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COMPUTER AND COMPUTATIONAL ANALYSIS OF THE BIOMECHANICS OF SWIMMING

Abstract. The article deals with the issues of computer and computational modeling and analysis of the biomechanics of one of the most technically complex sports - swimming.

Computer and computational modeling is currently an important part of various scientific researches. Such modeling in many cases allows either to replace full-scale experiments or to determine their rational parameters, thereby accelerating research. Computational modeling and simulation is widely used in the study of movement in various sports, which belongs to a wide class of biomechanical problems. Here, the use of computer calculations makes it possible to determine the rational parameters of an athlete's sports actions, which lead to higher sports results. It should be noted that the accuracy and reliability of computational modeling in the biomechanics of sports depend on the degree of approximation of computational schemes and models to reality. The creation of design schemes and models is impossible without the use of the results of field measurements.

Based on the analysis of existing sources of information, an approach was formulated to create design schemes for studying the movement of an athlete-swimmer along the distance. The systems of differential equations of motion for different stages of the distance are presented. For computer modeling, the KiDyM

software package is applied, which uses the relations of the computer algebra system to construct differential equations of complex mechanical systems motion.

The analysis of the presented and similar graphical information allows determining the rational values of certain parameters of the athlete-swimmer's sports actions, which allow achieving high sports results. This information allows us to adjust the technique of a particular athlete, taking into account the characteristics of his anatomy and physiology. Similar computational studies based on computer simulations can be performed for other technically complex sports.

Keywords: biomechanics, computer and computational modeling, differential equations of motion, design scheme, swimming

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КОМП'ЮТЕРНИЙ ТА ОБЧИСЛЮВАЛЬНИЙ АНАЛІЗ БІОМЕХАНІКИ ПЛАВАННЯ

Анотація. У статті розглядаються питання комп'ютерного та обчислювального моделювання та аналізу біомеханіки одного з найбільш технічно складних видів спорту – плавання.

Комп'ютерне та обчислювальне моделювання на сьогоднішній день є безсилою частиною різноманітних наукових досліджень. Таке моделювання в багатьох випадках дозволяє або замінити натурні експерименти, або визначити їх раціональні параметри, тим самим прискорюючи дослідження. Обчислювальне моделювання та імітація широко використовується при дослідженні руху в різних видах спорту, що відноситься до широкого класу біомеханічних задач. Тут використання комп'ютерних розрахунків дає змогу визначити раціональні параметри спортивних дій спортсмена, які призводять до вищих спортивних результатів. Слід зазначити, що точність і достовірність

обчислювального моделювання в біомеханіці спорту залежить від ступеня наближення обчислювальних схем і моделей до реальності. Створення розрахункових схем і моделей неможливе без використання результатів натурних вимірювань.

На основі аналізу наявних джерел інформації сформульовано підхід до створення проектних схем для дослідження переміщення спортсмена-плавця по дистанції. Наведено системи диференціальних рівнянь руху для різних етапів дистанції. Для комп'ютерного моделювання використовується програмний комплекс KiDyM, який використовує співвідношення системи комп'ютерної алгебри для побудови диференціальних рівнянь руху складних механічних систем.

Аналіз представленої та аналогічної графічної інформації дозволяє визначити раціональні значення окремих параметрів спортивних дій спортсмена-плавця, які дозволяють досягти високих спортивних результатів. Ця інформація дозволяє коригувати техніку конкретного спортсмена, враховуючи особливості його анатомії та фізіології. Подібні обчислювальні дослідження на основі комп'ютерного моделювання можна проводити для інших технічно складних видів спорту.

Ключові слова: біомеханіка, комп'ютерне та обчислювальне моделювання, диференціальні рівняння руху, розрахункова схема, плавання.

Problem statement. Swimming is one of the most technically demanding sports. The results in swimming are very much dependent on the rational behavior of the athlete in the process of movement. Rational behavior, in turn, is based on the use of information about the rational parameters of sports activities, which can be determined in the process of computational and computer simulation of the swimming process.

Recently, there has been a quite definite idea that the achievement of winning results in professional sports is impossible without a preliminary comprehensive research analysis, which includes theoretical studies, field experiments, computational and computer studies and their synthesis. As for sports swimming, there are many scientific papers published in open information sources, for example [1-4], devoted to research into the biomechanics of sports swimming.

