УДК 796:612.76

Erdmann W.S.

GEOMETRY AND INERTIA OF THE BODY AS IMPORTANT FACTORS IN SPORT BIOMECHANICS

A paper describes two important areas of sport science and biomechanics. Geometry takes into account dimensions of the body – linear, planar, spatial. Also angular data and shape of the body are important in sport static conditions and movement. They are obtained using anthropometric devices, images from photography, video, or NMR. Inertial quantities, i.e. mass, density, radius of center of mass, moment of inertia are used to describe resistance of the body or trajectory of the body while in movement.

Key words: *body morphology, geometry, inertia, biomechanics, sport.*

1. BODY MORPHOLOGY

Biomechanics of sport encompasses several important areas, namely: talent identification, body morphology, training, body fitness, technique, tactics, interaction of body and devices, influence of environment, control, cooperation of competitors, diagnosis, competition, refereeing, biological renewal [Erdmann and Grubecki 1995, Erdmann 2008].

Body morphology is one of the first areas of research within biomechanics. There are few branches of morphology, namely: structure of the body, biomaterials, construction, geometry and inertia of the body.

Structure of the body deals with the number of parts that constitute human or animal body and their connections. Here degrees of freedom are analyzed. Human body has, except one (translation movement forward and backward of mandibula), rotational degrees of freedom (Fig. 1 A). There are altogether 244 degrees of freedom for the whole body [Fidelus 1971]. Some researchers presented simplified models of the human body – whole body [Hanavan 1964] – Fig. 1 B, or for the trunk only [Erdmann 1995] – Fig. 1 C. Analysis of structure of the body is necessary when disabled people are analyzed. Here some lack of body parts or using an orthoses or prostheses decides to what parasport group sportspersons should be qualified.

Human body consists of many organs. Every organ has specific tissue content. Tissues have different density, i.e. mass divided by volume. Density of human tissues is within the range between 0.6 (lung tissue) up to 2.0 g/cm^3 (compact bone). The most tissues have density of 1.0 to 1.2 g/cm^3 [Erdmann and Gos 1990]. Biomaterials should be resistant to many internal (muscle) and external forces. They are sensitive to diet, lack of movement or overloading. Human materials can be substituted by other natural or by artificial materials.

Construction of the body takes into account interaction of body build and human movement, maintaining of balance, protection of internal organs. Vertebral column, bones of thorax and of pelvis play a role of protecting internal organs. Vertebral column is also a base for muscle attachments, upper extremities are for reaching and holding goods, and lower extremities are mostly for standing and locomotion. Unfortunately human feet are small for maintaining good balance.

Geometry of the body can be described in one (linear), two (planar), and three (spatial) dimensions. The most important aims of biomechanics of human geometry are:

1) description of body dimensions (internal and external),

2) description of angular movement of body parts with given length and hence reaching objects in space or performing locomotion,

3) presentation of human organism as biomechanism moving within the fluid. The length of body parts can be described between:

a) bony end points,

b) anthropological landmarks,

c) axes of rotation of links.

Inertia of the body describes resistance of the body against acting forces and moments of forces. This is described in translation motion through mass of the body and in rotational motion through moment of inertia of the body (which takes into account mass and its distribution around axis of rotation). Specific distribution of mass can be presented by one point only, i.e. center of mass. Location of center of mass of the body is an important point. This substitutes the whole body during specific analyses. A radius of center of mass is a distance between center of mass and acquired system of reference.

