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center of mass for human body and
its individual parts**

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Tekst jest udostępniony do wykorzystania w ramach
dozwolonego użytku.

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COMPUTER AIDED CALCULATIONS OF CENTER OF MASS FOR HUMAN BODY AND ITS INDIVIDUAL PARTS

Introduction

Center of Mass (CoM), also known as center of gravity, is a point in the object where the entire mass is considered to be concentrated. Another word is the balancing point of an object. In the case of humans the center of mass varies by height and weight and is defined as the weighted average location of the mass particles of the body. By learning the center of mass, one can improve its balance and stability significantly, which is particularly important in sport. Nowadays the difference between competitors is very slight, that is why the coaches started taking into consideration the newest science accomplishments for enhancing the sport results. The good example of these accomplishments may be the precise analysis of the sportsman movement and its body position, which allows to observe and eliminate errors.

In the article the new approach to the problem of calculating the center of mass for whole human body is presented. The algorithm was implemented in the computer program which is able to calculate both center of mass for

whole human body and its individual limbs and additionally compare them with traditional methods.

1. Different methods of calculating center of mass for human body

From mechanical point of view human body should be represented as a solid figure with irregular form. In the case of such figures for calculating the center of mass the experimental approach is used. It is time consuming because of carrying out many tests to find a point where the solid is in equilibrium point regardless its rotation. When the solid figure is more complicated the experiments required even more time, that is why this method is rarely used. Much easier approach is dividing a solid into several simpler elements. However, in the case of human body it is still difficult¹.

Finding the center of mass for human body is one of the topics in which biomechanics is interested in from the beginning of its existence. One of the first researchers was Harles, who in 1860 carried out some experiments on corpses to find out the center of mass of the particular parts. The nowadays literature basis on research of Clauser who in 1969 transferred findings of interrelationships in cadavers to living persons during research where 13 male cadavers were dissected into 14 segments². The another approach had Zatsiorsky in 1981 where by means of a gamma-ray scanning technique the relative body segment masses, center of mass positions, and radii of gyration for samples of college-aged Caucasian males and females were obtained³. Both of them are consider to be the most accurate because they take into account height and weight of an examined person and the adjustments to their methods are still developed.

¹ M. Zok, C. Mazzà, U. Della Croce, *Total body center of mass displacement estimated using ground reactions during transitory motor tasks: application to step ascent*, "Medical Engineering and Physics" 2004, No. 26 (9), pp. 791-798.

² C.E. Clauser, J.T. McConville, J.W. Yound, *Weight, volume, and center of mass of segments of the human body*, AMRL technical report. Dayton (OH): Wright-Patterson Air Force Base, 1969, pp. 69-70.

³ T.C. Pataky, V. Zatsiorsky, J.H. Challis, *A simple method to determine body segment masses in vivo: reliability, accuracy and sensitivity analysis*, "Clinical Biomechanics" 2003, No. 18 (4), pp. 364-368.

The calculation of the center of mass for human body can be based on an experiment, which is the direct reaction board method or on indirect analytical method (moment of force sum)⁴. For calculating the center of mass for limbs also the analytical method is used⁵ while for particular parts of the body percentage method and regression equations are the best choice.

1.1. Direct method – reaction board method

A reaction board (second class lever) is a stiff beam supported from one side⁶. The rotary movement is possible in relation to the support point. If the reacting forces and moment of force are in balance then the reaction board is in equilibrium. With the help of the board it is possible to determine the center of mass for lying human body (fig. 1).

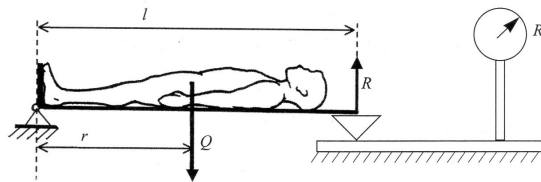


Fig. 1. The center of mass for human body calculation by reaction board method
Source: T. Bober, J. Zawadzki, *op. cit.*, p. 97.