Analysis of recent researches and publications. The attention of researchers in these and similar scientific articles is focused on various aspects of the process of sports swimming, concerning both the problems of achieving the highest results and the problems of preventing injuries in swimmers. The articles offer various research methods based on both natural experiment and computer simulation. Various factors influencing the process of sports swimming are being studied: athlete's technique, athlete's biophysics, athlete's gender, etc. [5-9]. A large number of articles, for

example [1,5,8,10-13] presents an analysis of the energy processes occurring in the swimmer's body and their influence on the passage of the distance.

In computational and computer studies of an athlete's movement along a distance, one of the main issues [4,6,11,14] is the creation of a design scheme, which depends primarily on the swimming style (crawl, backstroke, breaststroke, and butterfly) and on the phase of the swimming process (start, smooth distance, turn, finish).

The degree of approximation of the design scheme to the real object affects the reliability of the results. On the other hand, it is necessary to clearly understand the purpose of the problem being solved and “not burden” the design scheme with insignificant details. For example, when determining the rational parameters of a swimming action to achieve the highest speed, one can use a solid-state design scheme, since here, in fact, the problem of mechanics is considered. In this case, the design scheme is a mechanical system of absolutely rigid bodies. Features related to indicators of biology and biophysics (for example, muscle strength, elasticity of ligaments, etc.) in this case can be taken into account by introducing power characteristics, elastic characteristics, dissipative characteristics.

In general, it should be noted that the analysis of the scientific literature on the problems of the biomechanics of swimming allows us to make an unambiguous conclusion that computer and computational studies in this direction are an actual task in the scientific and practical aspect.

Goal of the article. The goal of the research presented below is to create a new calculation method for studying the dynamics of an athlete's movement over a distance in the process of sports swimming, as well as to conduct research in order to determine rational parameters that provide a high sports result. Within the framework of the stated goal of research, the following tasks should be decided: the creation of a calculation scheme, mathematical modeling, the choice of a calculation method and the conduct of appropriate calculation studies.

We also note that this work is ideologically a continuation of the studies presented in [15].

The presenting of main material. The mathematical framework of almost any problem of studying the motion of mechanical and biomechanical systems can be conditionally divided into 3 stages: the creation of a design scheme, the mathematical formulation of the equations of motion of the design scheme itself, the algorithm and method of numerical integration of the equations of motion.

As a first approximation, the process of sports swimming can be divided into 4 parts, for which separate design schemes can be created, each of them should include those features that are characteristic of this particular part of the swimming process. The first part of the swimming process is the start (from jumping off the bollard to entering the water). Depending on the starting position adopted by the

swimmer, the departure angle of the gravity center of his body, the flight path of the center of mass will be different and, accordingly, affect the efficiency of the start. The starting position and the departure angle from the starting position are those parameters that the swimmer can consciously vary. Thus, the swimmer can choose the most rational flight path for him from the starting position. The second part - "exit" from under the water - sliding without rowing actions (actually moving by inertia). The third part - "exit" from under the water - sliding, taking into account the rowing actions of the lower limbs. The fourth part is swimming along the distance, taking into account the rowing actions of the upper and lower extremities.

Two types of sports swimming: butterfly and breaststroke are characterized by the synchronism of the rowing actions of the right and left limbs [14]. In this case, to study the movement of an athlete, design schemes can be drawn up within the framework of a plane-parallel setting. The definition of rational parameters that determine the effectiveness of sports swimming, in the first approximation, can be made for solid elements of design schemes.

Below are design schemes for studying the movement of an athlete at the stages of start, "exit" and swimming along the distance in the framework of a plane-parallel setting (in all figures, the x-axis coincides with the water surface).

