TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue II, June, 2025

REVIEW OF METHODS FOR DETERMINING THE LOCATION OF THE CENTER OF MASS (COM) FOR THE HUMAN BODY. APPLYING THE SEGMENTATION METHOD FOR CALCULATING COM

Ionel ȘERBAN, Corneliu Nicolae DRUGĂ, Barbu Cristian BRAUN, Alexandru Constantin TULICĂ

Abstract: *This paper aims to review the methods used to determine/calculate the location of the center of mass for the human body. Considering the review, the authors intend to apply the segmentation method to determine/calculate the location of the center of mass of a human body that executes a specific activity to identify whether it is in a stable equilibrium or not. The review, along with the applied method, might aid, in the biomechanical field, examining various situations/activities in which the human body is taking part. The center of mass (COM) of the human body plays a critical role in understanding movement, stability, and balance. Determining COM accurately is essential for applications in biomechanics, physical therapy, sports science, ergonomics, and robotics. There are various methods used to calculate COM, ranging from simple to more complex, depending on the accuracy needed and available tools. The paper presents a review of the methods commonly used for determining the COM of the human body, followed by a detailed explanation of the segmentation method for calculating COM.*

Keywords: *center of mass, segmentation method, biomechanics*

1. INTRODUCTION

The stable state of equilibrium and posture of the human body requires specific parameters to be described/modeled mathematically and mechanically. Of these, the most important is the COM (Center of Mass) of the human body.

From the point of view of solid mechanics, the COM enjoys remarkable properties: The COM of a body is the point where all its mass is concentrated.

COM is the point at which a body is in equilibrium without the tendency to rotate, i.e. the conditions of zero torsion of all forces acting on it are met.

Due to the common confusion between COM and center of gravity (COG), the main differences have been stated. (see Table 1)

All COM analysis methods are made from the perspective of knowledge of physics-mechanics, mathematics, and statistics. These analyses as well as others related to the human body have direct applications in the field of robotics, where the analyzed segments are rigid, but they also affect the field of biomechanics (sports science, rehabilitation, gait analysis, animation industries, posture analysis, ergonomic assessments), where the segments are assimilated as rigid.

Table 1.
Key differences between COM (Center of Mass) and COG (Center of Gravity)

Aspect	Center of Mass (COM)	Center of Gravity (COG)
Definition	Average position of mass in an object.	The point where the gravitational force acts on the object.
Dependence on Gravity	Independent of gravity.	Dependent on the gravitational field.
Location in a	Always at the same position	Usually coincides with

Received: 30.04.25; **Similarities**: 29.05.25: **Reviewed**: 04.06./03.06.25: **Accepted**:18.06.25.

Uniform Field	(regardless of gravity).	the COM in a uniform field.
Location in Non-uniform Fields	Fixed for an object (based on mass distribution).	It can shift depending on gravitational variations.
Application in Human Body	Used to calculate body movements and balance.	In everyday life, COG is generally the same as the COM.

In addition to the location of the COM, its trajectory is also very important within the various daily activities to which the human body is subjected.

2. REVIEW OF THE METHODS

There are numerous methods known for estimating the center of mass of a body, of which we list a few below, all of them consist of both theoretical and practical elements (see Table 2).

Table 2.

General methods to determine COM and their short description

Method	Short description	Applications	Limitations
Suspension method-Plumb line (visual estimation) [1,2]	A string with weight at the end is suspended from various points on the body (e.g., head, shoulders, torso). The intersection of these lines can give a rough estimate of where the COM lies	Used in clinical settings or when only an approximate COM location is needed, such as in posture analysis.	It is an approximate method and does not provide highly accurate results, especially for dynamic activities.
Segmentation method (Body segmental modeling) [3,4,5,6, 7, 8, 9]	Locating the COM for each segment that makes up the human body and calculating the geometric coordinates x_{COM} and y_{COM}. (See Fig.1)	This method is highly accurate and commonly used in biomechanical studies, gait analysis, and ergonomic assessments.	Requires detailed anthropometric data for each body's segment. It's a model-based approach, so it may not account for individual variations in body shape or posture.
Balance or force plate method (Experimental method-Dynamic Measurement) [10, 11,12,13 ,14]	By using a force platform, for example, Kistler.	Commonly used in research, clinical gait analysis, sports science, and rehabilitation studies. It's highly useful for dynamic activities such as walking, running, or jumping; or in evaluation of stability.	Requires specialized equipment and can be costly. It is primarily used in controlled settings.
3D Motion Capture and Modeling [15,16, 17, 18, 19]	Advanced techniques using 3D motion capture systems can create a detailed model of the body's movement.	Used in research, biomechanics, sports, and animation industries. It provides high accuracy and can measure COM during dynamic activities.	Requires expensive equipment and can be complex to set up and interpret

