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Mathematical modelling of basic anthropometric and mass inertial characteristics of young tennis players versus nonplayers: I case study for Bulgarian boys

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Abstract

Sport has a profound impact on the development of teenagers, contributing to their physical health, psychological well-being, character building, and social interactions. In the current article, we report results from the anthropometric measurement of 43 boys tennis players (BTP) and 55 non-players (BN) 14-17 years old. We determine the average mass and height of each group and generate a mathematical 3D model of the so-defined average tennis player (ATP) and nonplayer (ANP). Within the model, every segment of the body is represented via a 3D geometrical body. Using the analytical properties of these bodies we determine the mass of each segment, its center of mass and the principal moments of inertia. We compare the results of both groups trying to elucidate the influence of the sport on the physical development the teenage players 14-17 years old. We hope our study will encourage teenagers to participate in sports activities, whether competitively or recreationally.

Keywords: Human body modelling, boys tennis players, mass-inertial parameters, anthropometry

1. Introduction

The assessment of the physical development of the population is a basic element of the monitoring of their health status [1]. Of great interest to specialists from various scientific fields is the assessment of physical development in the periods of childhood and adolescence, when growth and development processes are most intense [2]. Even though morphological features are genetically determined, external factors, such as socio-economic, geographical-territorial, household, labour and sports activities, etc., have a great impact on them [3,4,5,6]. Body height and weight, circumferences and widths of the body are anthropometric characteristics exhibiting great adaptive potential, therefore their characteristics vary significantly during the period of childhood and adolescence.

The anthropometric characteristic is an important marker for the selection of athletes in each discipline, as well as for their proper physical development at each stage of their sports practice [7,8]. Santos et al. [9], performed detailed anthropometric characteristics of athletes practising 21 types of sports and developed normative values for the investigated characteristics (height, weight, body mass index, circumferences and skinfolds of the body and limbs). Significant gender differences were observed in athletes from each sport, which vary by type of sports activity. Assessing the morphological profile in 8-14-year-old tennis players, with a sports experience of at least one year, Girard and Millet [10] found that tennis had a beneficial effect on the physical development and health status of adolescent athletes, expressed in higher values of height and normal maintenance of body weight, highlighting the osteogenic influence of it. Nacheva et al. [11] established the most significant sexual differences at the age of 14-17 years in the following anthropometric characteristics: the diameters of the chest and pelvis; and the circumferences of the chest, abdomen and waist.

The accurate determination of anthropometric and mass-inertial characteristics is a problem of crucial importance to sports biomechanics research.

In the current study, we presented a 3D mathematical model of the ATP and ANP aged 14-17 years, which provides a possibility to calculate the mass-inertial parameters of all segments of the body. We compare the findings from the two groups in an effort to clarify how the sport affects the physical growth of adolescent players.

2. **Model and Method**

This study was conducted during the period 2016-2018 in tennis clubs and primary schools in Sofia, Bulgaria. The sample includes 98 adolescent boys (43 tennis players and 55 boys, who not doing any sports, as a control group) aged 14-17 years. All boys and their parents completed informed consent and voluntarily participated in the study. The study protocol was reviewed and approved by the Ethical Committee of the Institute of Experimental Morphology, Pathology and Anthropology with Museum - Bulgarian Academy of Sciences (Protocol № 8/12.11.2018) and was prepared in agreement with the principles stated in the Declaration of Helsinki for human studies [12]. The classical methodology of Martin-Saller's was used for measuring the following anthropometric dimensions: body height, body weight, lengths, diameters, and circumferences of the body and limbs. Body lengths are defined as projections between the distances of specific anthropometric points according to the anthropometric methodology.

The proposed 3D mathematical model of the human body used in the current study is made up of 16 segments following the anthropometric points used by Zatsiorsky [13] (singular: head + neck, the upper part of the torso, the middle part of the torso, the lower part of the torso, and double: thigh, shank, foot, upper arm, lower arm, and hand), all of which are meant to be shaped using relatively simple geometrical figures (see Fig.1). In terms of the sagittal plane, we presupposed complete "left-right" symmetry or full body symmetry.

We take the average values from our anthropometric investigation and design a model, which represents the so-defined ATP and ANP. For instance, it turns out that the ATP is 1.74 m tall and weighs 60.5 kg, while the ANP is 1.71 m tall and weighs 68.5 kg.

