9.4 Methodology for studying the topic «energy conservation law in biomechanical systems» in biomechanics

In teaching the course of biomechanics, methodological orientation is of great importance, which should form students' logical thinking and a number of specific skills.

The law of conservation and transformation of energy is a universal law of nature. All energy transformations occurring in the human body obey this law. Therefore, when studying a biomechanics course, it is important to deepen and generalize students' knowledge of energy and the law of conservation and transformation of energy and apply them to explain the processes occurring in inanimate nature and the processes occurring in the human body.

The relevance of developing methodological foundations for studying the law of conservation and transformation of energy is due to the importance of determining the meaning and place of studying the law of conservation and transformation of energy in the course of biomechanics in order to ensure a high level of its assimilation and development of students' skills to apply the law to explain and predict phenomena observed in the human body, in solving practical problems.

The research chain is to develop a methodology for a successive, step-by-step study of the law of conservation and transformation of energy based on the generalization of knowledge about the concept of «energy» in the course of biomechanics.

The object of research is the process of studying the law of conservation and transformation of energy in the course of biomechanics.

The subject of the study is the methods and techniques of managing the process of studying the law of conservation and transformation of energy in the course of biomechanics.

The authors proceeded from the following hypothesis: if in the process of studying the law of conservation and transformation of energy in the course of biomechanics, using a phased generalization of students' knowledge in organizing their active cognitive activity and implementing successive links with the physics course, this will contribute to:

– increasing the level of students' knowledge on the issues of energy exchange of the human body with the environment; awareness of its essence and application in medicine and sports;

– understanding the role of the law of conservation and transformation of energy in the biophysical processes occurring in the human body.

Based on the goal and hypothesis, the following tasks were set in the work:

– to analyze the origin, historical formation and development of the law of conservation and transformation of energy in science, as well as the modern interpretation of the content of the law in scientific and methodological literature;

– to carry out the selection of educational material, including issues considered on the basis of the law of conservation and transformation of energy, for use in practical classes in the course of biomechanics;

– determine the main stages of disclosure of the content of the law of conservation and transformation of energy in the course of biomechanics; to develop a methodology for a phased and consistent study of the issues of the course of biomechanics, considered on the basis of the law of conservation and transformation of energy; formation of knowledge among students of the concept of «energy», using a phased generalization, implemented on the basis of successive links with the course of physics and the organization of active cognitive activity in practical classes.

The theoretical and methodological basis consists of: at the philosophical level: the scientific theory of knowledge and the ideas of a systematic approach, the dialectic of the process of knowledge; at the general scientific level: a systematic approach, the concept of systematization and generalization of natural science knowledge.

In particular methodological terms: didactic foundations for the study of fundamental laws, the concept of successive-sequential, phased formation and development of concepts, methods of generalization and systematization.

To solve the tasks, the following research methods were used:

– theoretical analysis of scientific, educational and methodical literature;

– modeling method (determining the strategy, stages and methods for studying the law);

– application of the method of generalization of knowledge in the study of the law.

Considering the methodology of the law of conservation and transformation of energy, it is indicated that the importance of the methodology of scientific knowledge is increasing in modern conditions, which is associated with the rapid development of science, especially its branches such as physics, mathematics, biology, cybernetics, etc.

The great interest in methodological issues is evidenced by the broad development of metatheoretical research (metatheory), the close connection of specific scientific research with the problems of methodology. With the further development of our knowledge of nature, the fundamental significance of the laws in modern physics, which are a concrete expression of the objectively existing law of conservation of matter and motion, becomes more and more clear.

Historical formation and development of the doctrine of energy and the law of its conservation and transformation in science.

Scientists and practitioners of all times turned to studies of various energy processes and made attempts to generalize, which contained elements of the formulation of the law of conservation and transformation of energy. If we turn to the history of the discovery of law, the term «energy» appeared only at the last stage of the history of the great law. In addition, it must be taken into account that the main achievements of physics, chemistry and biology, which made it possible to make a real generalization, became known only from the beginning of the 19th century.

Even the thinkers of antiquity (Democritus, Epicurus) asserted the eternity and indestructibility of matter and motion. Everyday practical activity required knowledge of the laws of motion, primarily the only known one - mechanical. And therefore it is no coincidence that the law of conservation of energy began to crystallize within the framework of mechanics.

In 1633, in the Treatise on Light, the idea of the conservation of motion was formulated by the famous French scientist René Descartes (1596-1650): take away from him only as much as he increases his own movement. This idea was further developed by the German scientist Gottfried Wilhelm Leibniz (1646–1716) in his law of the conservation of living forces.

After the classical works of Isaac Newton (1643–1727) and Gottfried Leibniz, the principle of conservation of motion was clearly formulated in the works of M. Lomonosov, who decided to combine two principles of conservation: motion and matter. It was M. Lomonosov is responsible for the discovery of the law of conservation of matter, which was later repeated by the French scientist Antoine Laurent Lavoisier (1743–1794) completely independently of him.

In 1744 M. Lomonosov wrote the words that have become famous, «All changes in nature that occur are such a state of affairs that how much of something is taken from one body, so much will be added to another, so if where a few matter decreases, it will multiply elsewhere ... this universal natural law extends into the very rules movement, for a body that moves another by its force loses as much of it in itself as it communicates to another, which receives movement from it».

So in the middle of the XVIII century M. Lomonosov clearly formulated the law of conservation of mass and motion as a universal law of nature [298]. Moreover, the first part of his expression («all changes in nature that happen ...») is formulated so broadly that if these words were written 100 years later, when other «changes in nature» became known - numerous mutual transformations of energy (electrical, thermal , chemical, mechanical), then other formulations of the law of conservation and transformation of energy and conservation of matter would be superfluous. But, unfortunately, the era was not yet the same, and the scientific works of M. Lomonosov remained unknown for almost 150 years.

In order to be able to comprehend the qualitative transformation of energy from one of its forms to another, the necessary and sufficient scientific and technical prerequisites had to be formed. The most important among these prerequisites were the development of the theory of heat and heat engineering practice. It is known what role fire played in the development of man at the dawn of his history. In the process of labor activity, a person learned to make fire by friction. In the production of fire by friction, a qualitative transformation of mechanical energy into thermal energy was already manifested.

The theory of caloric objectively prevented the establishment of interrelations between mechanical and thermal energy for a long time. It was believed that caloric is squeezed out of a substance when it is compressed, for example, when a gas is compressed, like juice from an orange. Brilliant thoughts of M. Lomonosov about molecular motion as a source of heat, about the kinetic nature of heat in a broader sense, remained out of sight of the general scientific community.

