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Center of Mass of Human's Body Segments

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In biomechanics, determination of the body's center of mass has always been an important part of many biomechanical studies. However, it is always a challenge to find it and often obtained results are only estimations, guesses. Indeed, to find someone's body center of mass isn't as easy as finding center of mass of simple rigid objects with uniform density, where it usually could be found at the centroid. The human body is different according to the gender, the age, the ethnicity, the physical shape, body fat distribution, etc. As it is composed of bones and muscles, results may differ drastically depending on which muscles are tense or on the body positioning.
Nowadays, as a new era of biomechanics is approaching with a superior kind of prosthesis or exoskeletons that calls upon an "augmented humanity", or even with gait modelling. It is important to find an experimental method that gives precise positioning of such an important data as the center of gravity of body segments, widely available to scientists that would need to go further in their researches, without having to use sophisticated equipment or time-consuming methods.

Keywords: biomechanics, center of mass, segmentation method, body segments parameters.

1. Introduction

1.1. *Positioning the Center of Gravity of body's segments*

The aim of work presented in this paper is to find an experimental way to approximate the center of gravity of body segments (which will be from now referred as COG) using common, modified du Bois-Reymond method and results from previous studies. During its realization, assumptions were made, in order to simplify experimental procedure and equations. They are as follow:

1. Mass repartition remains unchanged and volume of muscles is constant regardless of the position of the body
2. Body is assumed to be symmetrical to the sagittal plane and divided into eight segments: head with neck, trunk, upper arm, forearm, hand, thigh, shank and foot; similar to the Zatsiorsky segmentation method, beginning and the end of each segment – according to the aforementioned method.
3. Anatomy remains unchanged regardless of the position of the body. In consequence, the considered beginning and end of body segments remains the same, giving the same spread whatever the position of the body.
4. The center of mass (COM) is the same as the center of gravity (COG) (in a uniform field of gravity)
5. COG positions in the plane perpendicular to the main axis of the segment influences are not taken into consideration and it is assumed at first that they remain in the middle distance of the segment of their respective axis.

1.2. *State of art*

3D Photogrammetry is used in some methods like in [1], involving many cameras, to determine the center on mass of the segments. The process accuracy can be adjusted according to the meshing accuracy realized during post-processing. These techniques don't take into account the difference of density of the body tissues.
In 1990 Zatsiorsky et. al. has determined the Center of Mass for different segments of human body. Each segment of the human body was divided according to the bony landmarks defined by Zatsiorsky (see Figure 1). Data used for this operation was collected via means of gamma ray scanning and the measurements were done on 100 male and 15 female Caucasian subjects, which age was between 19 and 25 years old [2, 3].
In 1993 de Leva has observed that data provided by Zatsiorsky leads to huge errors in the body COM calculation of USA college athletes. The source of those errors was caused by the method of body segmentation, specifically by setting the reference points at bony landmarks. To obtain more precise results de Leva has decided to change the reference points from bony landmarks to the axis of rotation of body segments [3]. To simulate the kinematic and dynamic behaviour of the body in movement, the body should be simulated. Methods of segmentation allows the body to be modelled as connected segments reduced to their center of mass.

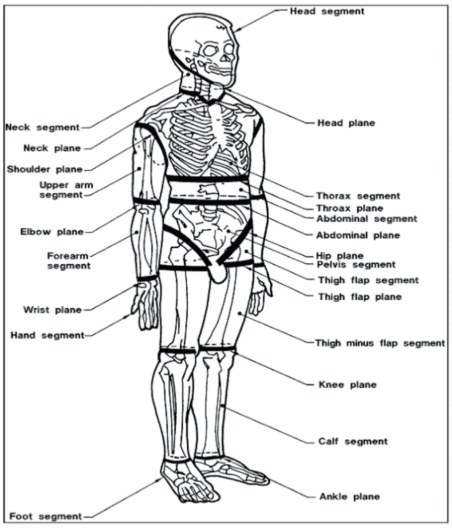


Figure 1 Segmentation of human body according to Zatsiorsky [3]

Table 1 was excerpted from de Leva body segment parameters (BSP) [5]. It is designed to describe body segment mass as a proportion of total body mass and the location of each segment's center of mass as a proportion of segment length. These ratios are Zatsiorsky's ratios corrected by De Leva and are considered by the biomechanical community as the most accurate ones.

