15th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering
and
3rd Conference on Imaging and Visualization
CMBBE 2018
P. R. Fernandes and J. M. Tavares (Editors)

BASIC INERTIAL CHARACTERISTICS OF HUMAN BODY BY WALKING

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Keywords: Human body walking, Mass-inertial characteristics, Robotics, Simulations

Abstract: *Nowadays the interest to humanoid robots, exoskeletons, human – machine interface is steadily increasing. From mechanical point of view, human body is composed of links connected by joints to form a kinematic chain. In machines and mechanisms joints are typically rotary (revolute) or linear (prismatic). However, in the human body hips, say, are revolute joints and links are bones. In the current article we study the human gait. More specifically, mass-inertial properties in 8 phases of the human gait cycle of the average Bulgarian man are studied. In order to achieve this goal a geometrical model of a human body walking is proposed. Simulations of male walking are done with 3D CAD software to find out how mass-inertial characteristics and the position of the body's center of mass changes in each phase of walking. The model allows to perform both computer simulation and computer design oriented to medical applications (orthopedics, traumatology, orthotics and prosthetics design) and can be used for applications in anthropomorphic robotics. The model could also be of interest in design of wearable or rehabilitation robotics and in other areas.*

1 INTRODUCTION

During the last decades the interest to develop human like humanoid and wearable robots has been progressively increasing [1-11]. Some of the most popular and advanced humanoid robots are Geminoid HI-2, ERICA, Geminoid F, Geminoid DK [1-3]. Using advanced control, based on artificial intelligent algorithms, this type of robots is trying to copy and represent human motion, including walking, behavior and mimetic, as well as emotions [1-5]. Various research on wearable and rehabilitation robotics has been done recently [6-8]. A humanoid robot, WABIAN-2R, capable of human-like walk with stretched knees and heel-contact and toe-off motions is considered. Furthermore, a new algorithm for generating walking patterns with stretched knees and heel-contact and toe-off motions based on the ZMP criterion is defined in [9]. Furthermore, there are many humanoid walking robots such as NAO [10-13].

Exoskeletons are mainly used to support and rehabilitate dependents, as well as to human power strengthening. Over the last decade, due to the ever-increasing number of dependent people, they experienced a huge expansion, constantly attracting the attention of the scientific and medical community. Research in this area began in the 1960s and aimed to help dependent people by coupling the exoskeleton to their limbs in order to allow the user to regain natural movements [8]. The key problem when dealing with wearable exoskeletons concerns the interaction between wearer and the exoskeleton. In addition, this interaction requires the use of a model of exact inverse dynamics that turns out to be very sensitive to human anthropomorphic parameters [8].

From the mechanical engineering and biomechanical point of view, it is well known that the big bones and joints of human body could be represented by links and joints [14-16]. Therefore, to study human mechanics and motion we are able to represent human body as mechanism [14-16]. In this approach, human body is composed of links connected by joints to form a kinematic chain. Joints are typically rotary (revolute) or linear (prismatic). A revolute joint is like a hinge and allows relative rotation between two links [17].

In order to design and control properly walking robots similar to human, as well as the corresponding exoskeletons, it is necessary to know physical human properties such as geometry, mass, and inertial parameters of the segments of the human body. To analyze human walking first we need to know geometric and mass-inertial characteristics. In the present paper we study the changes of mass center and inertial characteristics of the average Bulgarian men during the walking. We have considered 8 distinct phases of human gait cycle, in accordance with the literature. First a model representing the mass and geometrical properties of the average Bulgarian men is introduced. It consists of 16-segments. After that, we derive a mathematical model describing mass inertial characteristics. Finally, simulations of human walking during the 8 phases have been done using 3D CAD software.

2 THE MODEL

We use a mathematical model of the human body that has been previously described in some details in Refs. [18, 19, 20]. There this model has been used to determine the mass inertial parameters of the different segments of the body. Here we only present some basic facts for the model used in the current study - see Fig.1.