The most tangible blow to the theory of caloric already in the era of steam engines (1798) was inflicted by the experiments of the American Benjamin Thompson (1753–1814), better known in Europe under the title of Count Rumfoord. When drilling gun barrels in Munich, Rumford observed the release of heat, which, however, was known to everyone. However, Rumfoord was able to show that an almost unlimited amount of heat can be released in this case. In his experiments, he took measures to isolate the drill and the barrel in order to exclude the flow of caloric, this «substance of heat», from somewhere outside.

But for about 30 years after Rumford's experiments, the theory of caloric, corrected and refined, continued to occupy a dominant position in explaining the cause of heat. Essential for understanding the fact of the transformation of one type of motion (for example, mechanical) into another (for example, thermal) was the idea of an equivalent, in particular, the mechanical equivalent of heat.

The drama of the history of the discovery of the law of conservation and transformation of energy consisted in the fact that almost until the moment of full recognition of this law, almost every previous discovery confirming its validity was either not published, or it was not paid due attention, or it was simply met with hostility by official science.

The relevant works of M. Lomonosov until 1904 were in oblivion, and being published in Russia at one time, they did not penetrate into the laboratories of the West. Rumfoord, having shaken the foundations of the theory of caloric, could not overthrow it, without finding evidence of the equivalence of the transformation of mechanical motion into heat.

The twenty eight year old talented French engineer Sadi Carnot (1796-1832) published in 1824 a remarkable work «Reflections on the motive force of fire and on machines capable of developing this force», in which he set forth what later became known as the second law of thermodynamics, or «Carnot principle». But later studies, in which S. Carnot abandoned the theory of caloric and determined for the first time the mechanical equivalent of heat, were not published in a timely manner, and his manuscripts became known only in 1878.

In an appendix to his only book, S. Carnot wrote: «Heat is nothing but a driving force, or, rather, a movement that has changed its appearance.» This is the movement of body particles. Wherever there is an annihilation of the motive power, there simultaneously arises heat in an amount exactly proportional to the amount of the vanished motive power. Conversely, always with the disappearance of heat, a driving force arises. According to the measurements of S. Carnot, the mechanical equivalent of heat was 370 kg*m (recall that this value is 427 kg*m, or 4186 J).

The theoretical studies of S. Carnot answered the specific question posed by the developing industry, how to make a heat engine more economical. S. Carnot proceeded from the conviction that it was impossible to implement a perpetual motion machine. But his contemporaries did not pay the attention that these works deserved.

Studies of the chemical, thermal and mechanical effects of electric current, the discovery of the phenomenon of electromagnetic induction in the first 40 years of the 19th century. served as the second important prerequisite for the discovery of the law of conservation and transformation of energy. In 1836, M. Faraday formulated two laws of electrolysis, by which he established the relationship between the amount of electricity and the chemical properties of a substance.

The great English physicist quite definitely emphasized the need to establish equivalents between different types of energy, or, in the terminology of that time, between different forces. He wrote: «We have many processes in which the external form of force can undergo such changes that it is clearly transformed into another. So, we can turn chemical force into electric current, and electric current into chemical force.

The excellent experiments of T. Seebeck and J. Pelte show the mutual connection of heat and electricity, and G. Oersted and my own show the convertibility of electricity and magnetism. But in no case, not even with the electric eel and the ray, is there any production of force without a corresponding expenditure of something that feeds it.»

In his diary in 1837, M. Faraday wrote: «It is necessary to compare the number of material forces (i.e., the forces of electricity, gravity, chemical affinity, cohesion, etc.), where it is possible to give an expression for their equivalents in one or another form».

An important role in the discovery of the law of conservation and transformation of energy was played by the works of E.Kh. Lenz and, in particular, his discovery of the law on the direction of the induced current and the principle of reversibility of electrical machines. An important prerequisite for the discovery of the law of conservation and transformation of energy was the success of biology.

The myth about a special «life force» in human and animal organisms was dispelled. A direct relationship has been established between the amount of food consumed and the ability to do work. The 40s of the 19th century were a time of broad generalizations. History assigns the decisive role in establishing the law of conservation and transformation of energy to the German scientists R. Mayer (1814–1878) and Hermann Helmholtz, as well as to the English physicist James Joule (1818–1889).

R. Mayer was a ship's doctor on a Dutch ship, when in 1840 «suddenly» he came up with the idea of the law of conservation and transformation of energy. The word «suddenly» is not in quotation marks for nothing: R. Mayer later wrote about a sudden insight, but can a discovery be sudden, the prerequisites of which were well known to a graduate of the University of Tübingen? For R. Mayer, the initial impetus was sudden: he drew attention to what was well known to doctors who constantly work in tropical latitudes.

During the stay of the ship in Java, a sailor fell ill, and R. Mayer, as was then customary, «let him bleed», opening a vein. Imagine his surprise when he saw that the venous blood was not as dark as in temperate latitudes. R. Mayer realized that at a high average air temperature, fewer nutrients and less «burning» of the latter are required to maintain vital activity and the necessary temperature of the body. A comparison of numerous scientific facts from the field of chemistry, physics and biology led him to the fact that the thoughts, according to the expression of R. Mayer, which pierced him like lightning, led him to the conclusion about the existence of a universal law of nature.

In 1841, R. Meyer wrote an article «On the Quantitative and Qualitative Determination of Forces», but the editor of a well-known physics journal in Europe did not consider it necessary to publish it. The manuscript of the article was found in the editorial archives and published only in 1881, i.e. 40 years later.

The next article «Remarks on the forces of inanimate nature» was published in 1842. In this work, R. Mayer pays much attention to the interconversions of mechanical work and heat, not knowing about the corresponding study by S. Carnot, determines the mechanical equivalent of heat (according to his data, it is equal to 365 kg*m/kcal), speaks of the «indestructibility» of forces and formulates his own principle. Here, R. Mayer, for the first time in the history of science, puts the meaning of «energy» into the concept of «force», without pronouncing this word yet (however, the word was uttered earlier; with this word, the English physicist Thomas Jung (1773–1829) designated a quantity proportional to mass and square of the speed of the moving body). The ideas of R. Mayer were of such a general and universal nature that at first they were not accepted by contemporaries. His life turned into a continuous struggle for the assertion of his principle.

Classical measurements of the mechanical equivalent of heat were carried out in 1841–1843. (published 1843) D. Joule. According to him, this equivalent was 460 kg*m/kcal. D. Joule also established, independently of E. Lenz, the relationship between electric current and the heat released (the Joule-Lenz law). It is interesting to note that the British Society (as the British Academy of Sciences is called) refused to publish D. Joule's work in full, demanding more and more experimental clarifications from him.

Finally, G. Helmholtz in 1847 in his work «On the Conservation of Force» gave the most general form of the conservation law, showing that the sum of potential and kinetic energy remains constant. G. Helmholtz derived the expression for the electromotive force of induction based on the law of conservation of energy. There, for the first time, a mathematical interpretation of the law is given. W. Thomson's report «On the dynamical theory of heat» (1851) can be considered the completion of the long path traversed by science to the exact formulation of the law of conservation of energy.