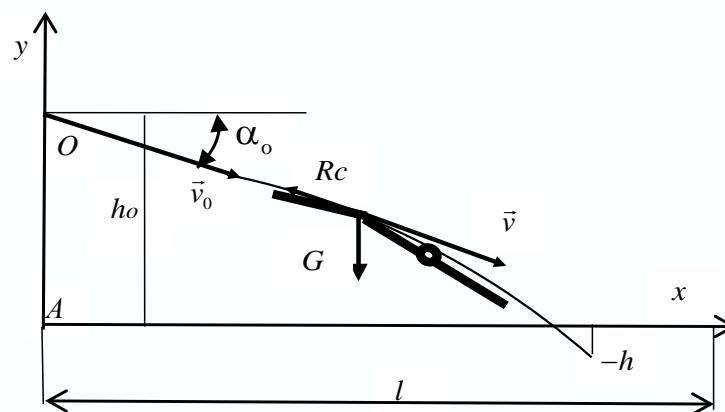


Fig. 1. Design scheme for studying the start process.

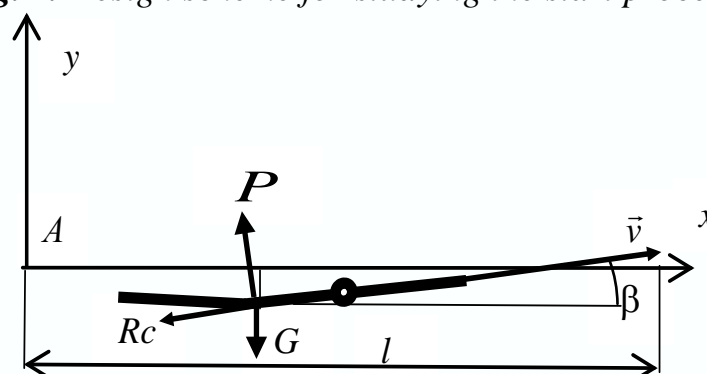


Fig. 2. Design scheme for studying the process of "exit" without taking into account rowing actions.

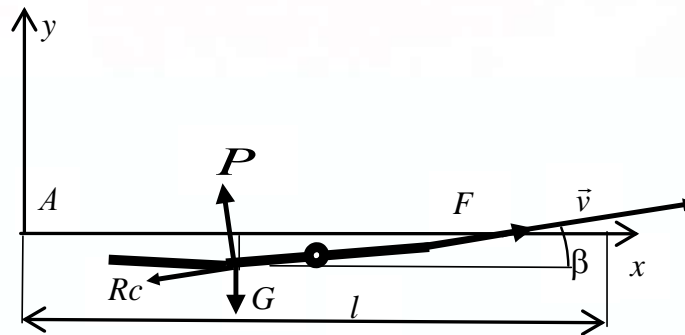


Fig. 3. Design scheme for studying the process of "exit" taking into account the rowing actions of the lower limbs.

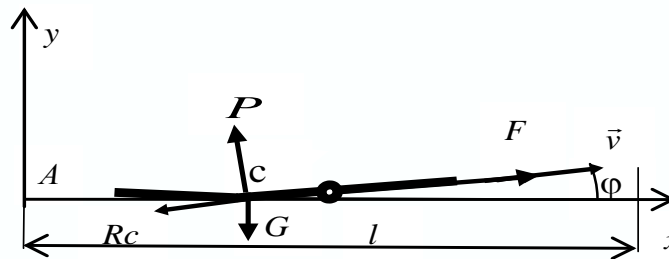


Fig. 4. Design scheme for studying the process of the movement when swimming along the distance.

In Figures 1-4, the following designations are adopted: v_0 – absolute initial departure velocity of the center of mass of the body, v – current speed of the center of mass of the body, h – immersion depth of the center of mass of the body, β , φ – exit angles of the center of mass of the body during sliding and rowing actions, respectively, h_0 – departure height of the center of mass of the body at the initial departure time, α_0 – departure angle of the center of mass of the body, G – body gravity, F – propulsion force (in this case, it is this force models the rowing actions of the athlete's limbs), R_c – resistance force of the aquatic environment, the value of which is a function of the movement speed, P – buoyancy force.

The value of the driving force F , realized during rowing actions, can be determined experimentally using a dynamometer installed between the two ends of the rope and fixed on the athlete's belt and on the side of the pool.

