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Artistic swimming – benefits of the critical blood flow velocity

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Abstract:
Aim: The article examines the biophysical, physiological, and field aspects of the "critical training zone" for artistic swimmers and their equivalents. Hemorheological changes during exercise are analysed. **Methods:** By connecting two scientific fields, the biophysical theory of sports training and physiology, it becomes possible to measure the integral physiological parameter, maximum aerobic capacity (VO_2 max). Blood rheology and vascular function continuously interact to ensure optimal oxygen and nutrient delivery, necessitating their parallel assessment. The structural analysis presented is based on theoretical concepts and scientific results from Bulgarian and international experts. Critical velocities (VMA = Vcr) can be practically applied for individual modelling of critical power. **Results:** External adaptation in artistic swimming is determined by critical movement velocity (VMA). Both critical velocity and critical power function as parallel indicators, defining the boundaries of the critical training zone. The specific training conditions correspond to the level at which maximal aerobic capacity is developed, typically associated with a heart rate of approximately 180–185 beats per minute. **Discussion:** These findings enable precise regulation of training load, allowing artistic swimmers to consistently operate within the critical training zone. This is particularly important given the sport-specific demands, including the use of equipment and the need for synchronised performance. The alignment between physiological thresholds and training intensity supports optimised adaptation to the unique requirements of artistic swimming. **Conclusion:** The established relationship between critical velocity, critical power, and physiological response ensures that the critical effort zone is effectively maintained and contributes to a better artistic swimming performance.

Keywords: artistic swimming, training process, critical blood flow velocity, critical muscle strength

1.Introduction

Our complex experiment aimed to establish the relationship between interdisciplinary and laboratory-based physiological indicators and their quantitative equivalents measured in real-world conditions, particularly in the context of individual practice [1, 2]. We refined our theoretical concept by integrating practical research findings from six Bulgarian doctoral and Doctor of Science dissertations, along with summaries from international research teams in Canada and France. The scientific contributions of Bulgarian researchers were analyzed, with only five experts working in this specialized field, including Dr. Georgi Dimitrov (PhD in Medicine), Prof. Dr. Il. Iliev (PhD in Medicine), and Prof. B. Serafimova [3-5]. Hemorheological changes during exercise were examined by advanced scientists at the Bulgarian Academy of Science, such as Antonova and Ivanov [2, 6]. This study focused on type, duration, intensity, and cyclicity to develop additional criteria for assessing physical performance and endurance. Regarding "critical training work" in swimming, only Prof. Biserka Serafimova specifically defines "critical effort under load of elite swimmers" in her dissertation [7-9]. Additionally, findings suggest that while planar registration and analysis of hip and knee joint movement provide satisfactory results in normal gait, values obtained for the ankle joint exhibit significant errors [10]. We joined to the scientific principles generally

accepted in the writings of sports experts in technical skills [11-13] and others on the nature of the plateau (steady-state) and methods for VO2max determination: Vaytsehovski, L. [14], Astrand, P.O. [15], Famos, J.P. [16], Bernal, H. [17], Morehouse L. et al. [18], Milner, A. et al, [19], Pineau, C. [20], Margaria, I. [21], Zatsiorskiĭ,V [22], Those physiologists with top rating served us for scientific justification of opportunities to create an equivalent field, starting from the integrated physiological parameters: Flandrois, M. R. [23] and Nadean, M. [24]. In support of that argument is made our biophysical analysis for the specificity of the processes in the cardiovascular system, explaining adaptation processes in "critical speed of blood flow" [25-27]. The name is scientifically approved - "critical" because the up-coming changes in the traffic of blood circulation, transform its form from "linear to turbulent" [28, 29]. Based on these scientifically validated facts, we built our work hypothesis on the assumption that the definition of the "parallel equivalents" and the determination of the "critical zone" during the effort in artistic swimming will improve the management of the functional preparation for top level competitors [30-33]. Aim of the research is to determine the value for the parameters characterising the specific function on the effort and the training border in the "critical zone" for the sport artistic swimming.