⁴ W. McKinon, C. Hartford, L. Di Zio, J. van Schalkwyk, D. Veliotes, A. Hofmeyr, G. Rogers, *The agreement between reaction-board measurements and kinematic estimation of adult male human whole body center of mass location during running*, "Physiological Measurement" 2004, No. 25 (6), pp. 1339-54.

⁵ S.J. Hall, *Biomechanics of the human upper extremity*, in: *Basic Biomechanics*, MA: McGraw-Hill, Boston 2003, pp. 183-227.

⁶ T. Bober, J. Zawadzki, *Biomechanika układu ruchu człowieka*, Wydawnictwo BK, Wrocław 2006.

Because moments of force Q and reaction R are in balance and moment of force in the support equals 0 (the arm of the force is 0) then:

$$M_Q - M_R = 0 \quad (1.1)$$

$$M_Q = M_R \quad (1.2)$$

$$Q \cdot r = R \cdot l \quad (1.3)$$

Finally:

$$r = \frac{R \cdot l}{Q} \quad (1.4)$$

where: M – moment of force, r – arm of the weight Q , l – beam length, Q – weight of the lying body, R – reaction force.

Length r measured from axis of rotation is the value of the distance to the center of mass from the person's feet. During the experiment it is crucial to lie motionless.

1.2. Indirect method (moment of force sum)

During the movement there is no possibility to find the center of mass for human body by applying the direct method. One should in this case use photos or frame movies and convert the three-dimensional image into two-dimensional. The transformation must be performed by keeping the constant scale which allows to calculate the center of mass. Taking advantage of the assumption that the human body can be segmented into 14 parts (head, corpse, two arms, two forearms, two hands, two tights, two shanks, two feet) it is quite simple to calculate the center of mass for the whole human body. Every segmented part is a solid figure with known weight and position of the center of its mass. The position of the center of mass for whole human body (OSC) is a theoretical point where resultant force of all 14 segmented parts is placed.

1.3. Percentage method

One of the most important factors for calculating the center of mass is the weight of the examined person. By knowing its value it is possible to determine weight of the particular parts of a human body by knowing their percentage participation in proportion to the weight of a whole body. The participation is called a relative weight of a body part (tab. 1).

Table 1

Percentage participation of a body part in proportion to the weight of a whole body and position of the center of mass measured from the higher joint⁷

Body parts	Percentage participation in proportion to the weight of a whole body [%]	Position of the center of mass measured as percentage of the body part length from the higher joint [%]
head with neck	7	external ear whole
corpse	43	44
arm	3	47
forearm	2	42
hand	1	50
tight	12	44
shank	5	42
foot	2	44

Source: own elaboration.

1.4. Regression method

Method of regression equations is based on relations between height and weight of an examined person, as well as between weight of a particular body part and its length, its volume and circumference. These relations create regression equations presented in table 2.

⁷ V.M. Zatsiorsky, A.S. Aruin, V.N. Seluyanov, *Biomechanics of the human Musculoskeletal System*, FiS, Moskwa 1981, p. 56.

Table 2

Regression equations for weight and for position of the center of mass measured from the higher joint of the body parts according to Zatsiorsky⁸

Body parts	Regression equations for weight	Regression equations for position of the center of mass measured from the higher joint
head	$1,296 + 0,0171 x_1 + 0,0143 x_2$	$8,357 - 0,0025 x_1 + 0,023 x_2$
upper corpse	$8,2144 + 0,1862 x_1 + 0,0584 x_2$	$3,32 + 0,0076 x_1 + 0,047 x_2$
middle corpse	$7,181 + 0,2234 x_1 + 0,0663 x_2$	$1,398 + 0,0058 x_1 + 0,045 x_2$
lower corpse	$-7,498 + 0,0976 x_1 + 0,04896 x_2$	$1,182 + 0,0018 x_1 + 0,0434 x_2$
arm	$0,250 + 0,03012 x_1 - 0,0027 x_2$	$1,67 + 0,03x_1 + 0,054x_2$
forearm	$0,3185 + 0,01445 x_1 - 0,00114 x_2$	$0,192 - 0,028x_1 + 0,093x_2$
hand	$-0,1165 + 0,0036 x_1 + 0,00175 x_2$	$4,11 + 0,026x_1 + 0,033x_2$
tight	$-2,649 + 0,1463x_1 + 0,0137x_2$	$-2,42 + 0,038x_1 + 0,135x_2$
shank	$-1,592 + 0,0362 x_1 + 0,0121 x_2$	$-6,05 - 0,039x_1 + 0,142x_2$
foot	$-0,829 + 0,0077 x_1 + 0,0073 x_2$	$3,767 + 0,065x_1 + 0,033x_2$