1.3. *Aim and hypothesis*

The aim of this research is to establish a convenient method to determine the center of mass of each segment of a body, using Zatsiorsky and de Leva segmentation method. However, with simple and quick method that is provided by modified du Bois-Reymond method.

Zatsiorsky and de Leva segmentation methods have been developed to estimate statistically the mass and position of the center of mass of the considered segments.

Unfortunately, data from these methods was not accurate for every range of parameters, like for obese subjects. These methods have been established using a restricted sample of people to gather data, and extrapolation of the data from this data to other types of body occurs to generate significant error. Therefore, they are for the authors potentially exposed to not being accurate enough for characterisation of all body types.

Other ways allow to determine the COM of segments of a body, but they are based on the use of high-technology equipment. It allows to attain accurate data, but requires also time and money, in such extend that it does not always fit for acquisition of data, for large amount of people, or research projects with limited means. These results are supposed to be close to the ones presented by De Leva and Zatsiorsky.

Table 1. Body segment parameter data from Zatsiorsky et al. (1990), as modified by de Leva (1996) [5]

Segment	Endpoint		Mass (%mass)		CM (%length)		Sagittal k (%length)		Transverse k (%length)		Longitudinal k (%length)	
	proximal	distal	female	male	female	male	female	male	female	male	female	male
Head	VERT	MIDG	6.68	6.94	58.94	59.76	33.0	36.2	35.9	37.6	31.8	31.2
	VERT	CERV	6.68	6.94	58.94	59.76	27.1	30.3	29.5	31.5	26.1	26.1
Trunk	SUPR	MIDH	42.57	43.46	41.51	44.86	35.7	37.2	33.9	34.7	17.1	19.1
	CERV	MIDH	42.57	43.46	41.51	44.86	30.7	32.8	29.2	30.6	14.7	16.9
	MIDS	MIDH	42.57	43.46	41.51	44.86	37.9	38.4	36.1	35.8	18.2	19.7
Upper Trunk	SUPR	XYPH	15.45	15.96	20.77	29.99	74.6	71.6	50.2	45.4	71.8	65.9
	CERV	XYPH	15.45	15.96	20.77	29.99	46.6	50.5	31.4	32.0	44.9	46.5
Mid Trunk	XYPH	OMPH	14.65	16.33	45.12	45.02	43.3	48.2	35.4	38.3	41.5	46.8
Lower Trunk	OMPH	MIDH	12.47	11.17	49.20	61.15	43.3	61.5	40.2	55.1	44.4	58.7
Upper Arm	SJC	EJC	2.55	2.71	57.54	57.72	27.8	28.5	26.0	26.9	14.8	15.8
Forearm	EJC	WJC	1.38	1.62	45.59	45.74	26.1	27.6	25.7	26.5	9.4	12.1
	EJC	STYL	1.38	1.62	45.59	45.74	26.3	27.8	25.9	26.7	9.5	12.2
Hand	WJC	MET3	0.56	0.61	74.74	79.00	53.1	62.8	45.4	51.3	33.5	40.1
	WJC	DAC3	0.56	0.61	74.74	79.00	24.4	28.8	20.8	23.5	15.4	18.4
	STYL	DAC3	0.56	0.61	74.74	79.00	24.1	28.5	20.6	23.3	15.2	18.2
	STYL	MET3	0.56	0.61	74.74	79.00	51.9	61.4	44.3	50.2	32.7	39.2
Thigh	HJC	KJC	14.78	14.16	36.12	40.95	36.9	32.9	36.4	32.9	16.2	14.9
Shank	KJC	LMAL	4.81	4.33	44.16	44.59	27.1	25.5	26.7	24.9	9.3	10.3
	KJC	AJC	4.81	4.33	44.16	44.59	26.7	25.1	26.3	24.6	9.2	10.2
	KJC	SPHY	4.81	4.33	44.16	44.59	27.5	25.8	27.1	25.3	9.4	10.5
Foot	HEEL	TTIP	1.29	1.37	40.14	44.15	29.9	25.7	27.9	24.5	13.9	12.4

Table 2. Population categories according to the body fat [6]

Description	Male	Female
Essential fat (Ef)	2-5%	12-15%
Athletes (A)	6-13%	16-20%
Fitness (F)	14-17%	21-24%
Acceptable (Ac)	18-25%	25-31%
Obese (O)	25%+	32%+

2. Method

2.1. *Subjects and equipment*

A sample of five individuals has been examined for the benefits of the study. The "Body Fat" formula has been used in order to classify the population used for the study.

