0.044$	1053	2.1268
Lower arm	Frustum of cone	$L_{LA} = 0.247$ $R_{EL} = 0.044$ $R_{WR} = 0.030$	1100	1.2463
Hand	Sphere	$R_{HA} = 0.047$	1137	0.4624
Hip	Frustum of cone	$L_{HI} = 0.510$ $R_{HI} = 0.095$ $R_{KN} = 0.055$	1062	11.0612
Shank	Frustum of cone	$L_{SH} = 0.372$ $R_{KN} = 0.055$ $R_{AN} = 0.04$	1088	3.2898
Foot	Frustum of cone	$L_{FO} = 0.263$ $R_{FO} = 0.046$ $R_{FE} = 0.018$	1092	1.0175

*Data according to Bjornstrup [9].

**Data found using the regression equations of ZatsIorsky [8].

Segment masses are estimated by means of the regression equations of Zatsiorsk [8] and our results are given in the last column of Table 1, accounting for a total mass of an average Bulgarian male person M = 77.7 kg. Based on the segment masses thus found, we optimize the anthropometric parameters of [6, 7] within a range of 10%, in order to attain a better agreement between the theoretically calculated values of segment masses and experimental data reported in literature, especially those published in [8].

These are the actual parameters that we further use in our model in order to calculate analytically segment mass center position and principal moments of inertia. The parameters thus found are given in column three of Table 1. The fourth column presents segment densities in kg/m^3, according to Bjornstrup [9]. Together with segment mass values given in [8], they are used to find segment volumes. The latter are compared to the analytically calculated volumes of the simple figures that model the segments, thus finding the parameters reported in column 3 of Table 1. For more details see Nikolova et al. [10].

3. Model generation in CAD Pro/Engineer™ environment

A 16-segment model of the human body is generated in Pro/Engineer™ environment (Fig. 1). The optimized anthropometric body dimensions (column 3 of Table 1) and density and mass given in the same table are used for the model design. Segments are linked to each other by means of hinges and spherical (ball) joints. Modeling of rotation elements (elliptical sphere – head, cone frustum– upper and lower limbs) is performed by using Revolve, the elliptical cylinders are build by means of Protrusion (middle torso) and the elliptical cone frustum is constructed using Blend Section. The lower body part is built using two functions – Protrusion and Blend sections and the design involves the following mobility degrees:

- Spherical joint (three degrees of freedom) – shoulder joint, hip joint, ankle-foot complex, wrist, neck, as well as links between the torso separate parts.
- Hinge joint (one degree of freedom) – knee and elbow joint. Joint axis limits corresponding to human limits are given in the Pro/Engineering Mechanism module.

The model thus designed can undergo a fast and easy modification introducing specific individual's dimensions. Depending on the model specific application, one can optimize dimensions with respect to mass and inertial moments.

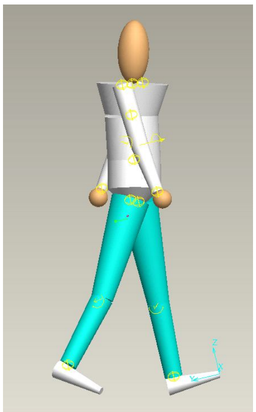

Fig.1. 3D human body model in Pro/Engineer environment

4. Estimation of the model mass-inertial characteristics

The Pro/Engineer model analysis of each part yields the following data:

- Volume and mass for given density;
- Position of the mass center;
- Inertial tensor with respect to a reference coordinate frame;
- Inertial tensor with respect to mass center (radius of gyration);
- Principal inertial moments and principal axis position;
- Rotation ellipsoid.

A comparison of the results found by using the present software and those of other methods (including analytical estimations and direct experimental studies) is done to confirm the correctness of the model generated. The model inertial moments calculated in CAD Pro/Engineer environment and experimental data published in literature are compared in Table 2 and good agreement is established. A system of axes with an origin at the segment mass center is defined for each segment. Those axes coincide with the approximate body axes: the saggital (x), the frontal (y) and the longitudinal (z) ones. Due to the $x – y$ symmetry assumed for the upper arm, forearm, hand, hip, shank and foot modeling, the principal inertial moments I_{XX} and I_{YY} are identical.

Table 2. Mass Inertial moments (MI) of the entire body and its segments through the mass center kg.cm^2

Human Parts	Chandler et al. [1]*			The model		
	MI around the saggital axis	MI around the transversal axis	MI around the longitudinal axis	MI around the saggital axis	MI around the transversal axis	MI around the longitudinal axis
Entire body	169 606.7	118 897.0	17 152.0	–	–	–
Head	170.8	163.8	200.8	262.9	262.9	105.1
Trunk	19 193.7	10 867.2	3 785.0	–	–	3 868.4
Upper arm	152.2/132.8	137.7/132.8	23.0/22.0	191.7	191.7	25.14
Lower arm	64.8/64.8	63.0/64.5	8.5/8.8	62.1	62.1	8.57
Hand	6.85/7.53	6.18/5.57	2.17/1.78	4.37	4.37	4.37
Hip	1151.5/1232.2	1221.3/1253.0	212.5/256.2	1 575.6	1 575.6	276.9
Shank	395.0/391.2	389.5/392.8	28.7/28.8	341.8	341.8	33.9
Foot	33.13/33.62	30.43/30.40	7.55/7.00	49.7	49.7	6.53

*Notation that the two numbers given correspond to the left and right body side.

5. Specificities of the model kinematics study in a Pro/Engineer™ environment

Knowing the low of motion of an end segment, the Pro/Engineer software package Mechanism Design Extension is capable of designing possible versions of intermediate segments. In the case of lower limb (hip and shank) modeling [7], a redundancy of the degrees of freedom is established – 7 DOF. The redundant degree of freedom enables the software to “commit” an error at a specific moment of time, where the intermediate segment position totally changes within two successive calculation steps. One can visually establish that fact inspecting the record. Since both neighboring positions are possible, the software does not generate an error message. This means that additional motion of the intermediate segments should be introduced between those two steps, in order to attain agreement with the two key positions. This however would yield increase of motion time. One could avoid the problem by modifying the initial conditions- either by changing the intermediate segment position or by specifying an initial velocity of some segment –the first segment (hip), preferably. However, the second option could produce a conflict between the possible solutions for the end segment and the specified motion law. The choice between one or another approach of avoiding the “jump” depends on a number of factors, whereas the decisive choice should consider the problem objective.

6. Conclusion

A 16-segment biomechanical model of the human body is proposed and 3D model realization in Pro/Engineering environment is performed. The model is suitable for the performance of static, kinematical and dynamic analysis. A modification for each specific case is possible by introducing individual dimensions. The model is applicable in anthropomorphic robotics design, computer simulations, medicine, sports and in other areas. In contrast to specialized systems for 3D biomechanics modeling, our model admit the test of new conceptual solutions and their implementation in the design of new sports equipment and medical auxiliary devices, employing codes of FE analysis.

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Тримерная модель человеческого тела, построенная в среде Pro/Engineer™

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(Резюме)

Основная идея настоящей работы, это построение простой, тримерной, сегментированной модели человеческого тела, основаной на данны антро-пометрии и биомеханики. Современная CAD система Pro/Engineer™ позволяет генерацию и анализ кинематики и динамики данной модели, в том числе и оценку масово-инерционных характеристик тела. Модель даёт возможности для компьютерной симмуляции и проектирования антропоморфических роботов, а также и возможности для применения в медицине.