W. Thomson in 1860 introduced the term "energy" into science in its modern sense. The well-known Scottish physicist W.J.McQ. Rankin (1820–1872), one of the founders of technical thermodynamics, came to the same interpretation of the term «energy» in 1853.

It is appropriate to finish the presentation of the history of the discovery of the law with the words of the outstanding English physicist and public figure J. D. Bernal (1901–1971), written 100 years later: «The law of conservation of energy ... was the greatest physical discovery of the middle of the 19th century. He combined many sciences and was in exceptional harmony with the trends of the time. Energy has become the universal currency of physics - so to speak, the gold standard of changes that have taken place in the universe .... All human activity in general-industry, transport, lighting, and ultimately food and life itself - was viewed in terms of being dependent on this one general term - energy».

Energy and its types

Energy is a scalar physical quantity, which is a single measure of various forms of motion and interaction of matter, a measure of the transition of matter from one form to another.

One of the reasons that energy is so difficult to describe is that it can take many forms, and not all of them are easy to understand. Here are the most common varieties:

– Mechanics distinguishes between potential energy (or, in a more general case, the energy of interaction of bodies or their parts with each other or with external fields) and kinetic energy (energy of motion). Their sum is called total mechanical energy.

– Energy is possessed by all kinds of fields. On this basis, they distinguish: electromagnetic (sometimes separated into electric and magnetic energies), gravitational (gravitational) and atomic (nuclear) energies (can also be divided into weak and strong interactions).

– Thermodynamics considers internal energy (the sum of the energies of molecular interactions and thermal motions of molecules) and other thermodynamic potentials.

– In chemistry, such quantities are considered as: binding energy and enthalpy, which have the dimension of energy related to the amount of substance; chemical potential. Explosion energy is sometimes measured in TNT equivalent.

– Vacuum energy is energy evenly distributed in a vacuum and causing repulsion between any material objects in the Universe with a force directly proportional to their mass and the distance between them. It has an extremely low density.

– Osmotic energy is the work that needs to be done to increase the concentration of molecules or ions in a solution.

– Energy can be enclosed in the mass of an object. Thanks to the well-known equation of the special theory of relativity, energy is associated with mass: $E=mc^2$, where E - system energy, m - its mass, c - the speed of light in vacuum.

– In any of these cases, there are exact formulas that describe the energy stored in the system and well-defined ways to measure it.

The law of conservation of energy

Energy is a special quantity of great importance to physics. The reason for this importance is that it is «preserved». Why is the energy saved? Because of the mathematical principle, correlating the fact that the laws of nature do not change over time, with the existence of a conserved quantity, which we by definition call «energy».

We owe the most famous and general definition of this principle to Emmy Noether, one of the greatest mathematical physicists of the previous century, a contemporary of Einstein. Some members of the physical and mathematical community treated her with deep respect, but at that time in her native Germany, she suffered from discrimination based on gender and nationality (there they blocked attempts to assign her the title of professor in Göttingen, and from there she had to flee after the Nazis came to power). After emigrating to the United States, after only two years of teaching at Brin-Mar College (which to this day accepts only women for training), she died of cancer.

The famous Noether’s theorem tells us that if there is symmetry in the laws of nature - in our case, this means that the laws of nature are the same at any moment in time - then this preserves a certain amount - in our case, energy. In other words, the law of conservation of energy is equivalent to the uniformity of time, that is, the independence of all laws describing the system from the point in time at which the system is considered [298].

The general formulation of the law of conservation and transformation of energy: in all phenomena occurring in nature, energy does not arise and does not disappear, it only turns from one species to another, while its value is preserved.

For each type of energy, the conservation law can have its formulation, which differs from the universal one.

Particular forms of the law of conservation of energy: in classical mechanics:

– in an isolated mechanical system, where only conservative forces act, the total mechanical energy is conserved;

– in thermodynamics - the first beginning of thermodynamics: the amount of heat received by the system goes to change its internal energy and perform work against external forces;

– in electrodynamics - Poynting's theorem: a change in electromagnetic energy enclosed in a certain volume for a certain time interval is equal to the flow of electromagnetic energy through the surface limiting a given volume and the amount of thermal energy released in a given volume taken with the opposite sign.

Many scientists have contributed to the establishment of the energy conservation law, among them: R. Descartes, G Leibniz, M. Lomonosov, J. Gay-Lussac, M. Faraday, S. Carnot, B. Clapeyron, D. Joule, R. Mayer, G. Helmholtz.

The law of conservation of mechanical energy

Elementary and complete work of force, power

Elementary work *dA* of force F on elementary movement *ds* defined as follows (see Fig. 1):

$$dA = F_\tau \cdot ds = F \cdot \cos\varphi \cdot ds \qquad (1)$$

where $F_\tau = F \cdot \cos\varphi$ – the projection of the force on the direction of the speed of the point of application of force or on the direction of elementary movement, which is considered to be directed along with the speed of the point; φ - the angle between the force and the direction of the speed of the point [299].

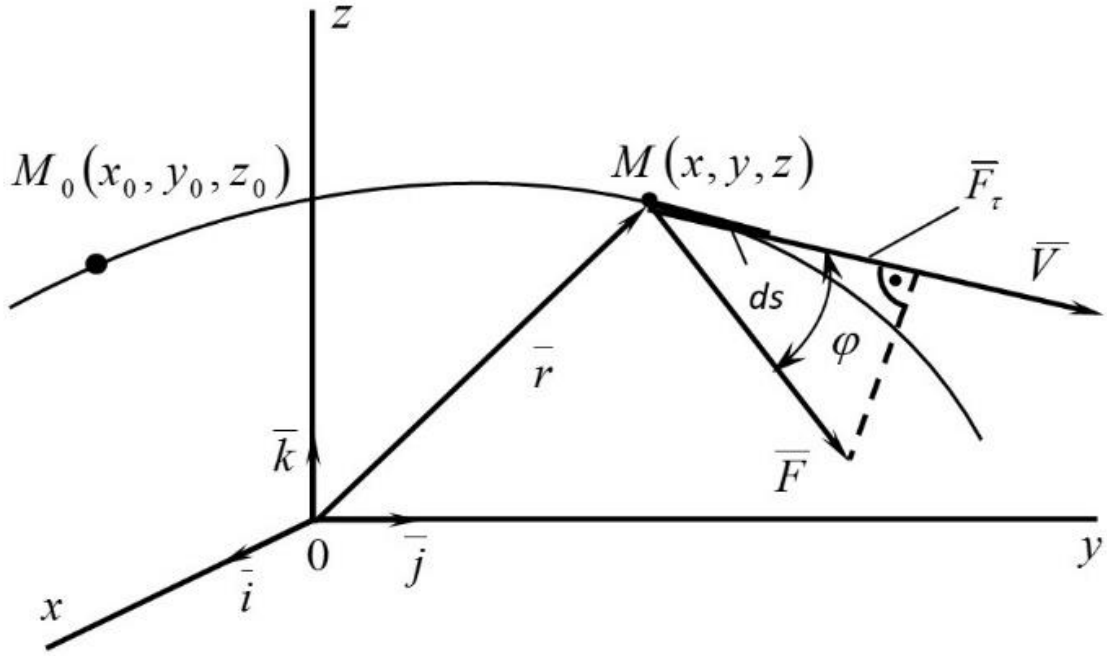

Figure 1. Elementary work dA of force F on elementary movement ds

The full work of the force F on moving from point M_0 to point M can be expressed by the formula