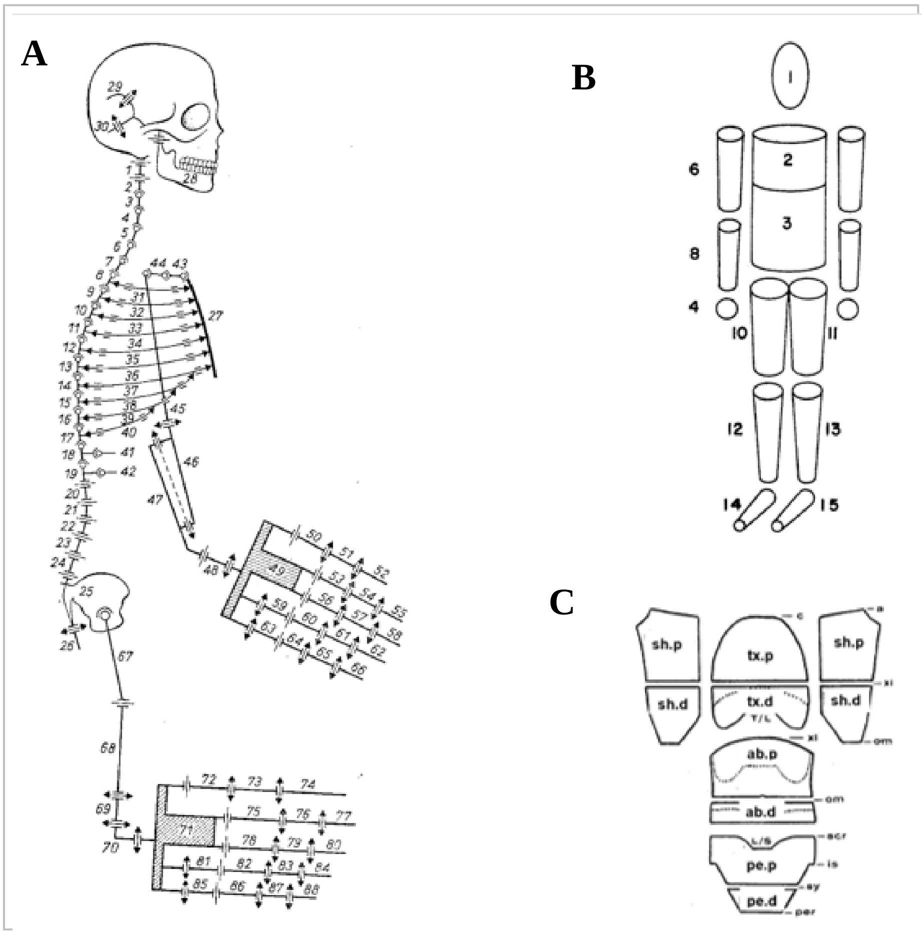


Figure 1. Structure of the human body: A – Full model presented by Fidelus [1971] with marked degrees of freedom; B – simplified model presented by Hanavan [1964]; C – trunk model presented by Erdmann [1995].

2. INVESTIGATIONS OF BODY GEOMETRY AND INERTIA

Geometric dimensions can be obtained using an anthropometric instruments, e.g. an anthropometer, caliper, tape, goniometer. Also photography and video frame (Fig. 2 A) with reference object for linear and planar dimensions, and also using images of the body obtained from different sides (Fig. 2 B and C), immersion in a tank filled with water, laser beam surrounding the body (Fig. 2 D) for spatial dimensions can be used.