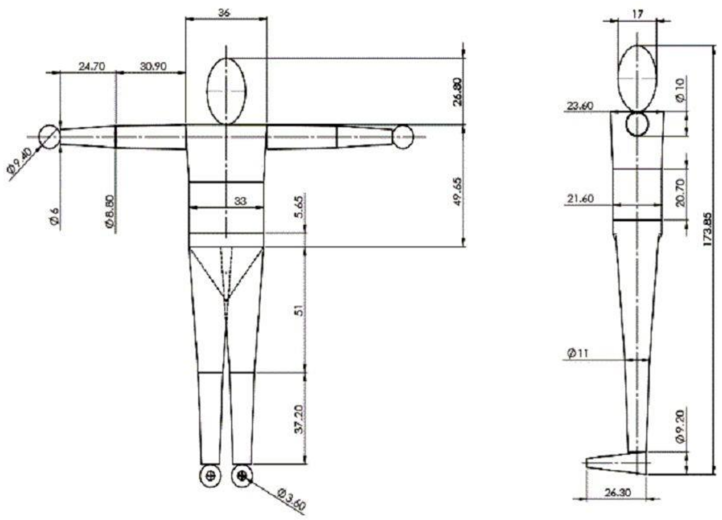


Figure 1: 16-segemental model of the human body and the corresponding dimensions.

The model consists of 16 segments defining: head + neck, upper, middle and lower part of torso, thigh, shank, foot, upper arm, lower arm and hand, assumed to be relatively simple geometrical bodies. We assume full body symmetry with respect to the sagittal plane.

The geometrical data needed is taken from a detailed anthropological investigation of the Bulgarian population [21]. Total of 2435 males were measured. We take the average values of the measured anthropometric parameters and design a model, which represents the so defined “average” Bulgarian male. After determining the mass inertial parameters of the segments, one can also study the corresponding characteristics of the total body assuming the body to be in a given position of interest. In order to achieve this goal, we have performed a realization of the model in CAD system – SolidWorks. We have verified the computer realization by comparing the results it delivers for the mass-inertial parameters of the segments of the body with those reported in [18].

In previous works of the current authors [19, 20] the mass-inertial characteristics in several basic positions of the body have been estimated and compared to literature sources concluding a reasonably good agreement. More specifically, data for the mass-inertial characteristics of the body in five of its basic positions have been obtained and compared with those reported in the literature. The comparison between our model results and data reported in literature gives us confidence that the model we generated can be used to calculate the mass inertial characteristics at any specific posture of the male body. This is way in the current study we will use the 3D CAD model obtained earlier to study also the changes of mass-inertial characteristics and position of mass center during the eight phases of human gait cycle.

2.1 Analytical model

After the geometrical parameters of the segments are determined, one can analytically obtain all the other characteristics of interest, such as volume, mass and moments of inertia. For instance, the inertial moments for a frustum of elliptic cone are given by the following equations:

$$I_{XX}=\frac{\pi}{240}h\rho\Big\{4h^2\big[r_1(2R_1+3R_2)+3r_2(R_1+4R_2)\big]+3\big[r_1^3\,(4R_1+R_2)+r_1^2r_2\,(3R_1+2R_2) \\ +r_1r_2^2\,(2R_1+3R_2)+r_2^3\,(R_1+4R_2)\big]\Big\}, \tag{1}$$

$$I_{YY}=\frac{\pi}{240}h\rho\Big\{4h^2\big[r_1(2R_1+3R_2)+3r_2(R_1+4R_2)\big]+3\big[r_1\,(4R_1^3+3R_1^2R_2+2R_1R_2^2+R_2^3) \\ +r_2\,(R_1^3+2R_1^2R_2+3R_1R_2^2+4R_2^3)\big]\Big\}, \tag{2}$$

$$I_{ZZ}=\frac{\pi}{80}h\rho\Big\{r_1^3\,(4R_1+R_2)+r_1^2r_2(3R_1+2R_2)+r_1\big[4R_1^3+3R_1^2R_2+3r_2^2R_2+R_2^3+2R_1\left(r_2^2+R_2^2\right)\big] \\ +r^2\big[R_1^3+2R_1^2R_2+4R_2(r_2^2+R_2^2)+R_1\,(r_2^2+3R_2^2)\big]\Big\}. \tag{3}$$

Using these equations, one finds, e.g., the moments of inertia of the lower torso:

$$I_{XX}=\pi rR\rho\left[L_3\left(\frac{1}{4}r^2+\frac{1}{3}L_3^2\right)+\frac{1}{3}L_4\left(L_3^2+\frac{1}{2}L_4L_3+\frac{1}{10}L_4^2\right)\right] \tag{4}$$

$$I_{YY} = \pi r R \rho \left[L_3 \left(\frac{1}{4} R^2 + \frac{1}{3} L_3^2 \right) + \frac{1}{3} L_4 \left(L_4^2 + \frac{1}{2} L_3 L_4 + \frac{1}{10} L_4^2 \right) \right] \tag{5}$$

$$I_{ZZ} = \rho \frac{\pi}{4} r R \left(r^2 + R^2 \right) \left(L_3 + \frac{1}{5} L_4 \right) \tag{6}$$

where $R = R_3 = R_4$ and $r = r_3 = r_4$.