Body fat parameters were calculated according to the formulas [6]:

Body fat calculator formula for man:

$$\frac{495}{1.0324 - 0.19077 \times \log\left(waist - neck\right) \ + 0.15456 \times \log\left(height\right)} - 450$$

Body fat calculator formula for woman:

$$\frac{495}{1.29579 - 0.35004 \times log(waist + hip - neck) + 0.22100 \times log(height)} - 450$$

According to these formulas, the population used for the study is divided into categories, following the table 3 below. The sample selected is for a first approach for the method and it may be enlarged to compare diverse type of population.

According to the table, the sample was composed of five males (two athletes (A) and three fitness (F)).

Table 3. Anthropometric data of the volunteers

Subject	Gender	Body fat [%]	Body mass [kg]	Body height [m]	Description
1	M	12.3%	63	175.5	A
2	M	14.1%	70	178	F
3	M	12.8%	66	175	A
4	M	16.5%	72	173	F
5	M	15.7%	68	174	F

Tools and equipment used:

1. Measuring tape
2. Martin's breadth caliper
3. Stadiometer
4. Measurement table
5. Goniometer
6. Camera

2.1.1. *Measurement table details*

The measurement table used during this project was designed and built in order to estimate the position of the COG of someone's body. To understand how this device is working one should become familiar with the assumptions done by the authors. First of them states, that the main dimension of each body segment is their length. Moreover, each of the body segments is treated as a solid of revolution. Therefore, the center of mass divides the its segment into two parts, what means that only value of one distance from the end of the segment to its center of mass is needed.
The measurement table is operating on the principle of one-sided lever. That means that the table is supported at three points, and that the rotation of the table along this point is possible. The lever is put in motion by the momentum acting on it. If the momentums are equal, then the lever remains in balance. In order to visualize the concept of working of the table a simple method of determining center of mass is presented below in Fig. 2.

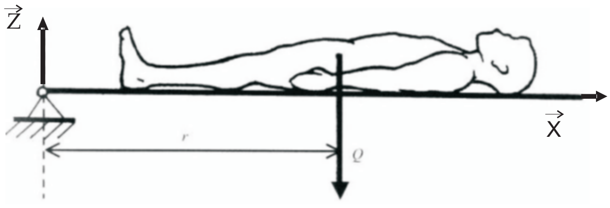


Figure 2 One-sided lever with human subject [7]

Mass of the human subject placed at the distance r from the support will cause a clockwise movement of the lever (see Fig. 3). Value of that moment would be $M_Q = Q\,r$. In order to compensate that moment, another moment R should be introduced to the system. Moment R should be equal in value to the moment M_Q but with an opposite direction.

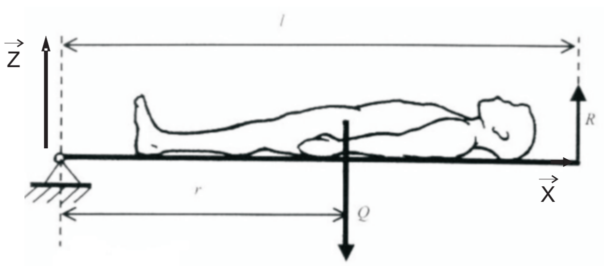


Figure 3 One-sided lever in static equilibrium [7]

In order to calculate the position of the center of mass using one-sided lever, the static equations were used to obtain following relation:

$$r = \frac{R\,l}{Q}$$

where:
r – distance,
Q – mass of human body,
R – reactive force,
l – length of the lever.
Data presented above shows, that the device should be able to determine the distance r in order to give a proper position of center of mass. To do so, the weight and height of the subject is needed as well as the value of the force R.

2.2. *Methods*

The measuring method was based on the functions of the measuring table described in previous paragraph. This equipment allows to measure the center of mass of a solid body (in this case human subject), knowing its total weight and mass. By changing the position of the body at each measurement it is possible to find the position of each center of mass of each body segment.

Measurements have been taken over the population used for the study in order to start calculations. Measurement of total weight, total height, neck circumference, waist circumference and hips circumference (for females) are performed with scale and the measuring tape. Then each body segments measurements were taken, with the measuring tape and according to Zatsiorsky and De Leva method.