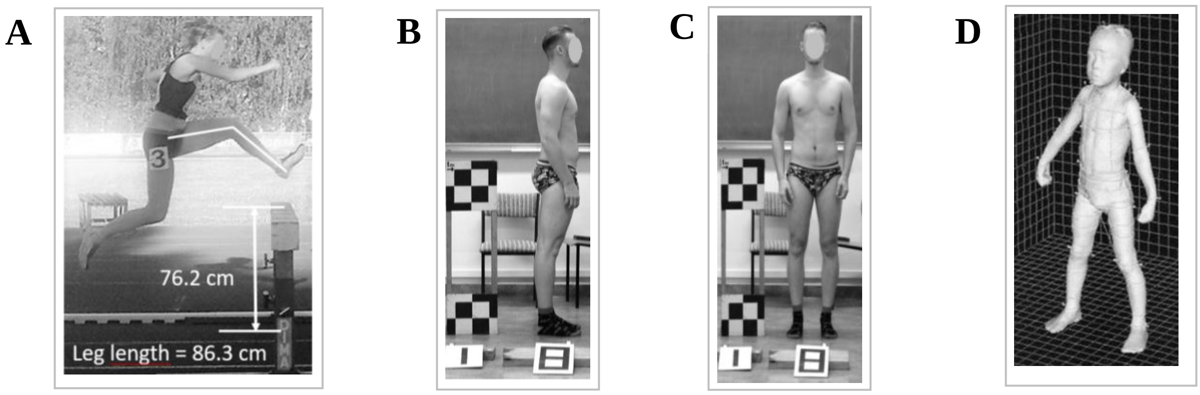


Figure 2. Obtaining dimensions of the human body: from the photography (A – at the stadium; B and C – in a laboratory [photo: W. S. Erdmann]); D – from the laser scanner [photo: Hamamatsu]

Mass of the body is measured using different types of scales with the accuracy usually up to 0.1 kg. There are several sport disciplines where body mass is regulated by the rules (boxing, judo, weight lifting, rowing). There are different types of scales. They are based on a lever (Fig. 3 A) or springs (Fig. 3 B).

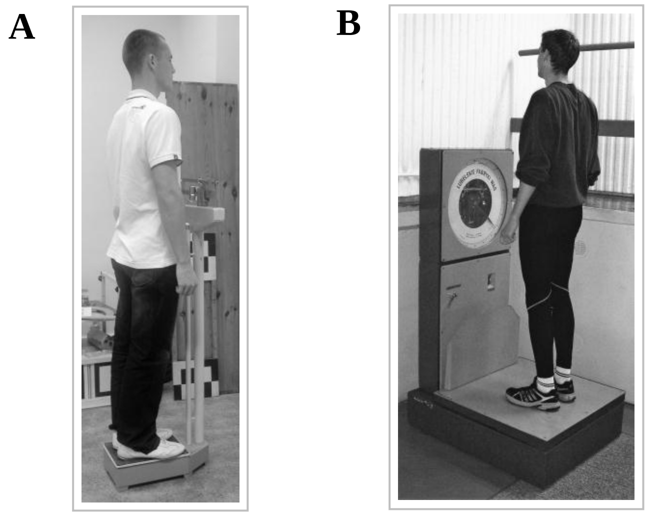


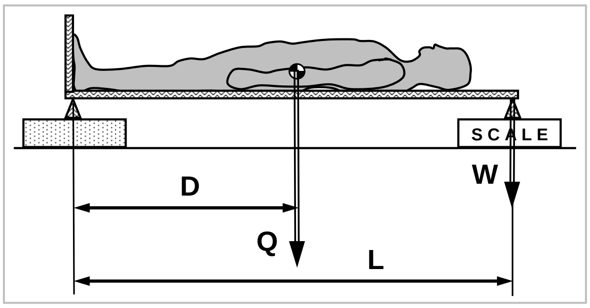
Figure 3. Obtaining mass of the whole body using lever scale (A) or spring scale (B). When a movement takes place in clothes, then a mass of a body with clothes should be measured.

Mass of body parts is obtained in different ways. The first approach was in the 19th century when dead and frozen body was cut into parts and then mass of those parts was compared to the mass of the whole body. In this way relative mass of body parts was obtained (Harless 1860). Then several other researchers repeated this procedure. Important development of methods was a procedure applied by Clauser et al. (1969). They measured geometry of body parts and compared this with inertial values of those part. Based on this they presented regression equations for calculating personal inertial quantities (mass and location of center of mass) of body parts.

Still another methods for acquiring values of inertial quantities are computerized tomography (CT) and magnetic resonance images (MRI). Here x-rays (in CT) and radio frequency energy (in MRI) are used. Erdmann (1995, 1997) presented a method where he utilized data on density of tissues (Erdmann and Gos 1990) and volume of tissues obtained with CT. Then utilizing data on density and volume he calculated mass of tissues and mass of trunk parts. He also gave procedure for calculating personal inertial values of the human trunk by measuring volume of body parts of investigated persons and using density data. The very good validation of both methods (of Clauser and Erdmann) were confirmed by Erdmann and Kowalczyk (2015).