2.Materials and Methods

2.1. Thematic focus

The paper studies the biophysical, physiological and field performance in the "critical zone" of the training effort for Artistic swimmers and their parallel equivalents. The subject of the study is to define the "critical area" concept of the training effort in artistic swimming. By combining border between two scientific fields will be possible through the biophysical theory of sports training, to measure the integral physiological parameter "maximal aerobic capacity (VO2max)". The analysed data are nonpublished part of our dissertation thesis for obtaining the scientific level: Doctor of science in 2017 and are available at the Bulgarian Centre of information and Documentation (nacid.bg). The structural analysis in this publication is based on the theoretical concepts and findings research of Bulgarian and foreign experts whose scientific interests are close to our working hypothesis.

2.2. Expertise and tools

Our research focused on creating a new standard methodology to evaluate the "critical zone"(critical zone for the pulse rate, blood flow and technical speed) efficiency in Artistic swimming. The study involved 111 top swimmers from Artistic swimming clubs, national teams of Bulgaria and Greece. The participants were primarily females and with an average age of 17,7 years. As this study is under the objectives of the Scientific Center of Excellence Heritage BG, all experts were recruited through a public announcement. The participants gave informed consent for the publication of their data. The study was conducted from May 2017 to February 2019.

3.Results

Our previously studies and analysis were on the adaptation reserves of the microvascular bed in individuals with varying levels of physical activity. Key parameters assessed included capillary density, average capillary diameter, microvascular perfusion, blood flow velocity, and heart rate. The effects of low-energy laser radiation on microcirculation were also evaluated concerning age, training duration, and sports discipline. Maximal oxygen consumption (VO2 max) was calculated to determine physical performance levels. Training-induced functional adaptations lead to a shift toward anaerobic support mechanisms, with long-term changes promoting a more efficient microvascular response. These adaptations serve as indicators of an athlete's functional orientation.

3.1. Hemorheological changes during exercise

3.1.1. Age-related changes in Hemorheological characteristics in persons with different modes of motor activity

P. V. Mikhaylov et al. [30] studied age-related changes in blood rheology across four age groups, comparing trained and untrained individuals. Blood viscosity in untrained individuals increased with age: 18% higher at 31–40 years ($p<0.05$), 25% at 41–50 years ($p<0.01$), and 30% at 51–60 years ($p<0.01$) compared to the 20–30 age group. Trained individuals showed a slower increase in viscosity and maintained better blood transport potential across all age groups. Aging led to increased viscosity, erythrocyte aggregation, and reduced deformability in both groups, but changes were delayed and less pronounced in trained individuals. Physical training reduces blood viscosity, making it more Newtonian, lowering circulation resistance, and improving oxygen transport.

3.1.2. Changes in Blood Plasma Proteins (Fibrinogen, Albumins, Globulins) in Different Training Regimens in Sports

Numerous studies have demonstrated a direct relationship between physical exertion and reduced fibrinogen levels. One of the earliest findings in this area was reported in Russia by Dudaev et al. (1986) [31], where a group of 30 patients with cerebrovascular disease participated in regular exercise for 30 days, resulting in a significant reduction in fibrinogen levels. The effectiveness of training programs depends on their individualised design, incorporating factors such as training plans, intensity of physical exertion based on objective physiological (cardiovascular) indicators, duration, intensity, and volume is concluded by Karsheva et al., (2011) [32]. Among various training regimens, aerobic exercise involving dynamic physical activities is considered the most effective and is widely recommended for treating arterial hypertension [33].

3.2. Specific indicators and changes in Artistic swimming performance

We begin by systematically defining the concept of "critical speed" of blood from a biophysical perspective, summarizing the key integrated physiological parameters identified through laboratory experimentation. Our research findings from sports science and pedagogical practice highlight the "effectively treated areas" of training load. Ultimately, we establish the "critical zone" of artistic-training effort, demonstrating its high-speed performance relevance for elite artistic swimmers. The occurrence of "critical speed blood flow" is linked to the transition from linear to turbulent movement, as defined by Reynolds' number. This model provides a visual framework for understanding how blood flow shifts under varying pressure conditions (see Fig. 1).