Before taking the measurements, the measuring table should be initialised, according to its own initialisation process. The subject then lies on the measuring table. His feet need to touch the end ($x = 0$ position) of the table. Its position must be its natural position, arm along the body with open palm orientated up and straight body.

2.2.1. *Procedure of measurement*

First the segments need to be measured. Segmentation is taken from Zatsiorsky and De Leva method [3]. All measures are done with the measuring tape, except for the measurement of the x distal of the head, done with the caliper. The measurements are taken with the subject lying on the measuring table. Each segment is characterised by two values: its x distal and its x proximal. The length of the segment is the difference between the x proximal and x distal of the segment. Where x represents the distance to the reference point at the base of the table following the horizontal plane.

- Upper arm:
  - Segment length: measured from 25 mm to the acromial end of the clavicle to articulation pivot between upper and forearm.
  - x proximal: measured value. Distance from the reference point $x = 0$ (base of the table) to 25mm to the end of the clavicle.
  - x distal: calculated value. [x distal upper arm] = [x proximal upper arm] - [length upper arm segment].
- Forearm:
  - Segment length: measured from the articulation pivot between upper and forearm to articulation pivot between forearm and hand.
  - x proximal: calculated value. [x proximal forearm] = [x distal upper arm].
  - x distal: calculated value. [x distal forearm] = [x proximal forearm] - [length forearm segment].
- Hand:
  - Segment length: measured from the articulation pivot between forearm and hand to top of middle finger.
  - x proximal: calculated value: [x proximal hand] = [x distal forearm].
  - x distal: calculated value: [x distal hand] = [x proximal hand] - [length hand segment].
- Head:
  - Segmentation: between top of the head and the jugular notch (neck base-cavity).

  - x proximal: measured value, From the point of reference x=*0* (base of table) to the top of the head.
  - x distal: calculated value: [x distal head] = [x proximal head] - [length head segment].

- Trunk:
  - Segment length: measured from the jugular notch to the symphysis.
  - x proximal: calculated value: [x proximal trunk] = [x distal head].
  - x distal: measured according to the segmentation. [x distal trunk] = [x proximal trunk] - [length trunk segment].

- Upper leg:
  - Segment length: measured from greater trochanter to knee articular cavity.
  - x proximal: calculated value: [x proximal upper leg] = [x distal trunk].
  - x distal: calculated value: [x distal upper leg] = [x proximal upper leg] - [length upper leg segment].

- Lower leg + foot
  - Segment length: measured from the knee articular cavity to the point of reference $x = 0$ (base of table).
  - x proximal: calculated value: [x proximal lower leg] = [x distal upper leg].
  - x distal: calculated value. [x distal lower leg] = point of reference = 0.

The measurement taking of the COM of the body in distinct positions is composed of several steps. Each step consists in measuring the COM body of the subject in various positions. They are done according to the established order.
Each step respects the following procedure:

1. Change the body position to the position to be measured.
2. Take measurement of the angles of the body if required.
3. Follow the procedure of the table to take the measurement. The body needs to stay stable during the measurement.
4. Once the measure is taken, the subject can relax and come back to resting position on the table.

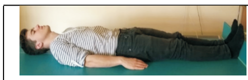
2.3. *Measurements and calculation*

The measurements are the different centers of mass of the body placed in different positions on the table. In order to obtain on each segment's COM from these total COM of the body measured, static equations based on the simplified model of the body are used.

In the following equations, the segments will be designated as below:

1: Head
2: Trunk
3: Upper arm
4: Forearm
5: Hand
6: Thigh
7: Shank + foot

Table 4. Initial position and basic formula

	$M_{tot}X_{tot}=\int_{p=1}^{7} m_p x_p$	(1)

Initial position is the referential one. During the next measurements, equation presented in Tab. 4 will be used to simplify the further ones.

To find the center of gravity of each part of the arm, three equations were needed to use a Cramer's rule for equations system (see Tab. 5). In any situation, it's possible to make a link between the new centers of gravities to the previous ones by geometric assumptions described in section 1.1.

There is only one unknown, to solve this problem, the angle between the head and the table has to be measured. To obtain the result of the head COM formulas presented in Tab. 6 were used.