Localization of center of mass can be done through direct and indirect methods. Direct method uses a board lying on two supports (Fig. 4 A), where $D = (W \cdot L)/Q$, after at first subtracting weight of the board. Location of center of mass is described according to the length/height of the whole body (Fig. 4 B). This value usually equals 53 to 55 % of the body height (Bober 1965), but among the sport people who developed extensively upper body part this value can reach even over 60 %.

A



B

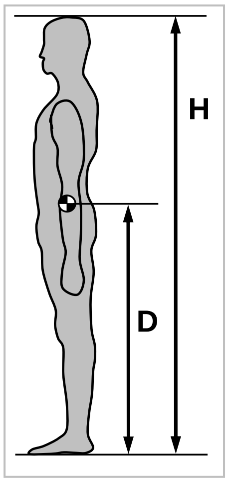


Figure 4. Direct obtaining location of center of mass: A – using a board (L – length of a board, Q – weight of the body, W – value shown by the scale, D – distance from the board's end to center of mass); B – location of center of mass according to the height [Erdmann 2015]

Indirect localization of the whole body center of mass can be performed using an image of the body. Here masses and localization of body parts' centers of mass are needed (Fig. 5 A – C). Two methods can be utilized: 1) summing of masses (graphic) or 2) summing of moments of masses (analytic). Fig. 5 D shows the principle of the first method. For example: mass of hand (ha) and forearm (fa) are added to form mass of koarm (ko) – Fig. 5 E and F. Then mass of arm (ar) is added to form free upper extremity (fu). Next mass of shoulder (sh) is added to form mass of upper extremity (ue). By adding masses of other parts one can obtain location of center of mass of the whole body (wb).