x_1 – body weight [kG], x_2 – body length [cm].

Source: own elaboration.

2. New algorithm of center of mass for whole human body calculation

Calculation of the center of mass for whole human body can be realized by the direct method (the reaction board) described above or indirect analytical method (moment of force sum). The percentage method and regression equations are used only for calculating the centers of mass particular body parts.

Authors of the paper decided to create a new method for calculating the center of mass for whole human body by applying the percentage method and regression equations (used only for one body part calculation).

It was assumed that a human body is symmetrical which applies that calculation results for one upper and one lower limb are sufficient. Firstly the center of mass for particular parts of the limb were calculated both by the percentage method and regression equations. Then moment of force equation was applied for calculating center of mass for whole body, because limbs were treated as levers fasten in the shoulder and pelvic joints. That is

⁸ *Ibidem*, p. 57.

why knowledge about the centers of mass for particular body parts allowed to find the whole body center.

In the algorithm at the beginning the center of mass for particular parts of the limb were calculated by using the moment of force sum method. In the case of lower limb the formulas for CoM calculating are as follows:

$$M_{LL} = Q_{LL} * r_{LL} \quad (2.1)$$

$$r_{LL} = \frac{M_{LL}}{Q_{LL}} \quad (2.2)$$

where: Q_{LL} – weight of lower limb, M_{LL} – moment of force of lower limb, r_{LL} – arm of the weight Q_{LL} .

$$Q_{LL} = Q_T + Q_S + Q_F \quad (2.3)$$

$$M_{LL} = M_T + M_S + M_F \quad (2.4)$$

where: Q_T – weight of thigh, Q_S – weight of shank, Q_F – weight of foot, M_T , M_S , M_F – appropriate moments of force.

$$M_T = Q_T * r_T \quad (2.5)$$

$$M_S = Q_S(l_T + r_S) \quad (2.6)$$

$$M_F = Q_F(l_T + l_S + r_F) \quad (2.7)$$

where: r_T , r_S , r_{ST} – arm of the weights Q_T , Q_S , Q_F ; l_T , l_S – length of thigh and shank.

In the next step distance between the centers of mass for two particular body parts was determined. After it their weight was also compared. In that way a segment which connects those two chosen parts was divided proportionally according to the simple calculations. From the first two calculated parts the position of the center of mass for them was found. In the next step analogically the next part was added and the position of the center of mass for the three parts for them was found. The algorithm finished calculations after adding all parts. As a result the window with the values of CoM positions of all parts and whole body as well as their graphical representation are visible (fig. 2).

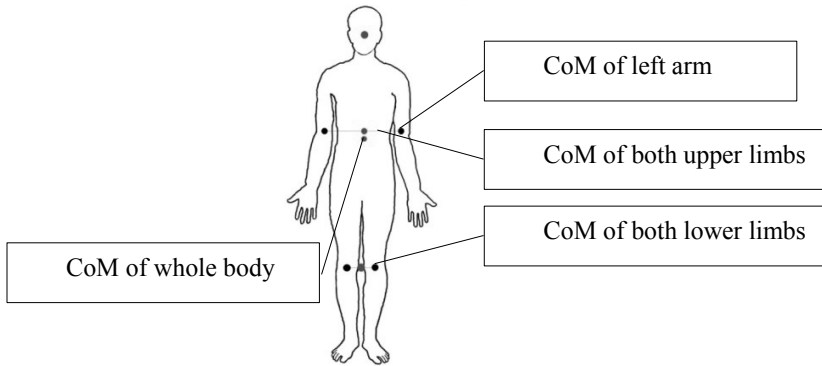


Fig. 2. The exemplary positions of the centers of mass in human body

Source: own elaboration.