Expressions (1) - (6) can be easily assessed numerically and the principal moments of inertia for the upper, middle and lower torso can be found using Steiner's theorem.

As it is clear from the above expressions, when performing the calculations, a system of axes has been defined for each segment. It is taken to have its origin at the segment mass center, while the axes have been aligned with approximate body axes: frontal (x), sagittal (y), and longitudinal (z). After determining the mass inertial parameters of the segments, one can also study the corresponding characteristics of the total body assuming the body to be in a given position of interest.

3 MASS-INERTIAL CHARACTERISTICS OF THE MODEL DURING WALKING

One field of biomechanics research, gait analysis, or motion analysis of human gait, has evolved since the early 19th-century. Human motion analysis is commonly used today for both clinical and research applications. The art and science of motion analysis extends beyond the outline descriptions of ambulatory models to include front-line clinical roles in the rehabilitation surgery, prosthesis, orthosis, ergonomics and athletics. The conjunction of cautious clinical evaluation and motion analysis can be a powerful tool for the clinician or researcher [22].

Gait analysis has also proved useful in the study of various areas such as neuromuscular disorders [23,24], the evaluation of prosthetic joint replacement [25,26], the study of athletic injuries [27,28], amputees [29,30], orthotics [31,32], assistive devices [33], and sports [34-36].

In recent decades, advances in new technologies have led to the use of different methods for assessing human gait: i) image processing: such as laser range scanner [37], time-of-flight methods [38], etc.; ii) floor sensors: force platforms and pressure measurement systems [39]; iii) sensors placed on the body or wearable sensors: they include force sensors, accelerometers, gyroscopes, extensometers, inclinometers, goniometers, active markers, electromyography, etc. [40].

There are different variations in the descriptions of the phases of the gait cycle during walking. The gait is normally considered as a sequel of periodic actions. One usually defines the gait cycle as the period from heel contact of one foot (for example, the right foot) to the next heel contact of the same foot.

In our study according to the literature we use the so-called new gait terms involving the following eight phases: 1) initial contact; 2) loading response; 3) midstance; 4) terminal stance; 5) pre swing; 6) initial swing; 7) mid swing; 8) late swing, see Figure 2.

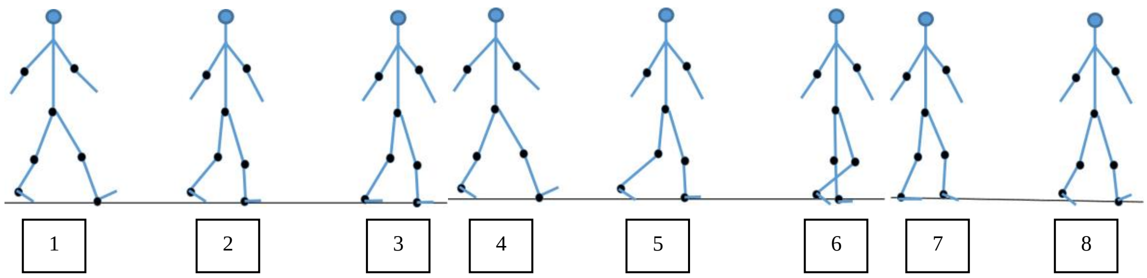


Figure 2: The eight phases of human gait cycle.

In Table 2 the joint angles of the lower extremity of the body (hip, knee and ankle angle) during the eight phases of human gait cycle used in our study are given.

Gait phases of human gait cycle	Initial contact	Loading response	Mid stance	Terminal stance	Pre Swing	Initial Swing	Mid Swing	Terminal Swing
Hip	20°	20°	0°	-20°	-10°	15°	25°	20°
Knee	0°-5°	20°	0°-5°	0°-5°	40°	60°-70°	25°	0°-5°
Ankle joint	0°	5°-10°	5°	10°	15°	5°	0°	0°

Table 1: Joint angles in gait cycle.

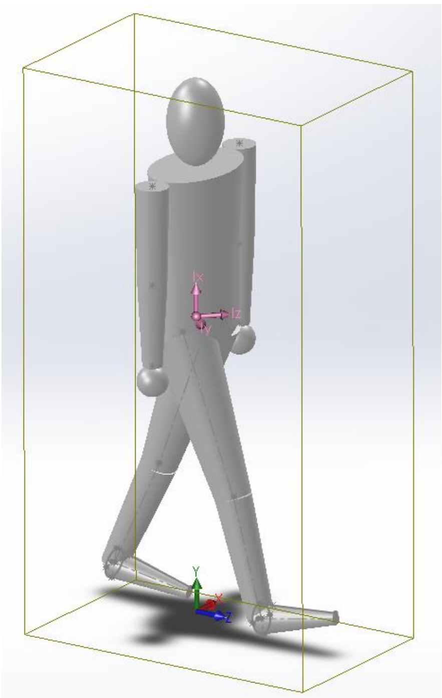
3.1 CAD Simulations

Based on our 16-segmental mathematical model of the human body described above in Section 2, we have generated 3D models using CAD software SolidWorks.