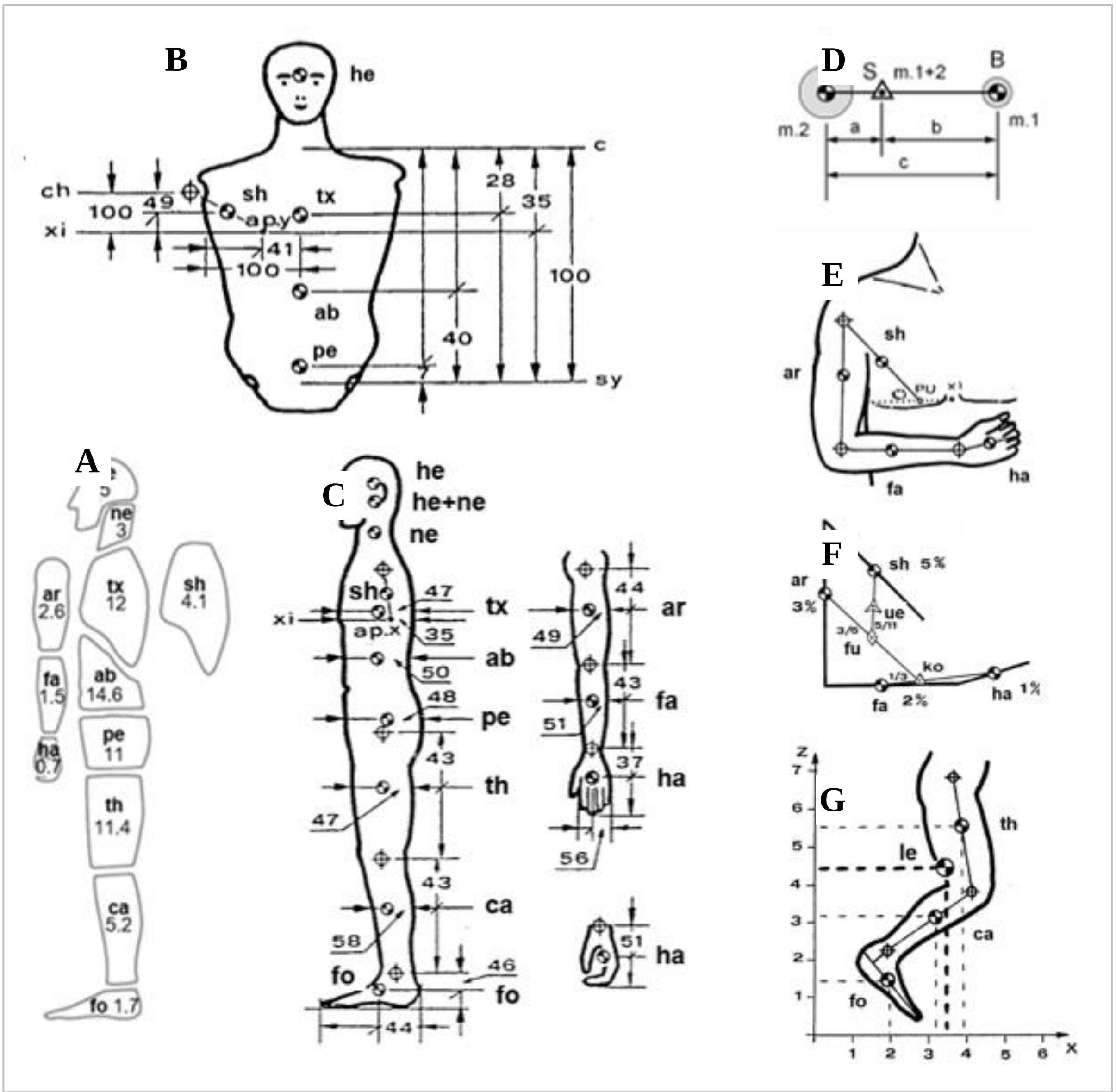


Figure 5. Mass of body parts (A) and indirect localization of center of mass: B and C – location of centers of mass of body parts; C – principle of localization of common center of mass: a = (m1/m1+2)/c; D and E – localization of common center of mass of upper extremity through sum of mass method (here rounded values were used); F – localization of common center mass of lower extremity through sum of moments of mass method [Erdmann 1999]

Within the second method a reference system (two axes for planar analysis) are drawn near the body and then projection of masses onto the reference axes are done. The distance of center of mass (radius of mass) is multiplicated by mass of body part, hence moment of mass is obtained. Moments of all body parts according to both axes are obtained. When sum of the moments is divided by mass of the whole body then the principal radius of mass is obtained. In the crossing of both principal radii (for both axes) lies center of mass of the whole body. Fig. 5 G shows localization of center of mass of lower extremity but this can be done for the whole body or body with the equipment also. This method is used during computerization of localization of center of mass.

3. BODY GEOMETRY AND INERTIA IN SPORT BIOMECHANICS

3.1. GEOMETRY OF THE BODY OF SPORTSPEOPLE

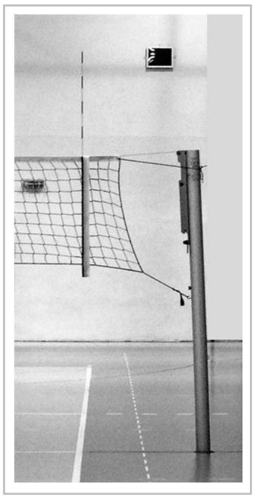
Many sport disciplines give possibility to participate in training and competition for people with very different body dimensions. For example gymnast, coxwain in rowing, female ice-skater in figure skating (pairs) are examples of small dimensions' sportspersons. On the other hand basketball and volleyball player, discus thrower are those who are of a tall body height.

Angular quantities are used for description of technique of movement both in static and in kinetic conditions. Curvatures of the trunk based on curvatures of the vertebral column are analyzed in archery, shooting, gymnastics. Other analyses take into account angular positions of a sprint runner during starting interval for both "on your marks" and "set" commands of the start referee. Yet another analyses deal with angular positions of a sportsperson during his or her movement according to the ground, equipment, partner or opponent.

Shape of the body together with area of surface perpendicular to the direction of movement are important in calculation of air resistance force (drag). An aerodynamical shape, i.e. rounded and broader at the front and slim at the end is a prerequisite for small drag. Sportspeople can adjust their body in order to diminish their drag. They wear special costumes overlying the whole body, e.g. in speed skating.