Mathematical and Computational Models [20, 21]	This method uses computational techniques to model the human body as a set of rigid segments. It uses mathematical and software programs to simulate COM.	Often used in advanced robotics, animation, and ergonomic design.	Requires specialized software and knowledge of computational techniques

Studies on the location of the COM have led to various formulas regarding the distance from the ground expressed as a percentage of the subject's height, such as:

- Palmer's formula- 55.7% (male and female);
- Crosky's formula- 55.44% (male); 55.18% (female);
- Hellenbrandt's formula- 55.17% (female);
- Davidovits and Peterson- 56%. [22, 23]

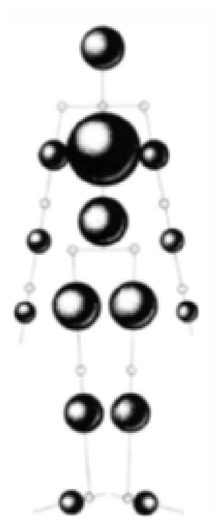

Fig. 1. Mass distribution in COM for each segment of the human body. [24]

When all body segments are taken together and considered as a single rigid body, in anatomical position, the COM of the body is located approximately in the anterior part of the second sacral vertebra (S2). (see Fig. 2)

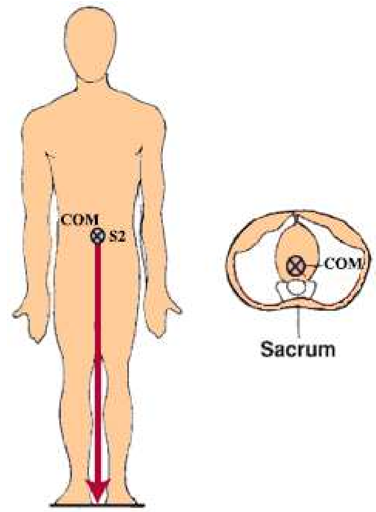

Fig. 2. The location of COM in frontal and transversal planes. [23]

Critical research (see Table 3), on February 14, 2025, was made, in known databases, using specific keywords and formulations, to determine the interest of other researchers with similar aims as this paper.

Table 3.

Search results on Science Direct and WoS

Keywords/ sentence	**Science Direct https://www.sciencedirect.com/ (no. of results)**	**WoS https://www.webofscience.com/ (no. of results)**
methods to determine center of mass human body	384,581	303
segmentation center of mass human body	17,776	24
Determine center of mass human	753,156	1807

It doesn't necessarily mean that all the found papers were oriented in the same direction as this paper, but they were offered as a solution by their search engines. Using analysis tools offered by the WoS platform, for the data searched on their platform, it was possible to add all the results and found a number of 1824 papers, so 310 were common in all three searches. For the summarized papers it was possible to analyze the research area, selecting 25, maximum available, research areas (most papers are found in the field of Engineering- 267, Chemistry- 214, Biochemistry Molecular Biology- 162 and the least Robotics- 31 and Infectious Diseases- 31) (see Fig. 3)