3. Implementation of the program

Described in the section above three methods for calculating center of mass both for particular parts and whole body were implemented in the computer program.

3.1. The program platform

The algorithm was implemented in an integrated development environment Microsoft Visual Studio 2010 in Express version and is dedicated to work in Windows system. The platform is used by programmers for creating both console and graphical (GUI) computer applications. It allows a programmer to create application for the following platforms: Microsoft Windows, Windows Mobile, Windows CE, .NET Framework and Microsoft Silverlight. It has also very useful tools like IntelliSense and refactorization code. For application creation C# was used. The application written in C# is compiled into Common Intermediate Language – special bite code which can be executed in platforms: .NET Framework, Mono or DotGNU.

3.2. Program description

The program was used by Polish students at Biomechanic Faculty University of Science and Technology AGH to validate the new algorithm in comparison to the traditional methods. That is why the menu is written in Polish language.

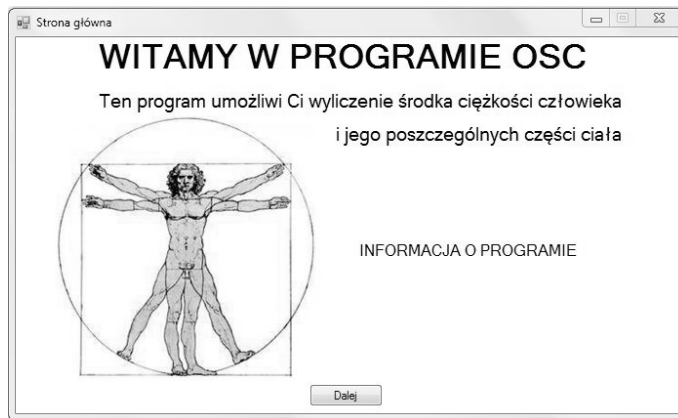


Fig. 3. The introduction window

Source: own elaboration.

The program for calculating center of mass of human body (in Polish: Ogólny Środek Ciężkości OSC) is installed from the installation file OSC.exe, which is working in MS Windows environment. The important feature of the program is its installation on a hard drive which eliminates need for the Internet connection. After installing the program the introduction window appears (fig. 3).

After pressing “Dalej” button the window with the choice of action is available (fig. 4). There are three possibilities of calculating the center of mass: the particular body part, the limb or the whole body (OSC). It is possible to choose only one option at the time. In the program the graphical representation of the current body part calculation is always available, which significantly helps the user.

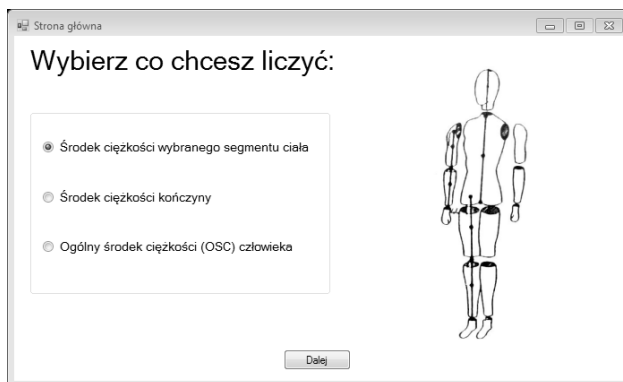


Fig. 4. The window with the choice of action
Source: own elaboration.

Choosing the option for calculating the CoM of the particular body part the window appears where the parts of the body and type of calculation are presented (fig. 5).