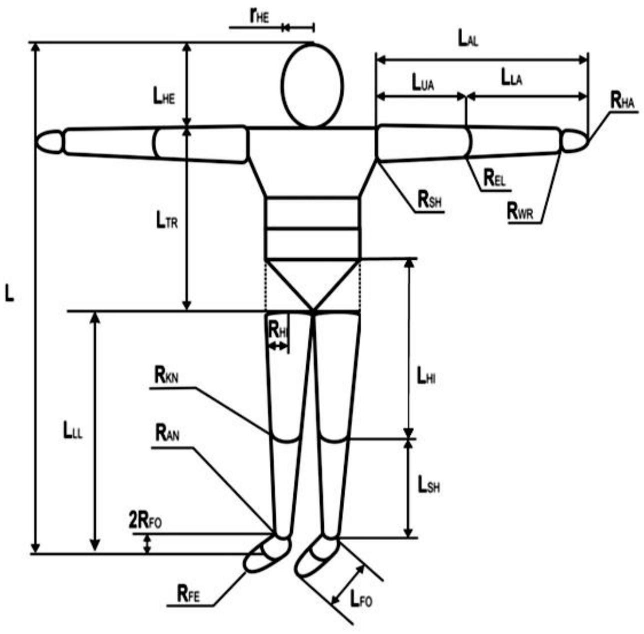

Fig. 1 Mathematical model of the human body

Table 1
Geometrical parameters of the segments of the body, their approximations via geometrical bodies, as well as the densities of the different segments of 14-17 years boys tennis players and nonplayers

Body segments	Anthropometric parameters Boys Tennis Players [cm]	Anthropometric parameters Boys Nonplayers [cm]	Density [kg/m^3]
Head + Neck (Ellipsoid)	R_{HE} = 16.3 r_{HE} = 7.3	R_{HE} =15.5 r_{HE} = 7.4	1087
Upper torso (Reverted right elliptical cone)	L_{TR}= 41.6 L_1 = 13.9 R^*= 18.1 r^* = 11.5 R_1 = 12.9 r_1 = 8.2	L_{TR}= 42.8 L_1 = 14.3 R^* = 18.7 r^* = 12.1 R_1 = 13.5 r_1 = 8.8	908
Middle torso (Elliptical cylinder)	L_2 = 14.5 R_2 = 12.9 r_2 = 8.2	L_2 = 14.9 R_2 = 13.5 r_2 = 8.8	1043
Lower torso (Elliptical cylinder+ reverted elliptical cone)	L_3 =6.9 L_4= 7.9 R_3= 12.9 R_4= 12.9 r_3 = 8.2 r_4 = 8.2	L_3 = 7.1 L_4 = 8.1 R_3= 13.5 R_4 = 13.5 r_3 = 8.8 r_4 = 8.8	1077
Upper arm (Frustum of a cone)	L_{UA} = 30.5 R_{SH} = 4.0 R_{EL} = 2.3	L_{UA} = 30.8 R_{SH} = 4.0 R_{EL} = 2.3	1053
Lower arm (Frustum of a cone)	L_{LA} = 25.7 R_{EL} = 4.0 R_{WR} = 2.6	L_{LA} = 25.9 R_{EL} = 4.0 R_{WR} = 2.6	1100
Hand (Sphere)	R_{HA} = 4.1	R_{HA} = 4.0	1137
Thigh (Frustum of a cone)	L_{TH} = 52.0 R_{TH} = 8.0 R_{KN} = 3.7	L_{TH} = 51.0 R_{TH} = 8.6 R_{KN} = 3.8	1062
Shank (Frustum of a cone)	L_{SK} = 40.2 R_{KN} = 3.7 R_{AN} = 3.6	L_{SK} = 39.3 R_{KN} = 3.8 R_{AN} = 3.8	1088
Foot (Frustum of a cone)	L_{FO} = 24.5 R_{FO} = 3.7 R_{FE} = 1.8	L_{FO} = 24.2 R_{FO} = 3.8 R_{FE} = 1.8	1092
Body height	174.24±7.75	171.99±7.35	
Body mass	60.46±8.11	68.47±1.99	

*Indexes: HE – head; TR – torso; TH – thigh; SK – shank; KN – knee; AN – ankle; FO – foot; FE – feet; UA – upper arm; LA – lower arm; SH – shoulder; EL – elbow; WR – wrist; HA – hand.