$$A = \int_{M_0}^{M} F_\tau \cdot ds \qquad (2)$$

Examples of calculating the work of force [299].

The work of gravity of a material point by mass m:

$$A = \pm mgh \qquad (3)$$

where mg – the force of gravity, h - vertical movement of a point.

It is noticed that when walking and running with an increase in the speed of movement of the human body, work increases. So, for example, the work of gravity on the vertical movement of the general centre of mass (G.C.M.) of the body is minimal at a walking speed of about 4 km/h, increases at a walking speed of up to 7 km/h, and then stabilizes. And when running at speeds up to 17 km/h, this work increases, and then stabilizes and may even decrease.

Increase to certain limiting values of the work of gravity on vertical movement G.C.M. body with an increase in speed when walking and running because there is an increase in the values of vertical displacements G.C.M. by lengthening the steps. With the then observed stabilization of vertical movement, G.C.M. energy expenditures go mainly on overcoming the path.

The work of the linear elastic force acting according to Hooke's law:

$$A = -\frac{c}{2}\lambda^2 \qquad (4)$$

Here c - stiffness coefficient, λ - deformation.

Dry slip friction force work:

$$A = -F_f s \qquad (5)$$

where F_f - constant in magnitude dry sliding friction force, s - distance travelled.

The full work of the moment M_z of force relative to the *z*-axis when turning through an angle φ is calculated by the formula:

$$A = \int_0^{\varphi} M_z d\varphi \qquad (6)$$

The power of the force, or the performance of a source of power, is often evaluated by the work that it can do in a unit of time:

$$W = \frac{dA}{dt} \qquad (7)$$

In the SI system, work is measured in *Joules (J),* and the power unit is *Watt:* 1 *W* = 1 *J/s.*

The ratio of the useful power W_u to the spent W_s shows how efficiently energy is used and is called the coefficient of performance (COP), which is expressed as a percentage:

$$COP = \frac{W_u}{W_s} 100\% \qquad (8)$$

The work and power that are characteristic of a person depend on many factors. With short-term efforts, a person can develop the power of the order of several kilowatts.

For example, if an athlete weighing 70 kg bounces so that his centre of mass rises by 1 m (relative to the normal stance), and the repulsion phase lasts 0,2 s, then he develops a power of about 3,5 kW.

Kinetic energy

The kinetic energy of the system *T* is the sum of the kinetic energies of all points of the mechanical system, i.e.:

$$T = \sum \frac{m_k v_k^2}{2} \qquad (9)$$

In the formula (9), m_k - the mass and v_k - velocity of the *k*-th point of the system.

In particular cases of the motion of a solid, the kinetic energy is determined by the formulas:

with progressive

$$T = \frac{MV^2}{2} \qquad (10)$$

with rotational

$$T = \frac{J_z \omega^2}{2} \qquad (11)$$

with flat

$$T = \frac{MV_C^2}{2} + \frac{J_{Cz}\omega^2}{2} \qquad (12)$$

Here: *M* and *V* – body weight and speed, J_Z - the moment of inertia of the body about the axis of rotation O_Z , ω – body angular velocity, V_{Cz} – the centre of mass velocity, J_{Cz} - the moment of inertia of the body about the axis C_Z , passing through the centre of mass of the body perpendicular to the plane of motion.

A theorem on the change in the kinetic energy of a system in a finite, or integral, form:

$$T - T_0 = \sum A_k^{(e)} + \sum A_k^{(i)} \tag{13}$$

Where T_0 and T -- kinetic energy in the initial and final positions of the system, $\sum A_k^{(e)}$ and $\sum A_k^{(i)}$ – the work of the external and internal forces of the system when it moves from the initial to the final position.

The potential energy of the system P in the considered position of the potential force field is the sum of the work of the field forces acting on the system, which these forces perform when the system moves from the considered position to the initial position.

For example, the potential energy of a body located in position B (see Fig. 2) is equal to the work that potential forces will produce when it moves to its original (zero) position A [300].

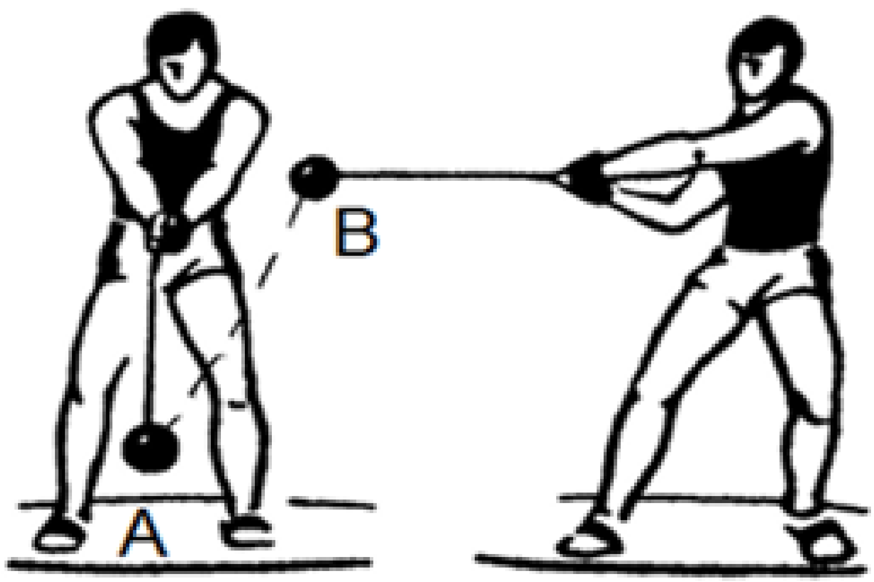

Figure 1. An example of determining potential energy

For a dissipative system, during the movement of which there is a medium resistance (external friction) or internal friction, the total energy of the system decreases and is equal to:

$$E = T + P = T_0 + P_0 + A_D \qquad (15)$$

where AD (AD < 0) - the work of dissipative forces, for example, friction forces in joints, friction forces between muscle fibers, etc. Dissipative (scattering) forces lead to a decrease in the total mechanical energy in the systems. In this case, the energy lost (dissipation energy) goes into heat energy.