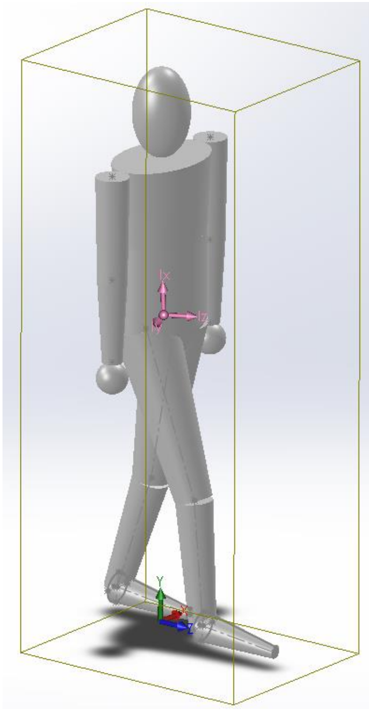
We introduce the model elements in SolidWorks medium as an aggregate of features. Each component is an independent 3D object, having different parameters and topology characteristics. We characterize each segment by its dimensions and density. The software calculates the segment volume, mass, surface area, position of the mass center, principal moments of inertia and the inertial tensor. Thus, the human body model is accomplished and the mass characteristics with respect to right-handed Cartesian coordinate frame oriented at its center of mass are determined.

As already stated above, the so computer-generated model is verified by comparing its results with those reported in [18] for the different segments of the body. The program reproduces segment-by-segment data about volume, mass, center of mass and moments of inertia. That gives us confidence that this model could be used to calculate these characteristics at different phases of human gait cycle.

Using the created 3D models of the human body in SolidWorks medium the mass-inertial characteristics of average Bulgarian men during the eight phases of human gait cycle is studied. 3D human body model in SolidWorks medium recreating phase 1 – initial contact and phase 3 – mid stance of human gait cycle is visualized in Figure 3. The phases 5 – pre-swing and 6 – initial swing of human gait cycle are shown on Figure 4.

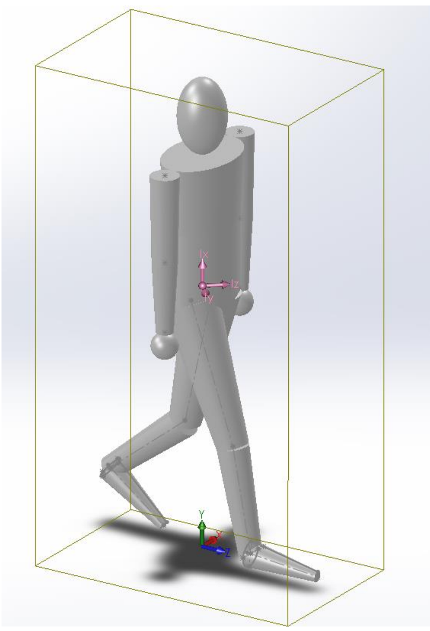


Phase 1 - Initial contact

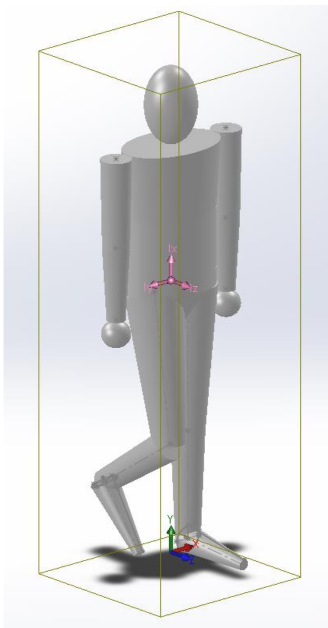


Phase 3 – Mid stance

Figure 3: 3D human body model in SolidWorks medium in phase 1 – initial contact and phase 3 – mid stance of human gait cycle.



Phase 5 - Pre-Swing



Phase 6 – Initial Swing

Figure 4: 3D human body model in SolidWorks medium in phase 5 – pre-swing and phase 6 – initial swing of human gait cycle.