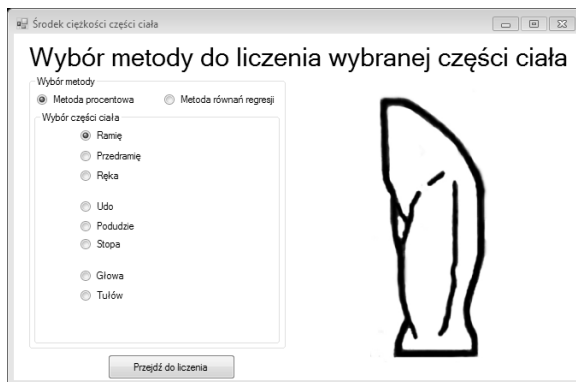


Fig. 5. Choosing the option for calculating CoM of the particular body part with graphical representation
Source: own elaboration.

Because of the body symmetry in the percentage method the body is divided into 8 parts (not 14): arm, forearm, hand, thigh, shank, foot, head, corpse. In the regression equation method additionally the corpse was divided into three parts.

After pressing button “Przejdź do liczenia” in the opened window the place for entering the appropriate data are visible. In any time the user can return to the previous window by using “Wstecz” button (fig. 6).

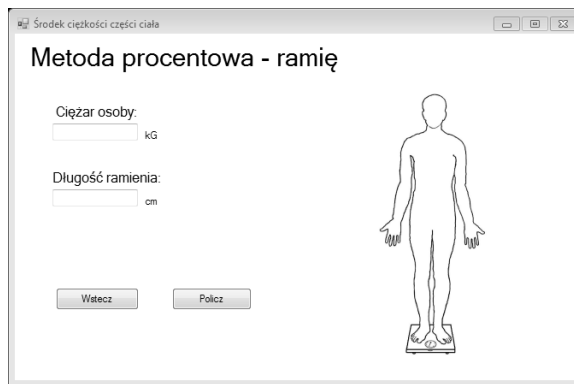


Fig. 6. Entering data for calculating CoM of an arm

Source: own elaboration.

The percentage method required additionally only the length of the body part. After entering the data and pressing “Policz” the program calculates the position and value of the center of mass which appear in the next window. Results for two methods: Zaciorsky and Clauser are presented, which allows easily to compare the values (fig. 7).

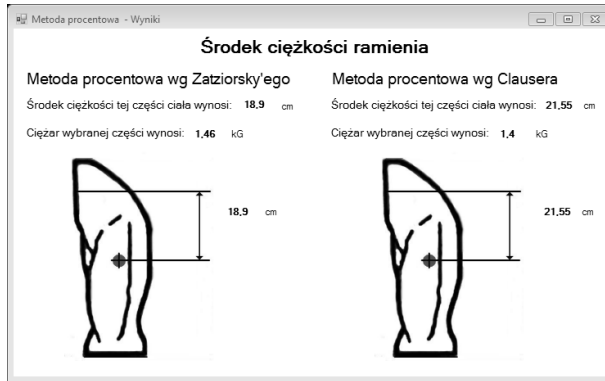


Fig. 7. Exemplary results of the position and value of the center of mass for arm
Source: own elaboration.

The implementation of the regression equations are shown in listing 1. The formula calculates the center of mass of the upper limb.

```

if (rb_reg_gorna.Checked == true)
{
    double sc_konczyny;
    string metoda, konczyna;
    metoda = „Równań regresji”;
    konczyna = „Górna”;
    //REGRESJI CIEZARY CZESCI CIAŁA
    cc_st_wyzszy = 0.25 + (0.03012 * waga) - (0.0027 * wzrost);
    cc_st_srodkowy = 0.3185 + (0.01445 * waga) - (0.00114 *
wzrost);
    cc_st_nizszy = -0.1165 + (0.0036 * waga) + (0.00175 * wzrost);
    //REGRESJI PROMIENIE WADZACE CZESCI CIAŁA
    pw_st_wyzszy = 1.67 + (0.03 * waga) + (0.054 * wzrost);
    pw_st_srodkowy = 0.192 - (0.028 * waga) + (0.093 * wzrost);
    pw_st_nizszy = 4.11 + (0.026 * waga) + (0.033 * wzrost);
    //REGRESJA MOMENTY SIL CZESCI CIAŁA
    msily_st_wyzszy = cc_st_wyzszy * pw_st_wyzszy;
    msily_st_srodkowy = cc_st_srodkowy * (dl_st_wyzszy + pw_st_
srodkowy);
    msily_st_nizszy = cc_st_nizszy * (dl_st_wyzszy + dl_st_srodkowy
+ pw_st_nizszy);
    sc_konczyny = (msily_st_wyzszy + msily_st_srodkowy + msily_st_
nizszy) / (cc_st_wyzszy + cc_st_srodkowy
+ cc_st_nizszy);
    Konczyny_WynikiKonczyna_Wyniki_Form = newKonczyny_Wyniki();
}