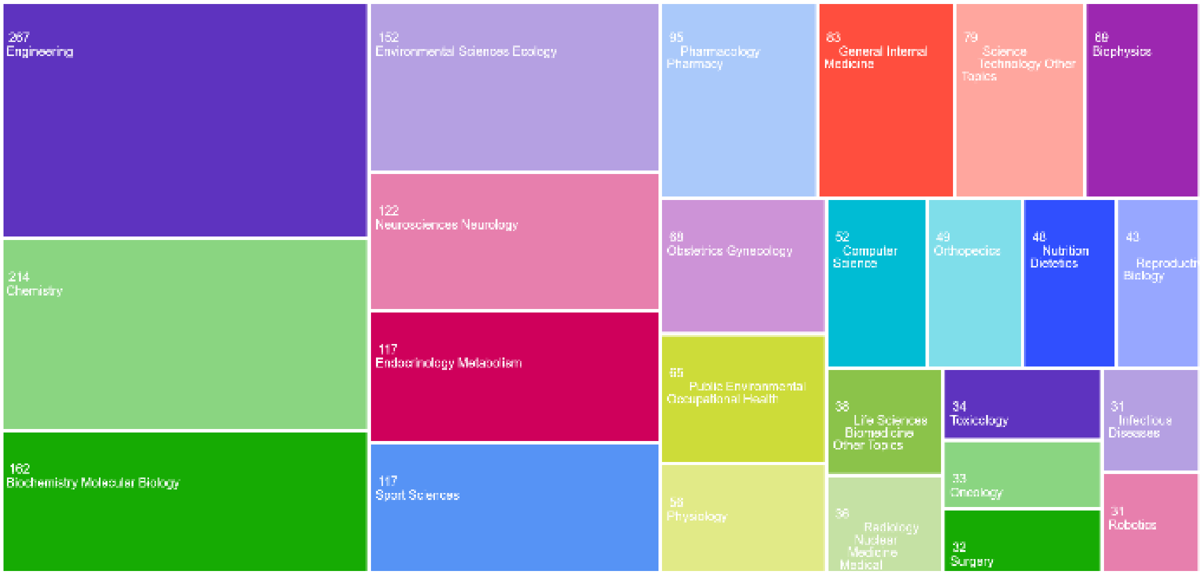

Fig. 3. Research areas distribution of papers, for WOS results.

Considering that some research areas might not be fitted for our search and might be an issue of the search engine or our limited knowledge (for instance, if reading the results found in Chemistry, there wasn't any involvement of center of mass of the human body). In this direction we extracted the main fields, that, from our knowledge, might be fitted: Engineering-267; Neurosciences Neurology- 122 and Sport Sciences- 117.

2. APPLYING THE SEGMENTATION METHOD

The segmentation method is one of the most practical and widely used approaches to determine the COM of the human body. Here is a detailed look at how this method works and its application.

Steps in the Segmentation Method:

1. A static image (or photo) of the activity is obtained (see Fig. 4), a recommendation would be to use graph paper, or if more experienced, can use software like Microsoft Paint, Adobe Photoshop, or CorelDRAW.
2. Body Segmentation: The human body is divided into smaller, simpler segments based on anatomical landmarks. (see Fig. 5). Mark these on the image (see Fig. 4)

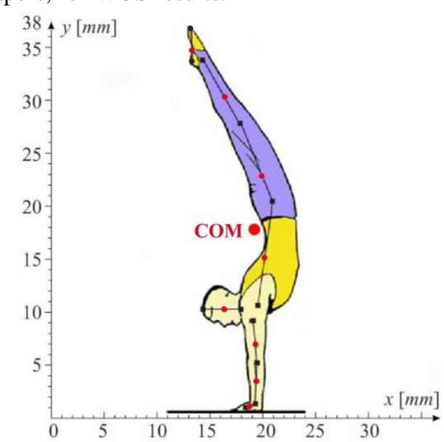

Fig. 4. The posture of a gymnast.

3. Obtaining Data for Each Segment: For each body's segment, anthropometric data provides the mass and COM location. These data come from studies that have measured body mass and the position of the COM for various segments. (see Table 4) Mark COM on the image (see Fig. 4) [26]
4. Measure the coordinates of the obtained COM for each segment. If a 2D analysis is made, obtain x and y coordinates for each COM.
5. Total COM coordinates can be calculated, mathematically, by the formula:

$$x_{COM} = \frac{\sum m_i \cdot x_i}{\sum m_i} \quad (1)$$

$$y_{COM} = \frac{\sum m_i \cdot y_i}{\sum m_i} \quad (2)$$

Where:

- m_i- the mass of each segment i
- x_i, y_i- the coordinates of the center of mass of each segment i, from a reference point (0 point of the axes)