Let's consider in more detail some simplifications concerning the account of resistance - external environment (water). To solve this problem, the force of hydrodynamic resistance R_C for bodies moving in an aqueous medium with density ρ is equal to $R_C = 0.5c_\tau \rho S v^2$. When calculating this force, the dimensionless drag coefficient c_τ is determined experimentally depending on the shape of the body and its orientation in the medium. The value S (middle) is determined by the value of the projection of the cross-sectional area of the body on a plane perpendicular to the axis of motion, v is the absolute speed of the body in the aquatic environment.

The posture of an athlete when moving in the sagittal anatomical plane is variable, and the value of the midsection S changes accordingly. Determining the variable values of the middle S and drag coefficient c_τ require additional theoretical and experimental studies; therefore, when solving this problem, we will take their averaged values.

It is also possible to determine the average values of the coefficient k , which is at v^2 – the absolute velocity of the body during swimming. Without taking into account the lifting force, the value of which is very small, we obtain the average values of the coefficient: $k = 0.5c_\tau\rho S \approx 0...1 \frac{\text{kg}}{\text{m}}$ then $R_C = kv^2$.

The chosen design scheme allows us to consider the problem of dynamics analysis in the framework of plane-parallel formulation. Differential equations of plane-parallel motion of each element of the design scheme in projections on the axis of the Cartesian coordinate system have the form:

$$m\ddot{x}_C = F_x^e; m\ddot{y}_C = F_y^e; J_z\ddot{\phi} = M_z^e, \quad (1)$$

where m is the element mass; \ddot{x}_C, \ddot{y}_C – projections of the acceleration of the center of mass of the corresponding element; F_x^e, F_y^e – projections of the main vector of external forces acting on the element; J_z is the moment of inertia of the element relative to the front axis Oz ; $\ddot{\phi}$ is the angular acceleration of the element when rotating the front axis; M_z^e is the main moment of external forces relative to the frontal axis.

General differential equations of plane-parallel motion (1) in this case can be specified for each of the design schemes (Figures 1 - 4). So for the design scheme of the start (Figure 1), differential equations (1) are concretized to the form:

$$\begin{aligned} m\ddot{x}_C &= -kv^2 \cos \alpha; \\ m\ddot{y}_C &= -G - kv^2 \sin \alpha; \\ J_z\ddot{\phi} &= -M_z^e, \end{aligned} \quad (2)$$

where α – the angle between the current projections of the velocity of the center of mass of the body and the vector of its velocity.

To study the movement of an athlete at the stage of "exit" without taking into account rowing actions (Figure 2), equations (1) are transformed to the form:

$$\begin{aligned} m\ddot{x}_C &= -kv^2 \cos \beta - P \sin \beta; \\ m\ddot{y}_C &= -G - kv^2 \sin \alpha + P \cos \beta; \\ J_z\ddot{\phi} &= -M_z^e, \end{aligned} \quad (3)$$

where β – the angle between the current projections of the velocity of the center of mass of the body and the vector of its velocity.

To study the movement of an athlete at the “exit” stage, taking into account rowing actions (Figure 3) and when swimming along the distance (Figure 4), equations (1) are transformed to the form:

$$\begin{aligned} m\ddot{x}_C &= -kv^2 \cos\beta - P \sin\beta + F \cos\varphi; \\ m\ddot{y}_C &= -G - kv^2 \sin\alpha + P \cos\beta + F \sin\varphi; \\ J_z\ddot{\varphi} &= -M_z^e, \end{aligned} \quad (4)$$

where φ – the angle between the current projections of the velocity of the center of mass of the body and the vector of its velocity.

Compilation of the above differential equations based on the use of the computer algebra system (CAS) and the apparatus of structural matrices, and then their integration by the Runge-Kutta-Merson method can be carried out using the KiDyM («Kinematics and Dynamics of Machines») software package, created at the Department of Theoretical Mechanics of NTU “KhPI”. The KiDyM software package is widely used for modeling and computational analysis of the motion of various complex mechanical, electromechanical and biomechanical systems [15].

A specific implementation from the point of view of compiling resolving equations in the KiDyM software package for similar tasks within the framework of setting a plane-parallel motion is presented in detail in the work [15].