There is a possibility for adjustment of sport devices for different body dimensions of competitors. For example in volleyball a net is hanged on different height (Fig. 6 A), in gymnastics parallel bars are adjusted to the width of a sportsperson'body (Fig. 6 B), in rowing a stretcher can be moved forward or backward according to the length of rower's lower extremities (Fig. 6 C).

A



B

C

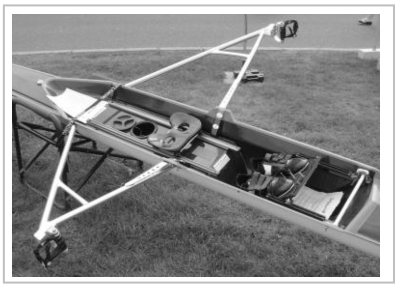


Figure 6. Sport devices adjusted to sportspersons' body dimensions in: A – volleyball; B – artistic gymnastics; C – rowing.

3.2. INERTIA OF THE BODY OF SPORTSPEOPLE

Mass of the body is taken into account in talent identification procedure. For example in athletic throwing, in fighting sports of higher classes, in team handball, in American football competitors of higher body mass are needed.

Several sport disciplines are divided onto categories (classes) according to body mass. This takes into account fighting sports, weight-lifting, rowing. In amateur boxing there are up to 10 classes of senior male competitors and 13 classes of junior male competitors. The highest body mass is recorded in sumo, where competitors can reach even more than 300 kg.

Sportspeople have specific distribution of body mass. Gymnasts, judoists have greater upper body, while football (soccer) players, cyclists have greater lower body. There is also specific mass distribution of disabled competitors. Those who run using bicycles propelled with upper extremities and with not using lower extremities have their body mass substantially moved towards the head.

Moment of inertia of extremities is important factor in all rotational movements in sports, e.g. in running (Fig. 7), throwing, or heating a ball with the racket or stick or bat. The whole body moment of inertia is analyzed in such sports like jumping into the water or gymnastics. In judo attacking competitor who prepares for throwing the opponent at first tries to pull the opponent as closer as possible to his or her body in order to diminish moment of inertia and to achieve higher angular velocity during a throw (Erdmann and Zieniawa 2011).