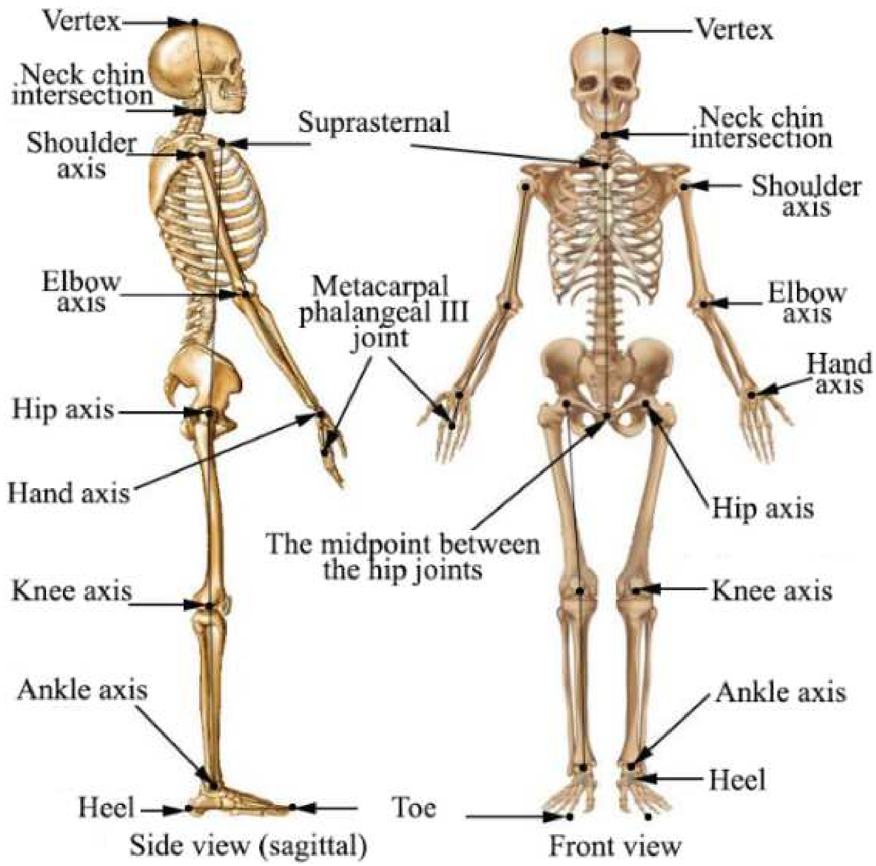

Fig. 5. Lateral and frontal view of the human skeleton with anatomical landmarks specific to COM calculation.

In this direction, segment length (measured on the static image, see Fig. 4) and COM location, of each segment, were calculated (as a percentage of the length of the segment) (see Table 4); along with relative mass (m_i- calculated as the percentage of total body mass), horizontal location x_i of COM, and vertical location y_i of COM.

Table 4.

Segment length and COM location (relative to its proximal end), are expressed as a percentage of the measured segment length. [3, 25]

Segment (i)	Segment length [mm]	COM location [% of length]	COM Location [mm]
Head	3,6	59,8% from vertex	2,15
Trunk	10,1	44,9% from suprasternal	4,53
Arm	4	57,7% from the shoulder axis	2,31
Forearm	4	45,7% from the elbow axis	1,83
Hand	1	79% from the hand axis	0,79
Thigh	8	41% from the hip axis	3,28
Calf	7,1	44,6% from the knee axis	3,16
Sole	3,6	44,2% from heel	1,59

In the next step, the projections of each COM are drawn on the 0X and 0Y axes, respectively. The values of these projections, to the center of the coordinate axes, are entered in Table 5, and then the product between the value of the relative mass (expressed as a percentage of total body mass, in our case, it was 100kg) and the coordinates on 0X and 0Y axes, respectively, are calculated. Finally, the mathematical calculation formula (see Equations 1 and 2) is applied, obtaining the coordinates of COM of the whole body.

Table 5.

Segmental calculation of COM of the whole body.

Segment (i)	Relative mass (m_i) (% of total body mass) [kg]	Horizontal location x_i of COM [mm]	$m_i \cdot x_i$ [mm]	Vertical location y_i of COM [mm]	$m_i \cdot y_i$ [mm]
Head	6,94	16,3	113.12	10,4	72.18
Trunk	43,46	20,1	873.55	15,2	660.59
Arm	5,42	19,2	104.06	6,9	37.40
Forearm	3,24	19,4	62.86	3,6	11.66
Hand	1,22	18,7	22.81	1,2	1.46
Thigh	28,32	19,9	563.57	23	651.36
Calf	8,66	16,3	141.16	30,4	263.26
Sole	2,74	13,1	35.89	34,8	95.35
	Body mass= $\sum m_i$		$\sum m_i \cdot x_i$=1917.02		$\sum m_i \cdot y_i$=1793.27

In our case the upper and lower limbs, considering a 2D system, have the same coordinates, so their relative mass was doubled, considering only one segment, see Table 5.