Table 1 provides an explanation of the specific segment geometrical models, their characterizing parameters, and the appropriate notations to be utilized moving forward.

Table 1 also provides the heights of the studied boys with the corresponding standard deviations. In the last column, the accordant densities of the different segments [14], as well as those of the individual parts of the torso [15], are also given. We refer the reader interested in specifics to [16] for an explanation of how we reached the numerical values of the geometrical parameters, selected the anthropometric landmarks, modelled the segments, etc. In Fig. 1, as well as in Table 1, abbreviations mean, respectively L

- the length of the corresponding segment, R - the large radius of the corresponding geometric figures, r - the small radius, of the corresponding geometric figures.

2.1. Volume and Mass of the Segments

Using the formulas for the corresponding geometrical bodies we obtain the volumes of the different segments.

For instance, the volume of the three parts of the torso can be determined using the following three equations.

- The upper torso volume is

(1) $$V = \frac{1}{3}\pi L_1 \left[r \quad R \quad + \frac{r \quad R \quad - r_1 R_1}{R \quad / R_1 - 1} \right]$$

- that of the middle torso is

(2) $$V = \pi r_2 R_2 L_2 \,,$$

- and the lower torso volume is

(3) $$V = \pi r R \left(L_3 + \frac{1}{3} L_4 \right)$$

Table 2 provides the data for the volumes of the different segments for the two groups under study.

Once we know the segments' volumes and the corresponding mass density of a given segment taken from the experiment, we calculate the masses of the segments (see Table 3).

Table 2
Volumes of the entire body and its segments, in [10^{-3} m^3], for tennis players and nonplayers

Segment	Tennis players	Nonplayers
Head + Neck	3.6	3.5
Torso	14.7	16.9
Upper arm	1.5	1.5
Lower arm	0.9	0.9
Hand	0.3	0.3
Thigh	5.8	6.5
Shank	1.7	1.7
Foot	0.6	0.6

Table 3
The mass of the segments [kg] for tennis players and nonplayers

Segment	Tennis Players	Nonplayers
Head + Neck	3.95	3.86
Torso	14.55	16.69
Upper arm	1.61	1.63
Lower arm	0.98	0.98
Hand	0.33	0.30
Thigh	6.20	6.86
Shank	1.83	1.93
Foot	0.63	0.67

2.2. Centre of Mass of the Segments

Finally, we calculated analytically and estimated numerically the positions of the mass centres of different segments and the segment's principal moments of inertia. The corresponding result for the position of the mass centre, measured from the upper cross-section of that segment, is directly following from the expression:

$$M_{CM} = h\frac{\frac{1}{4}R^2 + \frac{1}{2} + \frac{3}{4}r^2}{R^2 + Rr + r^2} \quad (4)$$

used for the upper and lower arm, thigh, shank and foot, which are modelled as a frustum of a cone with upper radius R and lower radius r.

The centres of mass of all the segments of the body we obtain using, e.g., Eq (4). Table 4 gives the relative locations of the centres of mass (the ratio between the distance from the proximal end of the segment and the length of the segment).

Table 4
Relative location of the centre of mass of the body segments, i.e., the ratio between the distance from the proximal end of the segment and the length of the segment in percents [%], for tennis players and nonplayers.

Segment	Tennis players	Nonplayers
Head +Neck	50.0	50.0
Torso	42.6	42.8
Upper arm	50.0	50.0
Lower arm	43.0	43.0
Hand	50.0	50.0
Thigh	38.2	37.7
Shank	49.5	50.0
Foot	38.9	38.6

2.3. Inertial Characteristics

For the calculation of inertial parameters, we start with the definition of the inertial tensor of any 3D body. Here one supposes a general laboratory coordinate, where the integrals run over, and denotes here the part of the space occupied by the 3D body:

$$\hat{I} = \begin{pmatrix} \iiint_V \rho(\vec{r})(y^2+z^2)d\vec{r} & -\iiint_V \rho(\vec{r})(xy)d\vec{r} & -\iiint_V \rho(\vec{r})(xz)d\vec{r} \\ -\iiint_V \rho(\vec{r})(yx)d\vec{r} & \iiint_V \rho(\vec{r})(x^2+z^2)d\vec{r} & -\iiint_V \rho(\vec{r})(yz)d\vec{r} \\ -\iiint_V \rho(\vec{r})(zx)d\vec{r} & -\iiint_V \rho(\vec{r})(zy)d\vec{r} & \iiint_V \rho(\vec{r})(x^2+y^2)d\vec{r} \end{pmatrix} \quad (5)$$