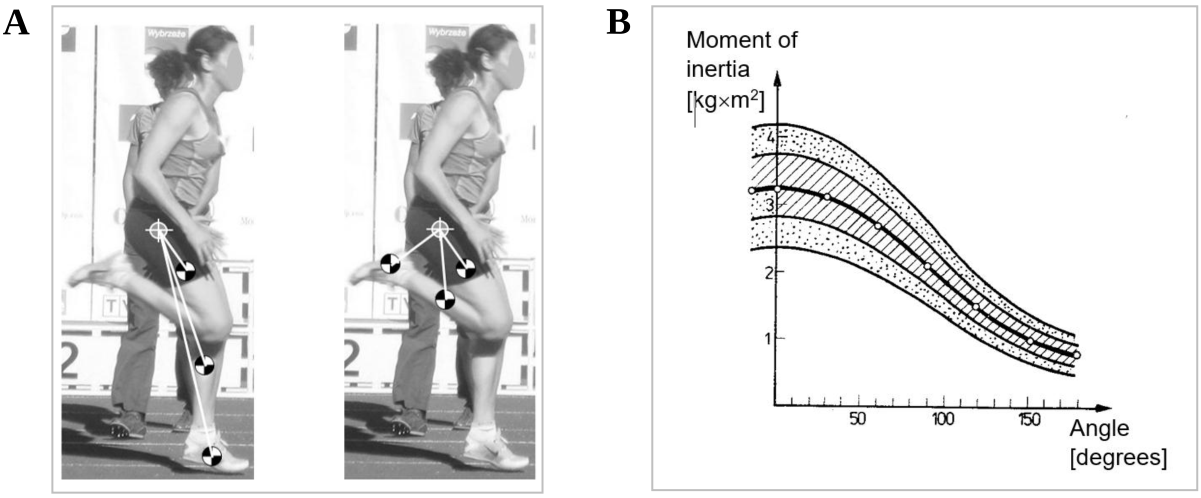


Figure 7. Problem of moment of inertia of the extremity: A – moment of inertia of the lower extremity is of a high value for the extended extremity (left) and is diminished for flexed extremity (right); B – moment of inertia of young fit males according to knee angle: when flexion in the knee joint reaches 150 degrees the moment of inertia diminishes about three times comparing to the straight leg [Erdmann 1987].

Knowledge on location of center of mass is helpful in many sport biomechanics analyses. In alpine skiing one can assess technique of movement by locating center of mass according to the skis (forward and backward), according to the ground/snow (up and down), according to the pole (left and right). In a long jump center of mass helps in dividing a jumping distance onto fragments (Fig. 8 A) , in a high jump location of the center of mass for erect standing body of the competitor is compared with the location of the center of mass during the position over the bar (Fig. 8 B). In judo an attacker needs to lower his or her body comparing to the opponent, which is assessed by location of a centers of mass, in order to execute a throw with higher efficiency.

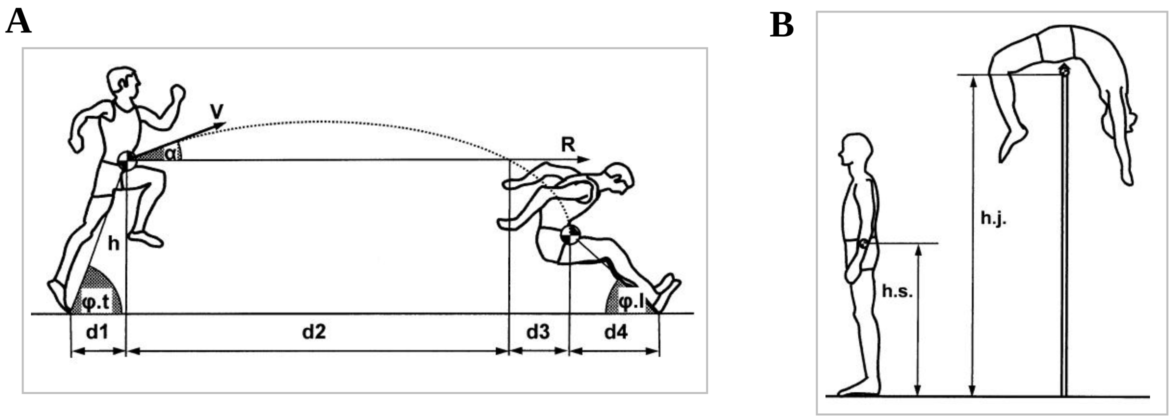


Figure 8. Center of mass utilized for assessment of technique during jumps: A – in a long jump it helps to divide the whole distance into the parts; B – in a high jump it helps to assess efficiency of a jump by comparing h.s and h.j [Erdmann 2007].

Yet another example of applying a knowledge on location of center of mass is hurdle running. The runner needs to lower his or her body during clearing the obstacle in order to rise center of mass as low as possible and not touching the hurdle. Difference of the height of center of mass during clearing the hurdle and height of the hurdle gives possibility for assessment of the clearing – Fig. 9.

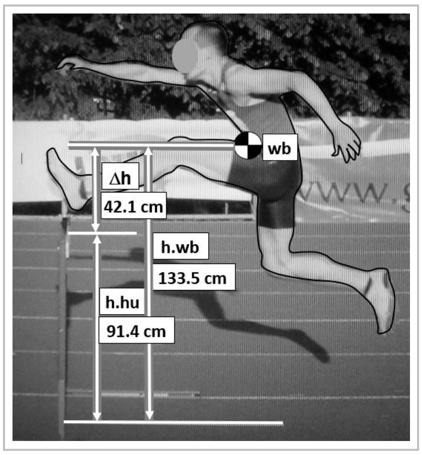


Figure 9. Clearing of the obstacle: a competitor lowers his body in order to diminish his center of mass. Position of competitor's center of mass of the whole body h.wb is compared to the height of the hurdle (h.hu). The difference of these two distances is shown (Δ h).