```

```

Konczyna_Wyniki_Form.Przeslij_Wyniki(sc_konczyny, metoda,
konczyna);
Konczyna_Wyniki_Form.Show();
}

```

List. 1. Implementation of the regression equations

Source: own elaboration.

If the user decides to make calculations for a limb the window appears as in figure 8. Analogically as in the case of a body part the user has to choose one of the calculating method: percentage or regression equations.

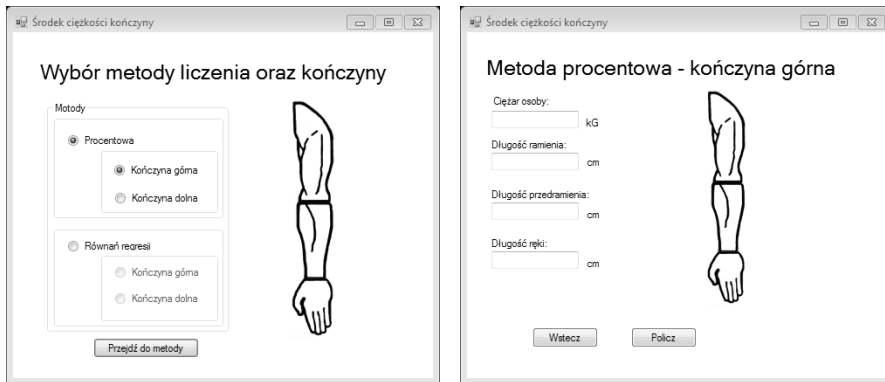


Fig. 8. At left: Window with calculations choosing for a limb; at right: entering data for calculating the center of mass of an upper limb

Source: own elaboration.

After choosing the method and limb the window to enter data appears (fig. 9). At the beginning the algorithm calculates weights and the CoM positions of each part of a limb, then the moments of force and finally it finds the center of mass of a whole limb. The last option from the start window (fig. 4) is calculating the center of mass for whole body (OSC).

The user has following options to choose:

- direct method - a reaction board (fig. 10)
- calculating positions of the center of mass of the human body by percentage method
- calculating positions of the center of mass of the human body by regression equations method

The first option which is the direct method - a reaction board is presented in figure 10.

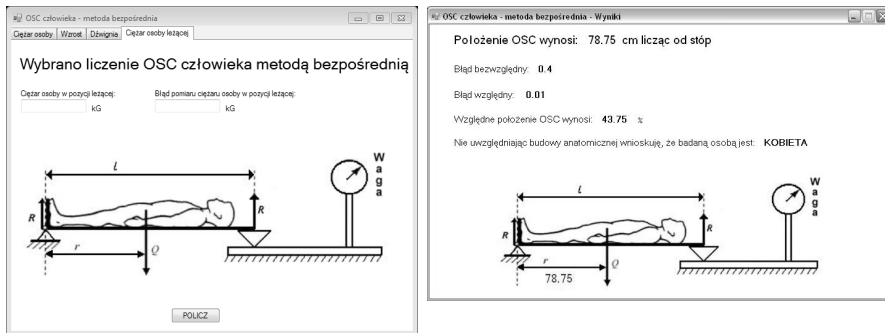


Fig. 10. Direct method – reaction board

Source: own elaboration.