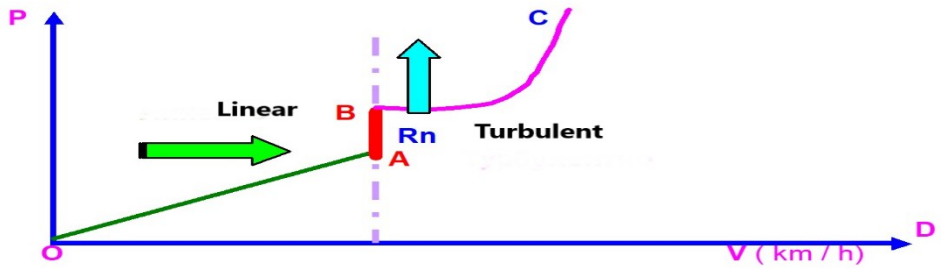


Fig. 1. Blood Circulation Based on Poiseuille-Hagen's Law

The figure illustrates blood circulation dynamics according to Poiseuille-Hagen's law. It shows how linear flow varies with applied pressure:

1. **Section A:** Represents the critical flow rate.
2. **Segment AB:** Marks the onset of turbulence and critical velocity.
3. **Segment BC:** Indicates changes in blood's chemical composition due to momentum shifts.
4. **V (Continuous Line):** Represents flow behavior within a flexible container.

Each coach can creatively interpret and apply the percentages of critical speed and power to optimize training management for elite artistic swimmers (see Fig. 1). An interdisciplinary approach was adopted, incorporating:

- Biophysical indicators – including Reynolds number (Rn), velocity (V), linear and turbulent flow transitions, blood circulation dynamics, and critical blood velocity (short thick vertical lines).
- Physiological indicators – values of VO_2 max deployment, primary length, and the progression from initial to critical and maximum power load.
- Terrain equivalents – effort duration (measured in minutes and seconds), distance covered (in meters), initial maximum velocity (km/h), and critical speed (m/s).
- Our analysis represents a pioneering attempt to establish an "interdisciplinary bridge" by quantifying the physical equivalents of well-known physiological parameters for functional diagnostics. This approach aligns with our scientific objective of defining key concepts within the "critical area" of effort in artistic swimming.

Our practical and theoretical contributions to the training of elite artistic swimmers validate a fieldwork methodology for determining individual "critical speed." This study aims to summarize and adapt theoretical contributions from various scientific studies to enhance artistic swimming training management. The analysis of laboratory and field experiment results supports a methodology that enables precise training zone identification in artistic swimming, including:

- Laboratory measurements in real-world conditions
- Translation of physiological parameters into quantifiable field values
- Adaptation of dry-land indicators to aquatic environments

Our goal is to define the "critical zone" of effort for top-level artistic swimmers by establishing parallels between biophysical and field equivalents for speed and power, demonstrating their effectiveness in sports practice. The study highlights the direct relationship between technical and functional parameters in athlete preparation. In artistic swimming, balance sustainability is multidimensional, with 42% of athletes right-handed, 16% relatively symmetrical, and 43% left leaning. For the first time, we introduce functional and technical training levels aimed at optimizing artistic swimming performance.

Drawing on theoretical and methodological expertise from international sports and scientific exchanges, we analyzed trends in the free routine competition at the Beijing 2008 Olympic Games. Artistic swimming achievements cannot be attributed to a single technical or functional training approach. According to FINA's international competition rules, which emphasize "high and controlled execution", these two types of training must be integrated into a cohesive and systematic preparation strategy. The term "high" in artistic swimming is attributed to functional preparation, while "controlled" performance is achieved through technical and educational artistic training. In our coaching practice with the national team, we assessed technical mastery using a subjective pedagogical expert evaluation, conducted by an independent panel of judges through regular video analysis. For the first time, our thesis introduces the quadrant assessment method, proving its advantages in evaluating the effectiveness of specialised techniques.