There are several important geometric and inertial quantities that help to analyze sport movement. Here one can change assessment from qualitative to quantitative. Some rich sport clubs or national teams have their analysts. As the manager Alexander Ferguson said an analyst is a full member of the team (Ferguson and Moritz 2016). But many other sport clubs do not have such a co-worker. The author thinks at the beginning of the 21st century it is a must to have an analyst who will apply knowledge of sportspersons' geometry and inertia of the body.

In order to use analytical quantities one should be accustomed with natural sciences and statistics in order to present data of biomechanics, physiology, motor learning, kinesiology of sport in numbers and to show relationships and dependences.

Bibliography

1. Bober T. [1965] Contribution to the research on center of gravity in humans (in Polish). Physical Culture, 3:156-160.
2. Clauser C. E., McConville J. T., Young J. W. [1969] Weight, volume, and center of mass of segments of the human body. Technical Report AMRL-TR-69-70, Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433.
3. Erdmann W. S. [1987] Individual moment of inertia of the lower extremity of the living young adult male. In: Jonsson B. (ed.) Biomechanics X-B. Champaign, Ill,: Human Kinetics Publishers, p. 1157-1161
4. Erdmann W. S. [1995] Geometric and inertial quantities of the male trunk obtained by computerized tomography method (in Polish with English abstract). Gdansk: J. Sniadecki University of Physical Education.
5. Erdmann W. S. [1997] Geometric and inertial data of the trunk in adult males. J Biomech, 30(7):679-688.
6. Erdmann W. S. [1999] Biomechanics. Guide to exercises (in Polish). Gdansk: May.
7. Erdmann W. S. [2007] Morphology biomechanics of track and field competitors. In: Menzel H. (ed.) XXV International Symposium on Biomechanics in Sports. Belo Horizonte, MG: State University of Minas Gerais, p. 19-26.
8. Erdmann W. S. [2008] Sport activity – systematic approach to science, technology and art. Part one: supportive sport sciences. Research Yearbook: Studies in physical education and sport (currently: Baltic Journal of Health and Physical Activity), Medsport Press, 14(1):44-56.
9. Erdmann W. S. [2015] Biomechanics. Bases for biomedical engineering (in Polish). Gdansk: Gdansk Technical University.
10. Erdmann W. S., Gos T. [1990] Density of trunk tissues of young and medium age people. J Biomech, 23(9):945-947.
11. Erdmann W. S., Grubecki K. [1995] Biomechanical, technology, and informatics problems (in Polish). In: Mroczynski Z. (ed.) Athletics. Part one: Jumps, Throws, Multithlons. Gdansk: J. Sniadecki University School of Physical Education, p. 189-239.
12. Erdmann W. S., Zieniawa R. [2011] Biomechanics of judo. Gdansk: J. Sniadecki University School of Physical Education and Sport.
13. Erdmann W. S., Kowalczyk R. [2015] A personalized method for estimating centre of mass location of the whole body based on differentiation of tissues of a multi-divided trunk. J Biomech, 48:65-72.
14. Ferguson A., Moritz M. [2016] Leading: Learning from my Life and My Years at Manchaster United. Hodder & Stoughton. In Polish – Krakow: SQN.
15. Fidelus K. [1971] Biomechanical parameters of the human upper extremity (in Polish with English abstract). Warsaw: Government Scientific Publishers.
16. Hanavan Jr. E. P. [1964] A mathematical model of the human body. Technical Report AMRL-TR-64-102, Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command. Wright-Patterson Air Force base, Ohio, USA.
17. Harless E. [1857] Static moments of the mass of human parts (in German). München: Abhandlungen der matematisch-physikalischen Klasse der köninglich-bayerischen Akademie der Wissenschaften, 8:71-97.

Стаття надійшла до редакції 26.08.2017