3. DISCUSSIONS

Applying values (see Table 5) in equations (see equations 1 and 2), the location of the body's center of mass was determined to be x_{COM}= 19.17 mm and y_{COM}= 17.93 mm. marking the coordinates in Figure 3 it can be seen that the projection of the COM on the ground can be found inside the support base (the area described by the contact between the palm and the ground) so it can be concluded that the gymnast is in a stable equilibrium.

4. CONCLUSIONS

The segmentation method is one of the most accurate and widely applied techniques for calculating the center of mass (COM) of the human body.

By dividing the body into segments, it provides an approach that combines anatomical realism with mathematical precision. This method, according to the review, is commonly used in biomechanics, sports science, ergonomics, and robotics.

The other methods offer practical, real-time measurements, but the segmentation method remains the gold standard for detailed and accurate modeling of human body biomechanics.

For our study, the segmental method offers the necessary tools to identify whether the gymnast is in a stable equilibrium or not, due to the projection, of the COM on the ground, found inside the support base, suggesting a stable equilibrium.

5. Acknowledgments. The authors have nothing to acknowledge.

6. Conflict of Interest. The authors declare that they have no conflict of interest.

7. REFERENCES

[1] Erdmann, W. S., *Center of mass of the human body helps in analysis of balance and movement*. MOJ Applied Bionics and Biomechanics, 2(2), 144–148, eISSN 2576-4519, 2018.

[2] Schafer, R. C., *Clinical Biomechanics: Musculoskeletal Actions and Reactions* (2nd ed.), Williams & Wilkins, ISBN 9780683075847, Baltimore, 1987.

[3] Dempster, W. T., *Space requirements of the seated operator* (NASA Technical Note D-451). Washington, D.C.: National Aeronautics and Space Administration, 1955.

[4] Winter, D. A., *Biomechanics and motor control of human movement* (4th ed.), John Wiley & Sons, ISBN 9780470398180, 2009.

[5] Wieczorek, B., Górecki, J., Kukla, M., Wojtokowiak, D., *The Analytical Method of*

Determining the Center of Gravity of a Person Propelling a Manual Wheelchair, Procedia Engineering, Volume 177, pp 405-410, ISSN 1877-7058, 2017.

[6] Dainis, A., *Whole Body and Segment Center of Mass Determination from Kinematic Data*, Journal of Biomechanics, vol. 13, no. 8, pp. 647-651, 1980.

[7] Clauser, C. E., McConville, J. T., Young, J.W., *Weight, Volume, and Center of Mass of Segments of the Human Body*, Air Force Aerospace Medical Research Lab TR-69-1 - TR-72-15, Wright-Patterson Air Force Base, Ohio, Aerospace Medical Division, 1969.

[8] Damavandi, M., Farahpour, N., Allard, P., *Determination of body segment masses and centers of mass using a force plate method in individuals of different morphology*, Med Eng Phys, 31(9):1187-94, 2009.

[9] Yusaku, F. et al., *A Method for Direct Measurement of the First-Order Mass Moments of Human Body Segments*, Sensors, vol. 10, no. 10, pp. 9155-9162, 2010.

[10] Cavagna, G. A., Kaneko, M., *Mechanical work and efficiency in level walking and running*, Journal of Physiology, 268(2), pp 467-481, 1977.

[11] Chen, B., Liu, P., Xiao, F., Liu, Z., Wang, Y., *Review of the Upright Balance Assessment Based on the Force Plate*, Int J Environ Res Public Health, 18(5):2696, 2021.

[12] Motomichi, S., Inoue, Y., *Center of Mass Estimation Using a Force Platform and Inertial Sensors for Balance Evaluation in Quiet Standing*, Sensors, vol. 23, no. 10, p. 4933, 2023.

[13] Lamkin-Kennard, K., Popovic, M.B., *Sensors: Natural and Synthetic Sensors*, Biomechatronics, Academic Press, pp 81-107, ISBN 9780128129395, 2019.

[14] Gouwanda, D., Gopalai, A.A., Lim, Z.S., Lim, K.H., *Measuring Human Balance on an Instrumented Dynamic Platform: A Postural Sway Analysis*, Goh, J. (eds) The 15th International Conference on Biomedical Engineering. IFMBE Proceedings, vol 43. Springer, Cham., 2014.

[15] Cappozzo, A., Catani, F., Della Croce, U., Leardini, A., *Position and orientation in space of bones during movement: Anatomical frame definition and determination*. Clinical Biomechanics, 10(4), pp 171–178, ISSN 0268-0033, 1995.