Energy on impact

Upon impact, the law of conservation of momentum and the law of conservation of angular momentum is satisfied, but usually (under real conditions) the law of conservation of mechanical energy is not satisfied. Loss of kinetic energy upon impact (according to Carnot's theorem):

$$T = (1-k^2)\frac{m_1 m_2}{m_1+m_2}\frac{(u_1-u_2)^2}{2} = \frac{1-k}{1+k}\left[\frac{m_1(u_1-v_1)^2}{2} + \frac{m_1(u_2-v_2)^2}{2}\right] \qquad (16)$$

Here: m_1 and m_2 - body mass, u_1 and u_2 - body speed before impact, v_1 and v_2 - body speed after impact, k - recovery ratio.

Besides, with a real impact of macroscopic bodies, the colliding bodies are deformed and elastic waves propagate along with them, transmitting interaction from the colliding boundaries throughout the body.

The factor (1 - k2) determines the fraction of the initial kinetic energy transferred to other types of energy upon impact. For biosystems, the value of k can be regulated by the forces of the muscles of the biokinematic chain involved in the shock. Note that the recovery coefficient when hitting the ball with the hand can be a value from the range of its values - 0.1 ... 0.2, and when hitting the ball with the foot -0.4 ... 0.5.

Bioenergy

Work and human power. Ergometry

When walking at a constant speed on level ground, a person also does the work, although his kinetic energy does not change. In this case, the energy is spent mainly on periodically raising the centre of mass of the body and on accelerating or slowing down the legs. Part of this energy goes to the heating of the body due to the «resistance» of its parts and the heating of the environment.

For example, a person weighing 70 kg when walking at a speed of 5 km/h develops a power of about 60 watts. With increasing speed, this power rapidly increases, reaching 200 watts at a speed of 7 km/h. When riding a bicycle, the position of the centre of mass of a person changes much less than when walking, and the acceleration of the legs is also less. Therefore, the power spent when riding a bicycle is much less: 30 W at a speed of 9 km/h, 120 W at 18 km/h [300].

The work done by the muscles when performing active movements is called dynamic. This work involves moving parts of the body. In the case when a person keeps his posture unchanged, such movements are absent, and in the absence of movement, the work of all forces is zero.

Therefore, it may seem that a person standing motionless does not spend energy. However, experience shows that maintaining a fixed posture for a long time causes significant fatigue. Even more tired is a person holding a dumbbell in his outstretched arm. A seated person also feels tired muscles of the back and lumbar region if a load is placed on his shoulders.

The cause of fatigue (and hence energy consumption) under static loads is that peace, in this case, is apparent. Due to the biological activity of muscles in humans, physiological tremor is always observed (Latin tremor - trembling). In this case, very small and very frequent contractions and relaxation of muscles occur that are invisible to the eye.

Consequently, the muscles are constantly doing work (such work is called static) and spend energy. Muscle strength decreases and a break is required to restore it. This explains the fact that a standing person from time to time transfers the weight of the body from one leg to another [301].

Ergometers. To measure the work of a person, instruments called ergometers are used. The figures show various types of ergometers.

Figure 3. Upper Body Ergometer Workout [302]

Figure 4. Bicycle ergometry [303]

Figure 1. Classic range ergometer Power Tower [304]

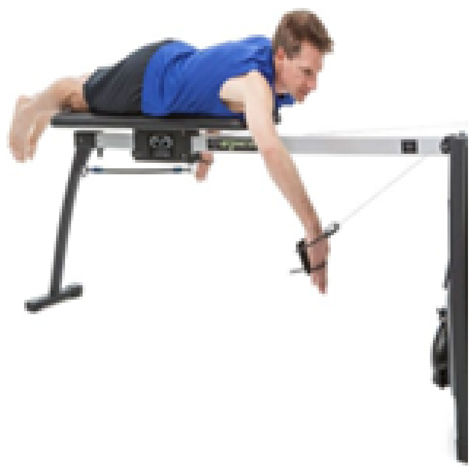

Figure 2. Swim ergometer [305]

Figure 3. Upper body ergometer [306]

Figure 4. Kayak ergometer [307]

Figure 9. Canoe ergometer [308]

Figure 10. The SUP Ergo Machine: Paddle [309]

For example, a bicycle ergometer (Fig 11, [310]) is designed to measure useful work and power when riding a bicycle.

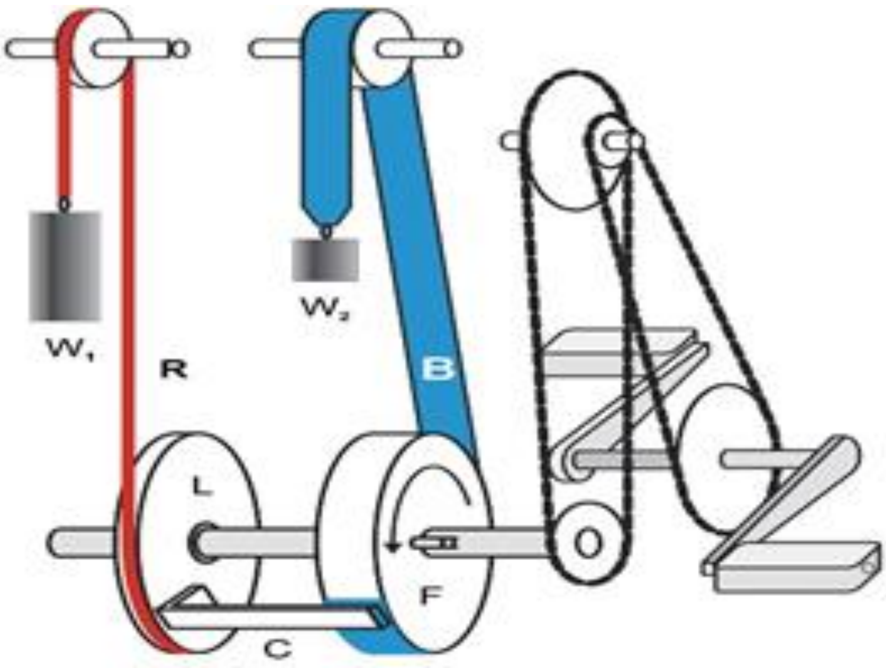

Figure 11. Fleish ergometer; F et L fast et loose wheels, C connection between pulley L and belt B that is attached to weight W_2 at the other end. [310]

To do this, a steel tape is thrown over the rim of the wheel that the subject rotates. The frictional force between the belt and the wheel rim is measured by a dynamometer. All the work of the subject is spent on overcoming friction. Multiplying the circumference of the wheel by the force of friction, they find work that is perfect for each revolution. Knowing the number of revolutions and the test time, they determine the total work and average power [311].