To solve the case of leg measurement, the procedure is the same as for the arm, but with this time only two unknowns (see Tab. 7).

For the trunk, another referential position is used, and because the position of the center of gravity of all the body part is known, it's possible to calculate the position of the center of gravity of the trunk. In order to obtain that position formulas from Tab. 8 were used.

2.4. *The methods used for data analysis*

The results calculated after the experiments have been compared with theoretical ones using the ratio of de Leva experimentation. These ratios, assumed to be the reference for the positions of the center of gravity for each body segments, have been applied to the measures done during the experiments on the subjects [4]. In the table [9], this is the ratio from the proximal length.

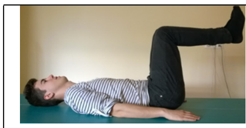
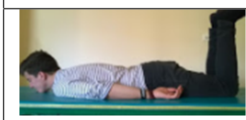
Table 5. Positions and formulas for arm measurement

	$M_{tot}X^{(1)}_{tot} = \int_{i=1}^{7} m_i x_i^{(1)}$ $M_{tot}\left(X_{tot} - X^{(1)}_{tot}\right) = m_3\left(x_3 - x_3^{(1)}\right)$ $+m_4\left(x_4 - x_4^{(1)}\right) + m_5(x_5 - x_5^{(1)})$	(2) (3)
	$M_{tot}X^{(2)}_{tot} = \int_{i=1}^{7} m_i x_i^{(2)}$ $M_{tot}\left(X_{tot}m - X^{(2)}_{tot}\right) = m_3\left(x_3 - x_3^{(m2)}\right)$ $+m_4\left(x_4 - x_{m4}^{(2)}\right) + m_5(x_5 - x_5^{(2)})$	(4) (5)
	$M_{tot}X^{(3)}_{tot} = \int_{i=1}^{7} m_i x_i^{(3)}$ $M_{tot}\left(X_{tot} - X^{(3)}_{tot}\right) = m_3\left(x_3 - x_3^{(3)}\right)$ $+m_4\left(x_4 - x_{m4}^{(3)}\right) + m_5(x_5 - x_5^{(3)})$	(6) (7)

Table 6. Position and formulas for head measurement

	$M_{tot}X^{(4)}_{tot} = \int_{p=1}^{7} m_p x_p^{(4)}$ $M_{tot}\left(X_{tot} - X^{(4)}_{tot}\right) = m_1\left(x_1 - x_1^{(4)}\right)$	(8) (9)

Table 7. Positions and formulas for leg measurement

	$M_{tot}X^{(5)}_{tot} = \int_{i=1}^{7} m_i x_{\mathrm{i}}^{(5)}$ $M_{tot}\left(X_{tot} - X^{(5)}_{tot}\right) = m_6(x_6 - x_6^{(5)})$ $+m_7\left(x_7 - x_7^{(5)}\right)$	(10) (11)
	$M_{tot}X^{(6)}_{tot} = \int_{i=1}^{7} m_i x_i^{(6)}$ $M_{tot}\left(X_{tot} - X^{(6)}_{tot}\right) =$ $m_6(x_6 - x_6^{(6)}) + m_7\left(x_7 - x_7^{(6)}\right)$	(12) (13)

3. Results, discussions and conclusions

3.1. *Presentation of raw results*

Two measurements per different positions were made on the measuring table to obtain an average, then obtained values were treated to find the positions of the center of gravity of each segments of the body. Results are presented in Tab. 10.

Table 8. Positions and formulas for trunk measurement

	$M_{tot}X_{tot}^{(7)} = \int_{i=1}^{7} m_i x_\mathrm{i}^{(7)}$	(14)
	$M_{tot}X_{tot}^{(6)} = \int_{i=1}^{7} m_i x_\mathrm{i}^{(8)}$ $M_{tot}\left(X_{tot}^{(7)} - X_{tot}^{(8)}\right) =$ $\int_{i=1}^{7} m_i \left(x_\mathrm{i}^{(7)} - x_\mathrm{i}^{(8)}\right)$	(15) (16)

Table 9. De Leva ratios [6]

Method de Leva	CM (% length)	
Head + Neck	59.8%	58.9%
Trunk	44.9%	41.5%
Upper arm	57.7%	57.5%
Forearm	45.7%	45.6%
Hand	79.0%	74.7%
Thigh	41.0%	36.1%
Shank	44.6%	44.2%
Foot	44.2%	40.1%
	Male	Female

3.2. *Discussion*

Total size of subject is greater when measured on the table. Due to position on the table (feet are not totally at $x{=}0$, and to the lying position that releases forces and compression of the body in the frontal plane. As the subject is lying on the measuring table, it is possible to make the hypothesis that the extension of the body in frontal plane is distributed on the entire length in a linear way. The measurements should be cross-product with the length measurement when standing and compared to the Zatsiorsky method with body length during stand.

