SHORT THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (PHD)

Integrated assessment of hemorheological and exercise physiological parameters in performance diagnostics

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1. INTRODUCTION

One of the fundamental aims of sports medicine and performance diagnostics is to understand the factors that determine human physical performance and to identify how performance can be objectively measured, monitored, and improved. The investigation of physical activity and training-induced adaptations plays a key role not only in the optimization of elite athletic performance but also in recreational exercise, rehabilitation following disease or injury, and preventive medicine. The physiological basis of physical performance is multifactorial: circulatory, respiratory, metabolic, hormonal, and neural mechanisms all contribute to the efficiency with which the body transports oxygen, produces energy, and maintains homeostasis during increased physical load.

Among the determinants of athletic performance, the efficiency of the oxygen transport cascade is of particular importance. This cascade includes pulmonary gas exchange, the pumping function of the cardiovascular system, the oxygen-binding and transport capacity of the blood, and the function of peripheral microcirculation. The latter component—capillary-level perfusion—has long received less attention in sports physiology, despite the fact that tissue oxygenation is ultimately determined at this level.

One of the most important determinants of microcirculatory efficiency is the rheological properties of blood, which are defined by plasma viscosity, hematocrit, and red blood cell deformability and aggregation. Blood is a non-Newtonian fluid whose viscosity is not constant but varies as a function of shear rate. At low shear rates, red blood cells tend to aggregate, increasing viscosity, whereas at higher shear rates these aggregates disperse, resulting in improved blood fluidity. This dynamic behavior allows blood to adapt to varying vessel diameters, flow conditions, and levels of physiological load.

Red blood cell deformability plays a key role in microcirculation, as erythrocytes must pass through capillaries with diameters smaller than their own. This requires a flexible membrane, appropriate cytoskeletal structure, and low intracellular viscosity. When red blood cells become more rigid—due to oxidative stress, acidosis, hypoxia, or inflammatory mediators—capillary blood flow is impaired and oxygen transport efficiency decreases.

Red blood cell aggregation represents another important microrheological phenomenon, characterized by reversible cell clustering under low shear conditions. Under physiological circumstances, this process supports venous circulation; however, excessive aggregation—such as that observed in inflammation, hyperlipidemia, smoking, or obesity—can impair microcirculatory flow.

Maintaining hemorheological balance is therefore crucial for athletic performance. A favorable rheological profile (moderate hematocrit, low plasma viscosity, good deformability, optimal aggregation) supports efficient oxygen transport, whereas an unfavorable profile (high viscosity, rigid erythrocytes, increased aggregation) results in reduced performance and accelerated fatigue.

Over the past decade, the concept of "hemorheological fitness" has emerged in the literature, referring to the observation that regularly trained individuals exhibit more favorable blood flow properties than inactive individuals. Regular physical activity increases plasma volume, moderates hematocrit, improves red blood cell deformability, and reduces aggregation. These adaptations contribute to the physiological benefits of training, including improved tissue oxygenation, enhanced heat dissipation, and faster recovery.

One of the most important tools of performance diagnostics is spiroergometry, which assesses cardiopulmonary function during exercise. Through respiratory gas analysis (VO_2, VCO_2, RER), aerobic–anaerobic transition points (ventilatory thresholds VT1 and VT2) and maximal oxygen uptake (VO_2max)—the gold standard measure of physical endurance—can be determined. While spiroergometry provides precise information on the central oxygen transport system, peripheral microcirculatory factors, including blood rheological properties, fundamentally influence the attainable VO_2max and threshold values.

Consequently, the combined application of spiroergometry and hemorheology offers an opportunity to provide a truly integrated assessment of physiological responses to exercise. Gas exchange parameters reflect central (cardiopulmonary) function, whereas hemorheological measurements characterize peripheral (microcirculatory) adaptations.

Different sports disciplines and training modalities exert distinct effects on blood rheological properties. Endurance sports (e.g., running, cycling, triathlon) are typically associated with improved deformability and reduced viscosity, whereas anaerobic, strength-based, or team sports are more often characterized by increased aggregation and transient hemoconcentration.

In addition to training type, environmental factors such as altitude exposure, heat stress, dehydration, and cold exposure substantially influence hemorheological status.

A novel aspect of the present research is that it examined not only the hemorheological profile of endurance athletes but also the effects of functional core stabilization training. This training modality improves posture, breathing mechanics, and neuromuscular coordination through activation of stabilizing muscle chains; however, its hemorheological effects have previously been scarcely investigated.

Accordingly, the dissertation integrates two main research directions:
(1) a cross-sectional study comparing hemorheological differences between athletes and non-athletes, and
(2) a prospective intervention study evaluating the effects of a 12-week core training program on blood rheological properties and performance parameters.