When relatively simple geometrical bodies are used in modelling the different segments of the body the above calculations greatly simplify. Of course, for very simple bodies, such as spheres, cylinders, and ellipsoids, the corresponding expressions for the principal moments of inertia can be directly found in the literature [17], where we have:

- for a sphere with radius R and mass μ

$$I_{XX} = I_{YY} = I_{ZZ} = \frac{2}{5}\mu R^2 \quad (6)$$

- for a cylinder with radius R, height h and mass μ

$$I_{XX} = I_{YY} = \frac{1}{4}\mu\left(R^2 + \frac{h^2}{3}\right), I_{ZZ} = \frac{1}{2}\mu R^2 \quad (7)$$

- for an ellipsoid with semi-axes a,b,c and total mass μ

$$I_{XX} = \frac{\mu}{5}(b^2 + c^2), \quad I_{YY} = \frac{\mu}{5}(a^2 + c^2), \quad I_{ZZ} = \frac{\mu}{5}(a^2 + b^2) \quad (8)$$

Table 5 shows the results for the principal moments of inertia of all body segments for tennis players and non-players, respectively.

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

Table 5
Moments of inertia of the body segments through the centre of mass [kg.cm^2] for tennis players and nonplayers.

	Tennis players			**Nonplayers**		
Segment	I_{XX}	I_{YY}	I_{ZZ}	I_{XX}	I_{YY}	I_{ZZ}
Head + Neck	252.3	252.3	84.3.5	228.0	228.0	84.7
Upper torso	250.1.8	479.7	539.4.0	315.0	585.2	669.7
Middle torso	172.5	297.1	293.6	219.6	371.6	376.6
Lower torso	73.6	134.8	80.7	94.3	169.1	103.2
Upper arm	131.6	131.6	12.9	135.4	135.4	13.0
Lower arm	54.4	54.4	5.7	55.6	55.6	5.8
Hand	2.2	2.2	2.2	2.0	2.0	2.0
Thigh	1280.0	1280.0	129.4	1357.4	1357.4	164.0
Shank	252.6	252.6	12.2	256.6	256.6	14.0
Foot	26.9	26.9	2.8	29.5	29.5	3.2

3. Discussion and Conclusions

We set forth a simple 3D mathematical model of the human body, representative of the ATP and ANP. Based on our own anthropometric data, we find the geometrical parameters of the body segments which have been approximated by relatively simple geometrical bodies. Using the model thus designed, we derive analytically and estimate numerically the positions of the segment mass centres, as well as their inertial characteristics.

It's important to note that tennis technique and strategy involve a combination of factors, including footwork, stroke mechanics, timing, and coordination. While inertial moments of the body are significant, they interact with other elements of the game to produce effective and efficient shots. Skilful players often train to optimize their body's moments of inertia, movement patterns, and coordination to enhance their overall performance on the tennis court.

From the anthropometric measurements made, it can be seen that tennis players are 3 cm taller and eight kilograms thinner than nonplayers. From the obtained results, it can be seen that the moments of inertia of the non-player group are larger than that of the tennis players, due to the different mass distribution in segments. Moments of inertia determine how resistant an object or body is to changes in its rotational motion. Having a lower moment of inertia allows athletes to maintain control during complex movements. Moments of inertia influence how quickly or slowly the body can rotate and affect the rate at which angular momentum is generated, thus lower moments allow for quicker spins, flips, or directional changes.

Understanding the principles of rotational motion and how moments of inertia influence movement can help athletes execute complex manoeuvres with greater efficiency and control.

Sport plays a significant role in the overall development of adolescents, contributing to their physical, psychological, and social well-being. Engaging in sports activities during adolescence not only promotes physical fitness but also instils essential life skills, cultivates character traits, and fosters social interactions.

Adolescence is a crucial period for physical development, and engaging in sports activities aids in the development of motor skills, coordination, and physical strength. Sports enhance cardiovascular health, muscular endurance, and flexibility, reducing the risk of obesity and chronic diseases later in life. By encouraging teenagers to maintain a healthy body weight and adopt healthy habits, sport serves as a powerful tool for combating sedentary lifestyles and promoting lifelong physical well-being.

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