Running energy. Suppose a runner moves at a constant speed on a horizontal surface. The work that is being accomplished comes down to overcoming friction and air resistance. When running, the effect of friction is small, but running at a constant speed is associated with significant energy costs.

Energy is spent on moving the runner’s body up and down and pushing it off the ground with his feet. Also, the runner's body turns energy into heat. An additional reason for the loss of energy is that the legs of the runner, whose mass is about 40% of body weight, are constantly accelerated and braked during the run. Therefore, the work performed by the leg muscles to maintain the body moving forward at a constant speed is great.

In a first approximation, we can assume that the work performed by the runner's muscles in one step is proportional to the kinetic energy imparted to that leg, which, after being repelled from the ground, is carried forward:

A ~ mv2 (т - foot mass). At the same time, this work is determined by the formula A=F·d, here F - muscle strength, d - the distance at which the muscles perform work at each step. It is believed that muscle strength (F) is proportional to the square of the characteristic length (L2), and mass (m) is proportional to the cube of the characteristic length (L3). Besides, the distance d is proportional to L. Therefore,

$$v^2 \sim \frac{2Fd}{m} \sim \frac{L^2 L}{L^3} = const \qquad (17)$$

Thus, we can assume that the speed that the runner can maintain does not depend on its size. The approximate values of the speeds that humans and some animals can develop are presented in table 1.

Table 1.

Animal and Human Speeds

An object	Speed m/s	An object	Speed m/s
1	2	3	4
Cheetah	30	Wolf	18
Gazelle	28	Hound dog	16
Fox	20	Human	11
Hare	18		

People are unimportant runners. This is because the weight of a person's legs is about 40 % of body weight and requires a significant amount of energy for each braking and acceleration. The fastest animals have thin legs, and the bulk is concentrated in the body. The large muscles of the legs in some animals (lion, tiger, big cats) are adapted for jumping, and not for fast running [300].

A person is limited in the amount of work performed by him, not only the energy required for this but also the speed of its use, that is, power. For example, a person can walk a long distance up the stairs before being forced to stop because too much energy has been used up.

However, when climbing at a high pace, he may fall exhausted, having overcome only a small part of the path. In this case, the limitation is set by the amount of power expended, i.e., the speed with which a person, through biochemical processes, converts the chemical energy of food into mechanical work.

The fact that an active body often functions to the point of its ultimate capabilities is confirmed by many cases when athletes tear muscles, ligaments, and tendons in competitions.

The power consumption of a person with a mass of 70 kg for various types of activity and when performing physical exercises is presented in table 2 and table 3 [300]. The idea of human efficiency is given by table 4, which presents information about the useful and spent power when performing exercises on a bicycle ergometer (60 rpm).

Table 2.

Human energy consumption for various activities (indicative values)

Kind of activity	Power consumption, W
1	2
Class preparation	105 - 125
Practical exercises (laboratory work)	110 - 125
Reading to oneself	100
Physical exercise	265 - 380
Swimming	550
Sleep	70
Calm lying	85
The stand is free	130
Motorcycle control	160

Table 3.

Human energy consumption during physical exercises in the group of physiotherapy exercises

Exercise	Power consumption, W
1	2
Running, 9 km / h	750
Cycling 8.5 km / h	345
Cycling, 15 km / h	490
Cycling, 20 km / h	690
Swimming 10 m/min	250
Swimming 20 m / min	355
Swimming 50 m / min	850
Rowing 50 m / min	215
Rowing 80 m / min.	440
Volleyball	265
Football	620 - 930
Basketball	780

Table 4.

The efficiency of a person when performing exercises on a bicycle ergometer (60 rpm)

Developed power, W	Power consumption, W	Efficiency,%
1	2	3
50	236	21
75	355	21
100	475	21
125	595	21
150	710	21
175	830	21

Bioenergy of motor actions

Bioenergy of the motor actions of the human body and its links is determined by the metabolic reactions of the body, supply and energy consumption. Sources of energy are chemical energy received by the muscles of the body as a result of chemical reactions, as a result of which contractile components are included in the work and their mechanical energy passes into the potential energy of deformation of sequential and elastic parallel components.

Another source of energy is the energy of the external environment, mechanically in contact with humans. All movements of the links and the human body are accompanied by the conversion of the potential energy of the muscles into the kinetic energy of the links with which the muscles are connected. The accumulation of potential muscle energy occurs due to their stretching in inferior work. The links and the human body can accumulate potential energy in some cases due to their movement against gravity. When moving, a person spends kinetic energy on the movement of his body, its links and external bodies. These costs are used to solve motor problems and to overcome external resistance. A significant part of the energy in the process of movement goes into heat, which is usually attributed to losses. As experimental studies show, for a person, only 25 % of the total energy consumption is spent on mechanical work. Because the human body from the point of view of mechanics belongs to the so-called non-conservative mechanical systems, which are characterized by partial dissipation (dissipation) of energy, determining the costs and energy of such systems, generally speaking, it is difficult to solve.

At the same time, with the adoption of certain assumptions, this problem can be solved under the assumption that these systems are conservative. The unaccounted-for scattering energy is estimated in various ways, for example, by separating the mechanical processes that occur due to the accumulated mechanical energy of muscle contraction and the thermal, electrochemical and other processes leading to scattering that accompany mechanical processes in biosystems during movement. The accumulated energy is acquired by the human body through nutrition and respiration, as well as other sources.

Energy models of biomechanical systems are used in biomechanics to determine the energy characteristics and energy costs of the muscle groups of the bone motor apparatus and its components during various movements carried out by biosystems. The main energy characteristics of biomechanical systems include mechanical work and different types of energy of the bone link and their joints in joints, power to maintain body speed, metabolic and non-metabolic energy of muscles during various motor actions, locomotion and other movements of the human body.

The mechanical work of internal forces in joints (joints) can be determined from the data on the values of the moments of forces and angular velocities of rotation of the links in the joints. Note that articular moments are called control moments, reflecting with this name the fact that a person controls his movements by changing their action on the links of a biokinematic pair.

The values of the articular moments are determined using the theorem on the change in the kinetic moments of the links relative to their centres of mass. To solve this problem, a biokinetic model of the musculoskeletal system of the human body is used, taking for it the geometric, mass - inertial characteristics and type of hinges modelling their joint (joint) corresponding to the biokinematic pair of bone links.

For a pair of bone links in the biokinematic chain, the acting muscle forces of the antagonists form a total of two joint moments of these forces relative to the axis of the joint, as shown in Fig. 12 [300]. The system of forces and reactions of bonds of a biokinematic pair is preliminarily led to a force and pair of forces, as was previously discussed in detail in the first section.