The view of a test stand helps the user to measure the needed values. Additionally in this method the relative and absolute error are calculated.

The options for calculating positions of the center of mass of the human body by percentage method or by regression equations method are based on the idea of the authors described in section 3. As it was mentioned for the calculation weight, height and length of the particular parts are needed. After entering the data in the following bookmarks (fig. 11) and pressing button "Policz" the appropriate coefficients are put into equations. After all calculations the results are presented as graphical representation of CoM together with its values (fig. 2).

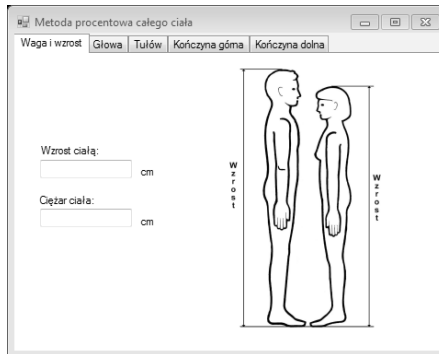


Fig. 11. Entering the data for the percentage method

Source: own elaboration.

3.3. Handling errors

The last function of the program is validation of the entered data. The validation algorithm examines whether the written data is a number or if the value is positive. If the data are incorrect the appropriate message appears (fig. 12).

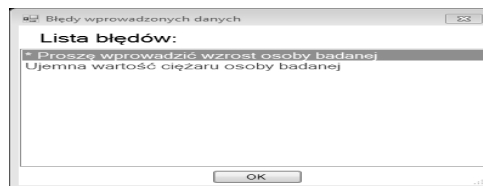


Fig. 12. Exemplary error message

Source: own elaboration.

One of the common mistakes is entering the wrong separation sign: comma instead of a decimal point which is required by the program. To overcome this problem the additional code was written which exchanges automatically the commas into the decimal points in the entering data. It assures that entering the new data is unproblematic.

Conclusions

The program presented in the article calculates the center of mass for human body. The body can be represented as a whole or as an object segmented into 14 parts. Additionally the program allows to calculate the center for an upper and lower limb. Variety of the calculating methods are implemented: the percentage methods (Clauser and Zatsiorsky), the regression equations as well as the direct reaction board method.

In the program the new conception of the calculating the center of mass for whole body was implemented. Using the data determined for the particular body parts and connecting them together to calculate the center of mass for whole body was the idea of the authors which was implemented in the program.

The complementary data obtained from our algorithm were similar to the experimental data from the direct method (less than 5% error).

The program allows to save time and eliminates the possibility of making calculation errors. The practical application will be the usage of the program as an additional tool in the education especially in the biomechanics faculties. The calculations will be easier both for a teacher and students. In the future the image analysis together with the live cameras maintenance will be implemented which may be very useful in professional sport training.

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**KOMPUTEROWE WSPOMAGANIE WYLICZENIA
POŁOŻENIA ŚRODKA CIĘŻKOŚCI CIAŁA CZŁOWIEKA
ORAZ POSZCZEGÓLNYCH JEGO CZĘŚCI**

Streszczenie

Artykuł prezentuje program umożliwiający wskazanie położenia środka ciężkości ciała człowieka, całej kończyny oraz poszczególnych części ciała. Bazuje on na wyznaczaniu środka ciężkości ciała człowieka metodą bezpośrednią (dźwigni jednostronnej) oraz wyznaczaniu środka ciężkości całych kończyn metodą pośrednią (analityczną – sumowanie momentów sił). Ciężary i położenie środków poszczególnych elementów składowych ciała człowieka wyliczane są w oparciu o metodę procentową i równań regresji. Zaprezentowano również nowatorskie podejście wyznaczenia środka ciężkości całego ciała człowieka polegające na opracowaniu algorytmu i jego implementacji w środowisku programistycznym Visual Studio 2010 w wersji Express przy pomocy metody procentowej oraz równań regresji.

Tłumaczenie Ireneusz Dominik