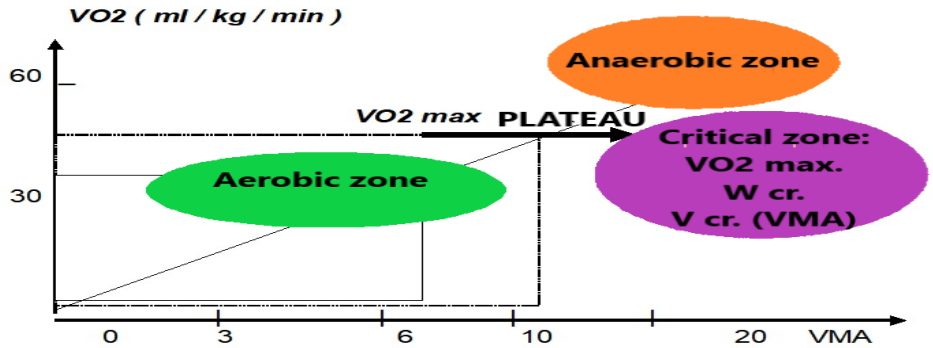


Fig. 2. Illustration of a critical area cycle effort (the timetable referred G. Dimitrov (1982) and B. Dimitrova (2017*)*. First, it establishes a parallel between pulse rate and critical power (WMA = Wcr) through laboratory experiments. Second, it draws a connection between maximum aerobic capacity and its corresponding critical speed (VMA = Vcr) through terrain-based experiments. This consensus is reflected in the thesis works of numerous medical experts. Additionally, we integrate scientific principles from conventional sports research, particularly those related to the nature of the plateau (steady - state) and indirect methods for determining aerobic capacity. These findings are translated into quantifiable values under real-world conditions, bridging the gap between laboratory and field research

The introduction of technical training levels establishes a scientific foundation for managing technical mastery. The term "control performance" accounts for individual anthropometric priorities, and through regression models, we have created an objective basis for predicting sports results across all disciplines. Despite the progress in functional training management through heart rate monitoring, the concept of "high" performance has traditionally been based solely on the subjective perception of individual swimmers. According to FINA rules, a "very good score" falls within 8 to 8.9 points, requiring a specific level of execution. Our theoretical analysis highlights the necessity of improving the management of the training process by integrating functional and technical training levels into practice. Historically, artistic swimming training has followed a separate management approach for functional and technical preparation. Traditionally, expert assessment methods and individual adaptation to altitude performance were used. This paper aims to minimize subjective factors in managing the training process, contributing to the development of future Bulgarian national teams. The theoretical summary of definitions and research findings in sports science is based on two key perspectives (see Fig. 2).

4. Discussion

In our previous publications, we provided an overview of studies on microcirculatory and hemorheological changes, as well as oxygen transport mechanisms occurring during physical activity and sports. We analyzed adaptation reserves of the microvascular bed in individuals with varying levels of physical activity, assessing microcirculatory changes in athletes across different sports disciplines both during high-intensity training and at rest. Hemorheological changes during exercise were examined in relation to type, duration, intensity, and cyclicity of physical activities. Given the continuous interaction between blood rheology and vascular function, they must be evaluated together to ensure adequate oxygen and nutrient delivery to tissues. Insights from physiologists have guided our scientific justification for developing a terrain test based on integral physiological parameters. Expert opinions have directed us toward laboratory and field testing for indirect measures of maximum aerobic capacity in artistic swimming. Our argumentation integrates physiological laboratory parameters with performance altitude objectification, identifying capacity ranges in the critical effort zone and linking them to verbal composition categories within FINA regulations. Establishing a connection between measurable terrain variables and laboratory parameters will enable the development of accessible and practical control tools, facilitating theoretical modeling and forecasting of functional preparation levels. This will also allow for objective monitoring of performance based on critical power. Therefore, we can define the key concepts of the critical strength area as follows: Critical speed (Vcr), or maximum aerobic capacity rate (VMA), are equivalent. Critical power (Wcr), or maximum aerobic power (WMA), is the point at which the maximum aerobic capacity indicator (VO2max) reaches approximately 100%, due to the onset of critical blood flow speed in the cardiovascular system.