The results obtained for principal moments of inertia [$kg.cm^2x10^3$], taken at the center of mass of the human body model, as well as the coordinates of the mass center [cm] are given in Table 2.

Gait phases of human gait cycle	**Initial contact**	**Loading response**	**Mid stance**	**Terminal stance**	**Pre Swing**	**Initial Swing**	**Mid Swing**	**Terminal Swing**
I_X [$kg.cm^2x10^3$]	16,12	16.55	13	17,38	15,67	10,45	13,02	16
I_Y [$kg.cm^2x10^3$]	101,06	100,44	102,78	99,92	100,48	99,71	103	102
I_Z [$kg.cm^2x10^3$]	105,74	105,23	107,51	105,07	104,76	105,58	108,2	105
The coordinates of the Mass Center [cm]	x= 0 **y=91,3** z=0,1	x= 0 **y=92,7** z=-0,4	x=0 **y=92** z=0,1	x=0 **y=90** z=-0,1	x=0 **y=92,4** z=0,1	x=0 **y=93,8** z=0,1	x=0 **y=92** z=0,1	x= 0 **y=91,3** z=0,1

Table 2: Mass inertial characteristics of avarage Bulgarian man in gait cycle.

The position of the body's centre of mass is a key factor in the analysis of human gait, as it reflects the motion of the whole body. Obviously, the knowledge of the three-dimensional movements of body mass centre, is prerequisite for calculation of walking parameters and design of artificial joints, or for other practical applications. In calculating the actual positions of the centre of mass one shall take into account the full body kinematics combined with the use of the proper anthropometric data. In the most straightforward approach the human body could be considered as a system of rigid segments. This greatly simplifies the calculations.

The center of the mass is located around the center of the pelvis and performs a sinusoidal motion with risings and fallings about 5 cm in vertical direction during walking, as shown in Figure 5.

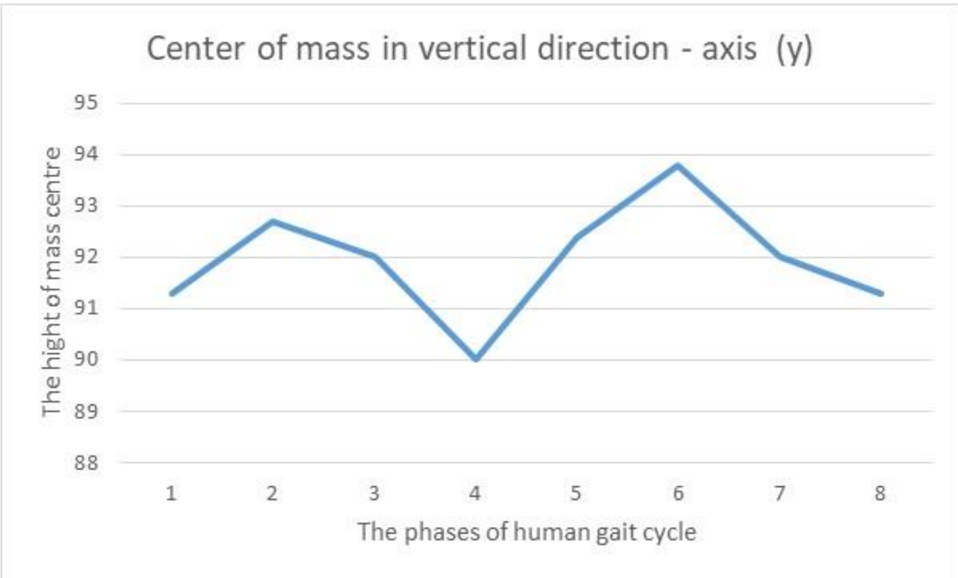


Figure 5: Vertical displacement of the center of mass [cm] of the body during walking.

4 CONCLUSIONS

This paper studies the mass-inertial characteristics of the average Bulgarian male in a gate cycle model. Also, the three-dimensional movements of body mass center during walking is investigated. The gate cycle is divided into 8 phases in accordance with the literature. The study could be beneficial for dependent people who need exoskeletons or orthopedic and prosthetic equipment for rehabilitation. The model and the mass-inertial characteristics obtained may be applied also in the study of athletic injuries, ergonomics and sports. Moreover, the results of this paper can be used later on to study the gait dynamics of a model of an average Bulgarian male.

The financial support by the Bulgarian National Science Fund: Contract DN-07/5 “Study of anthropometric and mass-inertial characteristics of the Bulgarian men and women via mathematical models of the human body” is gratefully acknowledged.

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