[16] Pavei, G., Seminati, E., Cazzola, D., Minetti, A.E., *On the Estimation Accuracy of the 3D Body Center of Mass Trajectory during Human Locomotion: Inverse vs. Forward Dynamics*, Front Physiol; 8:129, 2017.

[17] Simonetti, E., et al., *Estimation of 3D Body Center of Mass Acceleration and Instantaneous Velocity from a Wearable Inertial Sensor Network in Transfemoral Amputee Gait: A Case Study*, *Sensors*, vol. 21, no. 9, p. 3129, ISSN 1424-8220, 2021.

[18] Maillard, T., *The Three-Dimensional Body Center of Mass at the Workplace under Hypogravity*, Bioengineering, vol. 10, no. 10, p. 1221, ISSN 2306-5354, 2023.

[19] Neptune, R.R., *Computer Modeling and Simulation of Human Movement: Applications in Sport and Rehabilitation*, Physical Medicine and Rehabilitation Clinics of North America, Volume 11, Issue 2, pp 417-434, ISSN 1047-9651, 2000.

[20] Hatze, H., *A Mathematical Model for the Computational Determination of Parameter Values of Anthropomorphic Segments*, Journal of Biomechanics, vol. 13, no. 10, pp. 833-843 , 1980.

[21] Minetti, A.E., Cisotti, C., Mian, O.S., *The mathematical description of the body centre of mass 3D path in human and animal*

locomotion, J Biomech., 44(8):1471-7, ISSN 0021-9290, 2011.

[22] Peterson, D.R., Bronzino, J.D., *Biomechanics: Principles and Applications,* 2nd ed., CRC Press, Taylor & Francis, ISBN-13 978-0-8493-8534-6, 2008.

[23] Șerban, I., *Studii si cercetari privind influenta mediului inconjurator asupra stabilitatii si locomotiei umane*, thesis, Universitatea Transilvania din Brașov, Facultatea de Inginerie Mecanică, 2011.

[24] Drillis, R., Contini, R., Bluestein, M., *Body Segment Parameters*, O & P Library, Artificial Limbs (vol.8), pp. 44- 66, 1964.

[25] https://www.slideshare.net/slideshow/centre-of-gravity-segmental-method/31269620#13, accessed 13 February 2025.

[26] https://msis.jsc.nasa.gov/sections/section03.htm, accessed 13 February 2025.

Studiul critic al metodelor de determinare a localizării centrului de masă pentru corpul uman. Aplicarea metodei prin segmentare pentru calculul centrului de masă

Rezumat: Această lucrare își propune un studiu critic al metodelor utilizate pentru a determina/calcula locația centrului de masă pentru corpul uman. Având în vedere studiul, autorii intenționează să aplice metoda prin segmentare pentru a determina/calcula locația centrului de masă al unui corp uman care execută o activitate specifică pentru a identifica dacă se află sau nu într-un echilibru stabil. Studiul literaturii de specialitate, împreună cu metoda aplicată, ar putea ajuta, în domeniul biomecanic, examinarea diferitelor situații/activități la care ia parte corpul uman. Centrul de masă (COM) al corpului uman joacă un rol critic în înțelegerea mișcării, stabilității și echilibrului. Determinarea cu precizie a COM este esențială pentru aplicații în biomecanică, terapie fizică, știința sportului, ergonomie și robotică. Există diverse metode utilizate pentru a calcula COM, mai simple sau mai complexe, în funcție de precizia necesară și instrumentele disponibile. Mai jos este o trecere în revistă a metodelor utilizate în mod obișnuit pentru determinarea COM a corpului uman, urmată de o explicație detaliată a metodei prin segmentare pentru calcularea COM.

Ionel ȘERBAN, Ph.D. eng., Lecturer, Transilvania University, Faculty of Product Design and Environment, Product Design, Mechatronics and Environment, ionel.serban@unitbv.ro

Corneliu Nicolae DRUGĂ, Ph.D. eng., Lecturer, Transilvania University, Faculty of Product Design and Environment, Product Design, Mechatronics and Environment, druga@unitbv.ro

Barbu Cristian BRAUN, Ph.D. eng., Lecturer, Transilvania University, Faculty of Product Design and Environment, Product Design, Mechatronics and Environment, braun@unitbv.ro

Alexandru Constantin TULICĂ, Phd. eng., Transilvania University, Faculty of Product Design and Environment, Product Design, Mechatronics and Environment, alexandrutulica@yahoo.com