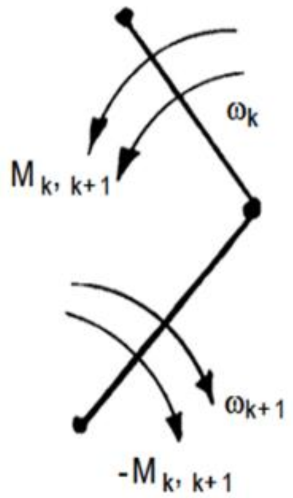

Figure 12. Scheme biokinematic pair

The found strength and pair are considered applied to each adjacent link of this pair in opposite directions (Fig. 12). In this case, the position of the axis of rotation of the links in the joint is unchanged. It should be noted that the mechanical work of the forces of the muscle groups of the joint increases with an increase in the control moment and in the interlink angular velocity. The results of theoretical and experimental studies have shown that muscles, when contracted, produce positive energy, giving it to other muscles and links, and lengthening, they absorb energy, i.e. get it from the links. This transfer of energy from link to link always happens so that if one link loses some of the energy, then the other link coupled with it gains energy. The work of the muscle pull forces is determined by experimental data. For this, the forces at the end of the muscle and the magnitude of the change in its length are recorded. The work of the muscle pull forces can be calculated as the product of the muscle pull force by the amount of its contraction. At the same time, a significant part of the energy is saved, and another part of the muscle energy is dissipated in the joints, ligamentous muscle joints and goes into the work of moving the parts of the body, called - visible or observed work. Such a transformation of muscle energy occurs during their isometric action.

If the significance of mechanical work and the energy expended in performing this work are known, then their ratio determines the so-called coefficient of mechanical efficiency (C.M.E.). The coefficient of mechanical efficiency of the observed work when walking is on average 0,44, while running – 0,36, and when cycling – 0,25.

The work spent on moving during locomotion includes: the work of external forces, for example, gravity on vertical movement G.C.M. body and environmental resistance forces, the work of internal muscle forces to move individual body segments and dissipative work that takes place in the joints of body segments, in muscles and other mechanisms of energy transfer in the body. Therefore, energetically optimal or comfortable can be considered, for example, human walking (gait), at which some point of the body, possibly G.C.M. body, moves rectilinearly in the direction of motion. In this case, that part of the overall work that relates to the work of gravity in the vertical movement under consideration will be zero. However, this will require large expenditures of internal forces. So, from the standpoint of bioenergy, not completely comfortable movement is energetically beneficial and this meets the principle of minimum energy costs realized in various natural phenomena. In biomechanical systems during movement, this is expressed in the optimal ratio of the work of external and internal forces. The above allows us to establish a several useful recommendations for moving a person with minimal energy, but with the greatest possible speed. Firstly, when moving, it is necessary to exclude unnecessary body movements, for example, make movements up or to the sides, wave your arms, swing the body. Secondly, the technique of movement should contribute to the preservation of maximum energy for moving the body compensated by the minimum work of internal muscle forces.

Power to maintain walking speed. Consider the movement of a person moving in the longitudinal direction. Such movements include walking and running. It is empirically established that when a person walks at a speed from the range of 3 .. 9 km/h, the power to maintain the average speed of movement - V_e can be calculated by the following formula 18:

$$W_{m-w} = 14.362 \frac{V_e}{0.362 + 0.257 V_e} (0.136 V_e + 0.066 V_e^2) \quad (18)$$

Similarly, it was found that when running

$$W_{m-r} = \frac{B V_e^2}{(1 + C V_e)} \quad (19)$$

where B- is an empirically determined coefficient, C - is the ratio of the average values of the duration of the flight phase to the distance travelled by G.C.M. human body during the flight phase.

For the priority choice of movement in the form of running or walking, from the point of view of energy consumption, you can use the comparison with the unit of the Froude number, determined by the following formula 20:

$$Fr = \frac{V^2}{gh} \quad (20)$$

where V - is the speed of movement (m/s), h - is the height of G.C.M. the human body in the main stance (m), g - is the acceleration of gravity (m/s2).

It is generally accepted that if the Froude number is less than unity, then walking is energetically more beneficial, and in other cases, running. Note that this approach does not take into account the surface topography, weights and other factors that complicate the movement. This approach is focused on comfortable conditions of movement.

Negative work. The concept of negative work is known in physics and theoretical mechanics, however, in biomechanics this concept has a broader meaning.

In biomechanics, three cases are considered when negative work is performed with the participation of internal muscle forces: negative work in the joint. In this case, the directions of action of the particular moment and interstitial angular velocity do not coincide, and the articular moment produces negative work; negative work of active muscles. This occurs when the active muscles are stretched by external forces. This mode of active muscle is called inferior (eccentric). Negative work of the active muscle is done with the energy expenditure of the muscle to counter stretching. Moreover, the energy expenditure of such a muscle can be less than the work done on it; negative work on the body link. In this case, the directions of action of the control moment and the angular velocity of the link do not coincide, and the control moment performs negative work on the link. In this case, the total mechanical energy of the link decreases.

Note that when moving biomechanical systems, as a rule, all these three cases take place simultaneously. For example, the negative work of muscles is carried out by gravity when a person squats with a load or when moving downhill without a load. In cyclic ground locomotions on a horizontal surface (running, walking) with insignificant horizontal external resistance forces (surface friction and airflow), the negative and positive work of the forces to move the body approach their values, that is, in this case, the energy loss will be small [312].

Biarticular muscles with simultaneous flexion or extension in two adjacent joints can work in isometric mode, however, negative work can be performed for one of the joints. In biomechanics, to assess the efficiency of energy costs, they do not use the concept of efficiency known in technical mechanics but use the previously introduced coefficient of mechanical efficiency (C.M.E.).

In experimental studies of the energy costs of producing negative work, experimental data are known for a person who has completed a full descent cycle with an ascent along an inclined plane, keeping the position of G.C.M. his body concerning this plane. In the experiments, the values of both negative and positive works were determined when the position of G.C.M. on the descent and ascent, and simultaneously recorded energy costs for the commission of these works. It was established that for positive work during the ascent, the energy costs exceeded by 4 - 5 times the costs of negative work during the descent. Note that these data were confirmed by other experiments and on this basis, generalized conclusions were drawn. So, for example, it was found that for negative work C.M.E. on average it turns out to be 3 times more than its values than for positive work. Some authors explain this by the fact that with negative work, mechanical energy is dissipated more and, therefore, the cost of its production will be less. Also, it is known that for lengthening with a certain speed of a single muscle fiber, the corresponding muscle groups, more effort is required than for shortening it at the same speed. Bending the forearm is harder than bending it. Negative work, developing in a full cycle with positive work, significantly increases the average mechanical work efficiency for performing cyclic actions.