5. Conclusions

In conclusion, the concept of critical speeds (VMA = Vcr) can be effectively applied in practice for individual modeling of critical power. This approach allows for load control based on equipment type, ensuring that the effort remains within the critical zone during training in artistic swimming. From our theoretical analysis, the following conclusions can be drawn:

- Utilising the concepts of critical speed (Vcr) or maximum rate of aerobic capacity (VMA) and critical power (Wcr) or maximum aerobic power (WMA) in artistic swimming coaching provides a scientifically supported method for managing individual training intensity.
- In the critical effort zone, the cardiovascular system is characterized by the internal adaptation to critical speed (Vcr Reynolds).
- The external adaptation corresponds to the critical speed of movement (VMA). Both critical speeds are parallel equivalents in the critical effort zone in artistic swimming, where critical power and critical speed align with the full development of aerobic capacity.

- Critical speed and power are essential tools for modeling individual training loads and improving the overall management of the training process in artistic swimming.

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References

[1] Åstrand, P. O., Rodahl, K., 1980. Manuel de physiologie de l’exercice musculaire. Editions Maloine, 71-84, Paris.
[2] Ivanov I.M., 2022. Sport and hemorheology. Sport i hemoreologiya. [In Bulgarian]. Sofiya, 42-49
[3] Dimitrov, G., 1982. Heart rate as a tool for optimizing road training for highly skilled cyclists. Pulsovata chestota kato sredstvo za optimizirane na shoseĭnite trenirovki na visokokvalifitsirani koloezdachi. PhD Thesis, [In Bulgarian]. Publisher ETSNPKFKS – VIF, 71-90, Sofia.
[4] Iliev, Il., 1980. On the applied importance of oxygen metabolism for functional diagnostics in sports. in two parts. Върху приложното значение на кислородния метаболизъм за функционалната диагностика в спорта. в две части. PhD Thesis, [In Bulgarian]. Publisher VIF “G. Dimitrov”, 67-83, Sofia.
[5] Serafimova, B., 1974. Study of the relationship between training loads, functional indicators and sports results of young elite swimmers. Izsledvane na vzaimovrŭzkata mezhdu trenirovŭchnite natovarvaniya, funktsionalnite pokazateli i sportnite rezultati na mladi pluvtsi ot visoka klasa. PhD Thesis, [In Russian], Moscow University, 89-96, Moscow.
[6] Antonova, N., Ivanov, I., 2023. Methods for assessing microcirculatory, hemorheological changes and oxygen transport in athletes of various sports disciplines. In Proceedings of the XXIV Scientific Conference „FIS Communications 2023 in physical education, sport and recreation, 197-204, University of Niš, Faculty of Sport and Physical Education, Niš, Serbia.
[7] Aleksandrova, V., 2021. Adapted swimming for children with disabilities. Adaptirano pluvane za detsa s uvrezhdaniya. Monograph, [In Bulgarian]. Ed. IPRESS, 56-73, Sofia.
[8] Margaria R., Mangili F., Cuttica F., Cerretelli P. 1965. The kinetics of oxygen consumption at the onset of muscular exercise in man. Ergonomics, 8: 49–54
[9] Morehouse, L, A. Miller, 1974. Physiologie de l`effort. Ed. Maloine, 78-88, Paris.
[10] Zhelyazkov, T., D. Dasheva, 2002. Theory and methodology for sports training. Teoriya i metodika na sportnata trenirovka, Textbook, [In Bulgarian]., Ed. NSA Press, 45-67, Sofia.
[11] Dimitrova, N., 2019. Resistance while managing its own inertial power field. Trakia Journal of Sciences, 17, 1, 631 – 634.
[12] Dimitrova, N., 2019. Reactions of the motor system in local and global activities. Trakia Journal of Sciences, 2019a, 17, 1, 635 – 637.
[13] Litvin, F.B., Bruk, T.M., Primneva, O.P., Krotova, K.A. 2023. The influence of main lymphatic drainage on microlymphatic and microcirculation in symmetrical areas of the body. Athletes' sports physiology and morphology. Vliyaniye magistral'nogo limfodrenazha na mikrolimfotsirkulyatsiyu i mikrogemotsirkulyatsiyu v simmetrichnykh oblastyakh tela. Sportsmenovsportivnaya fiziologiya i morfologiya. Journal Science and sport, [In Russian], Modern