The KiDyM software package uses the given mathematical formulation to compose differential equations of motion and their subsequent integration (in automatic mode). The user of the KiDyM software package needs to set the numerical values of the main process parameters. As a result of the solution, the researcher receives a variety of information (graphical and tabular) concerning the main kinematic characteristics of the system elements motion, as well as (if necessary) – information regarding the distribution of unknown forces-reactions (forces of interaction between the elements of a mechanical system).

Let us consider some results of the mechanical system motion analysis "swimmer" obtained using the KiDyM software package. Sufficiently useful information for adjusting the swimmer's sports actions is provided by the study of the movement of his center of mass. In differential equations (2-4), the movement of the center of mass is described by the coordinates x and y .

Further, in Figures 5-8, there are graphs of changes in these coordinates depending on some parameters, the values of which can be adjusted in the process of performing sports actions by an athlete-swimmer.

For example, when performing starting actions, the athlete's posture affects the direction of the initial velocity vector of the center of mass, and this parameter (the angle between the velocity vector of the center of mass and the horizontal – α_0) also affects the movement at the second stage. In the future, when the athlete begins to perform rowing actions, the magnitude of the driving force becomes an important

parameter. It is these two parameters that were varied in the process of computer simulation of the movement of an athlete-swimmer, the results of which are presented below.

It should be noted that the used values of the vector inclination angle of the initial velocity of the center of mass and the magnitude of the driving force are averages and generalizations of the relevant available information, which was obtained as a result of field measurements.

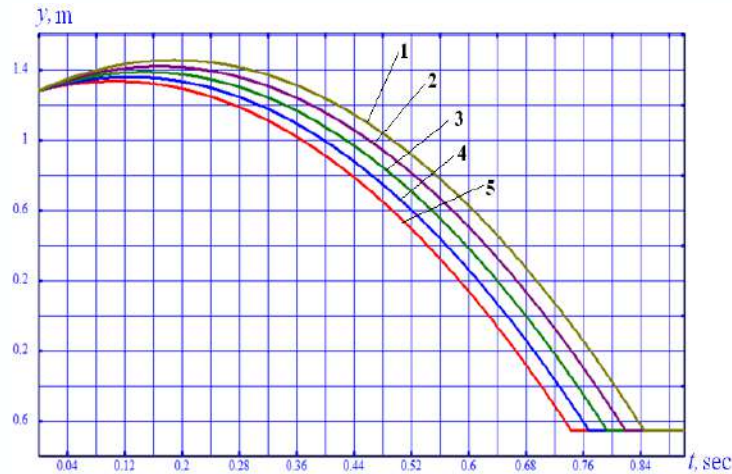


Fig. 5. Vertical coordinate of the center of mass during the start process at different initial velocity angles.

Figure 5 shows change in the vertical coordinate of the center of mass in time during the start process at various angles of inclination α_0 : 1 – 2 deg, 2 – (–1 deg), 3 – (–4 deg), 4 – (–7 deg), 5 – (–10 deg). Here, the calculation was limited to the moment of time when the vertical coordinate of the center of mass became equal to zero. From the graphs presented in the figure, it is clearly seen that the smaller the angle α_0 , the faster the center of mass «splashes down».

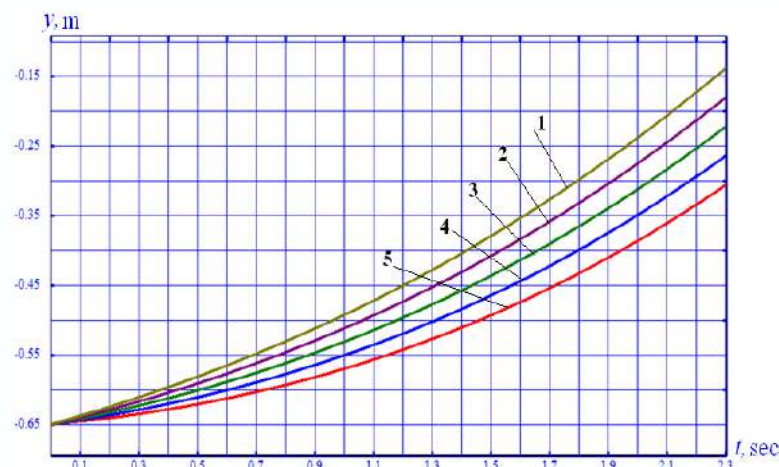


Fig.6. The vertical coordinate of the center of mass in the process of "exit" without taking into account rowing actions at different angles of the initial speed.