The body position is changing during different measurement taking. Order and choice of position should be reorganized to minimize the movement of the body during measurement.

The assumption made that the segments rotate comparing to the other segments over their distal and proximal positions is wrong. The ensemble head and neck does not rotate around the Jugular notch for example. Moreover, the ensemble neck and head is not staying in the same position during its rotation. The head also rotates over the neck. It makes the determination of an accurate model difficult. Another solution would be to separate the neck from the head in the model, but it would require two measurements instead of one, and very difficult to estimate the real position on the neck and head.

Table 10. COM measurements results*

Results	subject 1 (A)	subject 2 (F)	subject 3 (A)	subject 4 (F)	subject 5 (F)
Head + Neck	145.0	157.0	169.0	167.7	162.7
Trunk	121.6	133.7	126.8	123.2	124.4
Upper arm	128.3	138.3	140.2	126.4	134.0
Forearm	86.8	90.0	100.1	90.3	113.6
Hand	213.1	105.8	64.2	152.0	52.2
Thigh	70.9	78.5	76.2	78.5	78.5
Shank + foot	27.1	24.9	26.7	23.4	27.1

*values are in centimetres using the graduation of the table measured from the bottom of the feet (base)

Table 11. Comparison of the results with Zatsiosrky and De Leva results (difference between presented method and ZDL method in percentage, where l-longer, s-shorter)

Results	Subject 1 (A)	Subject 2 (F)	Subject 3 (A)	Subject 4 (F)	Subject 5 (F)
Head + Neck	5% L	4% s	5.9% s	5.5% s	3.5% L
Trunk	4% L	4% L	4% L	1% L	4% s
Upper arm	5% s	4% L	6.8% s	2.0% s	4.1% s
Forearm	9% L	16% L	5.7% L	12% L	8.5% s
Hand	195% L	23% s	16% s	111% s	31% L
Thigh	3% s	2% s	3.4% L	1.9% L	5.5% L
Shank + foot	4% s	5% s	9.9% s	9% L	9.8% L

No specific influence from the Body Fat category of the subject has been observed. The method seems to fit for these two categories of individuals and needs more examination with other types of body, then athletic and fit.

A graphical determination of the position could help earning in accuracy of this method. It would require taking photos during measurements, put markers on the identified center of rotations of the segments on the body, and to analyse the lengths and angles taken by the body during the measurement.

While comparing the results with the one obtained by Zatsiorsky and de Leva, one can observe that most of the records differs in less than 5%. Such tendency was expected and it is caused by the assumptions, equipment's' precision and the fact, that each human being differs. Moreover, Zatsiorsky's and De Leva's method are not totally accurate and also have potential error regarding to the reality. Therefore, those results obtained during this project could be treated as valid ones, however, an experiment with the same subject with different, precise methods should be done for further evaluation. In a few cases larger differences had also occurred like for the hand segment. Most probably they were caused by the movements of the subject during the measuring procedure or to an inaccurate positioning of the subject during measuring. The largest error occurred for the hand. This phenomenon was caused by the fact that hand is the last segment of the upper limb and it was moved in nearly every measuring position change. Combining it with the respectively insignificant weight comparing to the rest of the body segments, even a smallest movement may cause relatively great errors in COM measurement for this segment. To obtain higher quality results more precise equipment should be used and also more strict measuring procedure should be applied to avoid unnecessary and unwanted movement of the subject.

3.3. *Conclusion*

Improvements can be done in the procedure to ensure better results. A graphical study of the positions taken would allow to adjust the model to the reality. The assumption of the rotational centers of segments is not accurate. Errors due to unwanted movements during experiment could be avoided by using different measuring positions and/or changing their order in the measurement procedure. The assumption of the unchanged center of mass of each segment in different positions, however, is difficult to verify. And the errors due to this hypothesis are hardly removable from the results.

Acknowledgments
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