trends, 11, 4, 30-37.
[14] Vaĭtsekhovski, L., 1978. Book for the coach. Kniga za tren'ora, Book, [In Bulgarian]. Ed. Medicina i Fizkultura, 45-59, Sofia.
[15] Astrand, P. O., K. Rodhal, 1980. Manuel de physiologie de l'exercice musculaire. Ed. Kasson, 39-47, Paris.
[16] Famos, J. P., 1988. Aptitudes et performance motrice. Ed. Revue EPS, 93-105, Paris.
[17] Bernal, H., 1970**.** Debit cardiaque et consommation de O2 au debut de l'exercice musculaire chez l'homme. J. Physiology de l'effort, 62, 3, 346-347.
[18] Morehouse, L., A. Miller, 1974. Physiologie de l`effort. Ed. Maloine, 63-74, Paris.
[19] Milner - Brown, H.S., Stein, R.B., & Lee, R.G., 1975. Synchronization of human motor units: Possible roles of exercise & supraspinal reflexes. Electroencefalografy & Clinical Neurophysiology, 38, 3, 245-254.
[20] Pineau, J-C., 1996. Potentialités physiques au cours de l'adolescence. Ed. Vigot, 55-67, Paris.
[21] Margaria & col., 1965. A historical review of the physiology of oxygen debit. Mamod, J. Applied Physiology, 20, 657-660.
[22] Zatsiorskiĭ, V. i kol., 1971. V. A. Zaporozhan, I. A. Ter-Ovanesyan, 1971. Materials for substantiating a system of ongoing pedagogical monitoring in speed-strength sports. Materialy k obosnovaniyu sistemy tekushchego pedagogicheskogo kontrolya v skorostno-silovykh vidakh sporta. Teoriya i praktika fizicheskoy kul'tury. [In Russian], Theory and Practice of Physical Education 6, 64–70.
[23] Flandrois. M., R., 1985. Physiologie du sport. Edition Masson, 44-51, Paris.
[24] Nedan, M., F. Peronnet et coll., 1980. Physiologie appliquée a l`activite physique. Edisem, 36-49, Ed. Vigot, Paris.
[25] Forbes, Margaret Swan, 1988. Coaching Synchronized Swimming Effectively. Champaign, IL, 1st ed., Human Kinetics, 1-126, Pennsylvania State University.
[26] Dimitrova, N., 2019b, Resistance while managing its own inertial power field. Trakia Journal of Sciences, 17, 1, 631 – 634.
[27] Connes, Ph. et al., 2013. Exercise Hemorheology: Classical Data, Recent Findings and Unresolved Issues. Clinical Hemorheology and Microcirculation**,** 53, 187–199.
[28] Dimitrova, N. 2020. Control of the spatial structure in preschool children. Trakia Journal of Sciences, 18, 1, 854 - 856,
[29] Nader E, Skinner S, Romana M, Fort R, Lemonne N, Guillot N, Gauthier A, Antoine-Jonville S, Renoux C, Hardy-Dessources M-D, Stauffer E, Joly P, Bertrand Y and Connes P., 2019. Blood Rheology: Key Parameters, impact on blood flow, role in sickle cell disease and effects of exercise. Front. Physiol, 10, 44-51.
[30] Mihaylov P.V., Osetrov I.A., Ostroumov R.S., Bulaeva S.V., 2017. Analysis of adaptation reserves of microvascular in persons of different physical fitness and age, Med.Ph., 91-98.
[31] Dudaev, V. A., Dyukov, I. V., & Borodkin, V. V., 1986. Changes in the level of fibrinogen and its high-molecular derivatives because of physical training in patients with coronary heart disease. Izmeneniye urovnya fibrinogena i ego vysokomolekulyarnykh proizvodnykh v rezul'tate fizicheskoy trenirovki u bol'nykh. IBS, [In Russian], Therapeutic archive, 58, 6, 62–67.
[32] Karsheva M., Dinkova P., Pentchev I., 2011. Short-term Blood Rheological Effects in Regularly Training Volleyball Players. Comp. Rend. Acad. Bulg. Sci., 64, 9, 1279-1284.
[33] Gokhale R., Chandrashekara S., & Vasanthakumar K. C., 2007. Cytokine response to strenuous exercise in athletes and non-athletes—an adaptive response. Cytokine, 40, 2, 123-127.

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