Figure 6 shows change of the vertical coordinate of the center of mass in time in the process of "exit" without taking into account rowing actions at the same angles of inclination of the initial speed α_0 as in the previous calculation. Here, the calculation process was limited to a fixed moment of time, which corresponds to the completion of the athlete's movement by inertia.

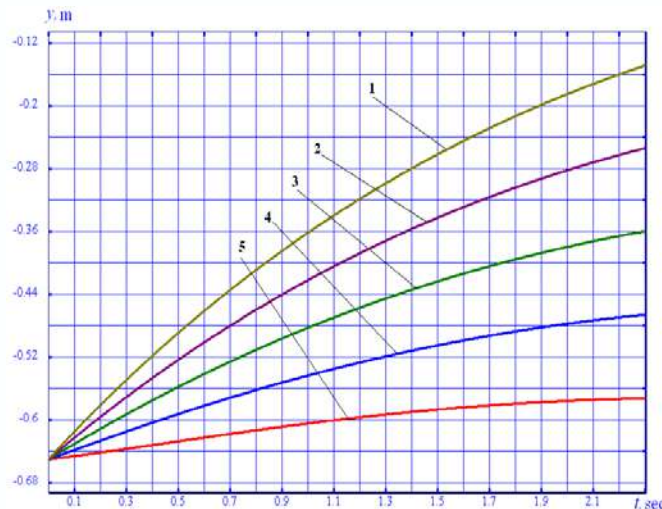


Fig. 7. The vertical coordinate of the center of mass during the "exit" process, taking into account rowing actions at different values of the driving force.

Figure 7 shows change in the vertical coordinate of the center of mass in time during the "exit" process, taking into account rowing actions at different values of the propulsion force : 1 – 88.29 N, 2 – 132.44 N, 3 – 176.58 N, 4 – 220.73 N, 5 – 264.87 N.

Figure 8 shows the trajectories of the center of mass in the process of swimming along the distance with the same values of the driving force as in the previous calculation.

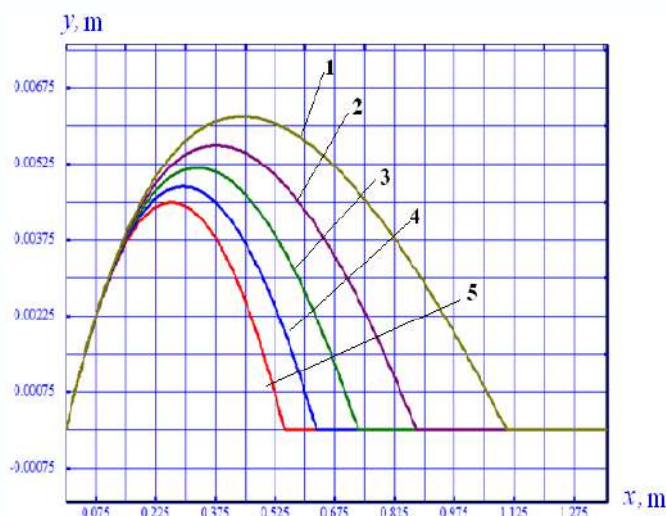


Fig. 8. The trajectories of the center of mass in the process of swimming along the distance at different values of the driving force.

The analysis of the presented and similar graphical information allows to determine the rational values of certain parameters of the athlete-swimmer's sports actions, which allow achieving high sports results. This information allows you to adjust the technique of a particular athlete, taking into account the characteristics of his anatomy and physiology. Similar computational studies based on computer simulations can be performed for other technically complex sports.

Conclusions. As conclusions, it should be noted that the article presents an effective method for the calculation analysis of the athlete's movement along the distance in the process of sports swimming.

Calculation schemes have been created that allow analyzing various phases of the process of sports swimming for the case of butterfly swimming. The corresponding systems of differential equations of motion are formulated.

KiDyM software package was used for computer modeling. Some results of computational studies are presented, illustrating the possibilities of the proposed approach for determining the rational parameters of sports activities.

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