Muscle and locomotion energy

In the process of performing any holistic movement in the muscles, metabolic reactions occur, i.e. chemical transformations of substances, energy production, and their metabolism both in the body and between the body and the environment. At the same time, in the preceding phases of any phase of the movement, deformation energy is accumulated in the elastic elements of the biomechanical model of muscles, which allows increasing the strength and speed of muscle contraction. The energy spent on muscle work is divided into metabolic and non-metabolic. The energy that is released during metabolic reactions and goes into the mechanical work of muscles is called metabolic energy. Non-metabolic energy in any of the phases of movement is the potential energy of elastic deformation the P_e component of the muscles in which it accumulates. Next, we will dwell on estimates of the contribution of non-metabolic muscle energy to the total cost energy - P_t, which are of most interest when analyzing the effectiveness of the total energy expenditure produced by muscles during movements in biomechanical systems.

It is known that with an equal amount of positive and negative work, the maximum efficiency of movements theoretically should not exceed the value of C.M.E. = 0,4..0,5. However, experimentally determined values of this efficiency are noticeably higher. So, for example, with a smooth run, the maximum efficiency is C.M.E. reaches a value of approximately equal to 0,8. An increase in running speed may not be accompanied by an equally significant increase in energy costs. These observations can be explained by the existence of an additional source of mechanical energy that does not require metabolic energy consumption. Such a source is considered to be the source of accumulation of non-metabolic energy related to the elastic elements of muscles and tendons. The contribution of non-metabolic energy to the total energy expenditure of the muscles is P_t, which are the sum of the energy expenditures for the negative- P_n and positive - P_p work can be found from the following equality:

$$P_e = \eta \cdot P \qquad (21)$$

where the coefficient of the contribution of non-metabolic energy to total energy consumption is determined by the values of the ratios of the coefficients of the mechanical efficiency of the negative - C.M.E.1 and positive - C.M.E.2 works to the coefficient of mechanical efficiency of the full work C.M.E.:

$$\begin{aligned} &\eta_1 = C.M.E./C.M.E.1 \\ &\eta_2 = C.M.E./C.M.E.2 \\ &\eta = (1 - 0.5 \cdot (\eta_1 + \eta_2))/(\eta_1 - \eta_2) \end{aligned} \qquad (22)$$

The efficiency of movements can be increased due to the rational use of non-metabolic energy accumulated during eccentric modes. With an increase in C.M.E. of total energy, elastic energy accumulated in the phase of negative work is effectively realized, which increases the value of the coefficient of the contribution of non-metabolic energy - η to the total energy consumption.

This, for example, makes it possible to increase the efficiency of motions in terrestrial cyclic locomotion. This efficiency is achieved by increasing the speed and frequency of movements, reducing the time of changing the phases of work and observing the sequence of positive work for negative work with minimal muscle relaxation (their relaxation and a sharp decrease in tone).

Muscle contraction energy. During muscle activation, an increase in intracellular Ca concentration leads to a reduction and enhanced ATP cleavage; while the intensity of muscle metabolism increases by 100 – 1000 times. According to the first law of thermodynamics (the law of conservation of energy), the chemical energy released in the muscle must be equal to the sum of the mechanical energy (muscle work) and heat generation.

Even isometric contraction is accompanied by the continuous cyclic activity of the transverse myosin bridges, and the “internal” work associated with ATP cleavage and heat generation is significant. No wonder even such a "passive activity" as a stand «quietly» is tiring. When the muscle lifts the load, performing "external" work, an additional amount of ATP is split. In this case, the effort of the metabolic rate is proportional to the work performed (Fenn effect).

Typically, the primary source of energy for muscle contraction is glycogen or fatty acids. In the process of cleavage of these substrates, ATP is produced, the hydrolysis of which delivers energy directly for the reduction itself [313].

Muscles, contracting, turn a very significant part (1/4 to 1/3) of chemical energy into mechanical work while releasing heat; it is one of the main sources of its formation in the body. The hydrolysis of one mole of ATP produces approximately 48 kJ of energy. However, only about 40 – 50 % of it is converted into mechanical energy, and the remaining 50 – 60 %. However, under natural conditions, the mechanical muscle efficiency is usually much lower - about 20 – 30 %.

A model of the educational process for the formation of students' beliefs in the universality of the description of physical phenomena of different nature in the energy language

The model of the educational process aimed at developing an energy approach in students should include the following steps:

– the creation of learning situations that encourage students to look for another way to describe them;

– the introduction of the necessary energy concepts, the formation of actions that are adequate to these concepts;

– independent selection by students of the content of the energy method;

– a special cycle of lessons in which the energy method is the subject of assimilation;

– solving problems-problems in various sections of the course using the energy method;

– a cycle of lessons to test the formation of students' beliefs in the universality of the energy approach in the study of biophysical phenomena of different nature in different topics of the course.

The first stage is connected with the creation of the necessary training situations. The initial situation should be introduced after studying the section «Fundamentals of Dynamics» in the topic «Conservation Laws» when considering elastic and inelastic collisions of bodies. Before studying other specific topics in which energy concepts are introduced, students should be presented with such initial situations that can be described by the energy method as the only possible one. In this case, the same cognitive task should be formulated: «What method can describe this situation?...».

The purpose of the second stage is to form in students the actions that are part of the content of the energy method. These actions are associated with certain knowledge and must be formed in students simultaneously with them (knowledge must be translated into actions). It is advisable to start their formation in the first lessons.

To do this, it is necessary to expand the «Introduction» somewhat and not only introduce the concepts of «physical object», «object state», «change in the state of an object», «reason for changing the state of an object», «conditions for changing the state of an object», but also form adequate types of activities for the recognition and reproduction of specific objects corresponding to these concepts.

These concepts are methodological. Having formed them when studying the «Introduction» section, it is necessary to constantly rely on them, use them when studying all topics of the biomechanics course. Other actions of the energy method associated with the assimilation of the concepts of «mechanical work», «kinetic energy», «potential energy», «closed system of bodies», «work of gravity», «work of the elastic force», as well as with the assimilation of the theorem on kinetic energy , the law of conservation of total mechanical energy, the transformation of one type into another, should be formed in the future when studying relevant topics. This requires special didactic means - tasks-exercises, in which the question encourages the performance of exactly the activity that is adequate to a certain knowledge.

For instance:

1. Calculate the kinetic energy of bodies in the initial and final states in the proposed situations (8–10 situations are given).

2. Determine the potential energy of the body in the state indicated in the figure (8–10 figures are given for situations).

3. Make an energy equation of motion in the given situations (texts of 8–10 specific situations are given).

Such tasks are carried out according to programs developed by the students themselves.