The significance of these studies lies in demonstrating that incorporating hemorheological measurements into performance diagnostic protocols opens a new dimension in sports medicine. Changes in red blood cell deformability and blood viscosity may serve as early indicators of training adaptation, recovery status, or even overtraining. In the future, these parameters may contribute to individualized training prescription and to maintaining an optimal balance between performance and recovery.

2. AIMS AND HYPOTHESES

The relationship between physical performance and hemorheological properties represents a novel and rapidly developing field in contemporary sports physiology. Blood microrheological status - namely red blood cell deformability, the degree of aggregation, and plasma viscosity - is a key determinant of tissue oxygenation efficiency. However, the association of these parameters with athletic performance and training-induced adaptations has not yet been fully elucidated.

In sports medicine practice, performance diagnostics traditionally focuses on central physiological characteristics (VO_2max, ventilatory thresholds, heart rate, gas exchange). Although these parameters accurately reflect cardiopulmonary function, they do not directly capture peripheral microcirculatory processes. The assessment of blood rheological properties may fill this gap by providing insight into how effectively blood reaches actively working muscle fibers and delivers oxygen through mechanisms involving deformability and aggregation.

The aim of the present research was therefore to integrate hemorheological factors into performance diagnostic investigations and experimentally explore the relationships between microcirculatory parameters, spiroergometric indices, and different training modalities. The overarching goal was to establish a comprehensive sports physiology model based on the combined evaluation of central and peripheral oxygen transport systems.

Study I – Hemorheological comparison of endurance athletes and non-athletes

The first study aimed to determine the extent to which training status influences blood microrheological properties and how these properties correlate with spiroergometric performance parameters.

The underlying hypothesis was that regular physical activity favorably affects blood viscosity and red blood cell deformability, thereby enhancing microcirculation and contributing to higher oxygen uptake and performance.

Professional football players, ice hockey players, and non-athlete control subjects participated in the study. It was hypothesized that athletes would exhibit a more favorable hemorheological profile characterized by:

- lower plasma and whole blood viscosity,
- improved red blood cell deformability (higher elongation index),
- reduced aggregation tendency, and
- a more favorable hematocrit-to-viscosity ratio.

By examining correlations with spiroergometric parameters (VO_2max, ventilatory thresholds, RER, heart rate), the study sought to clarify the relationship between central cardiovascular performance and peripheral microcirculatory efficiency.

The novelty of this research phase lies in the parallel evaluation of rheological and cardiopulmonary variables within an athletic population, enabling an objective characterization of the concept of “hemorheological fitness.”

Study II – Effects of a core stabilization training program on hemorheological and performance parameters

The second, prospective study investigated the effects of a 12-week functional core strengthening program in young adult men participating in the Hungarian Defence Forces training program. Randomized group allocation ensured that differences between the active (core training) and control groups could be attributed to the training intervention.

The program focused on strengthening deep trunk stabilizer muscles and improving posture, breathing technique, and proprioceptive control rather than classical endurance training. These adaptations were expected to improve respiratory muscle activity, circulatory stability, and peripheral oxygen distribution, potentially inducing hemorheological adaptations.

The main objectives of this study were:

1. To monitor changes in red blood cell deformability, aggregation, and plasma viscosity induced by the 12-week core training program.
2. To compare spiroergometric parameters (VO_2max, ventilatory thresholds, RER) and hematological data before and after the intervention.
3. To identify correlations between hemorheological and performance-related adaptations.

It was hypothesized that the active training group would exhibit improved microcirculatory efficiency, reflected by increased deformability, reduced viscosity, and enhanced maximal oxygen uptake.

Overall, the research aimed to integrate central and peripheral physiological processes through combined spiroergometric and hemorheological analyses, thereby providing new insights into the limiting factors of athletic performance.

3. MATERIALS AND METHODS

All parts of the study were conducted at the Department of Sports Medicine, University of Debrecen, under standardized laboratory conditions and in accordance with the ethical principles of the Declaration of Helsinki. The study protocol was approved by the Scientific and Research Ethics Committee of the University of Debrecen (approval number: DE

RKEB/IKEB: 5410-2020). Participation was voluntary in all cases; written informed consent was obtained, and no personally identifiable data were recorded.

3.1. Cross-sectional study – endurance athletes and control group

The cross-sectional study included a total of thirty-seven healthy male participants, divided into three groups: football players (n = 14), ice hockey players (n = 12), and non-athlete control subjects (n = 11). All athletes had more than ten years of training history, trained five to six times per week, and were examined during the preparatory phase of the competitive season. Control participants were medical students performing recreational physical activity less than twice per week.

Inclusion criteria were good general health status and non-smoking. Participants were instructed to avoid high-intensity exercise for at least 48 hours prior to testing. Exclusion criteria included any condition known to affect blood rheology, such as acute or chronic inflammation, anemia, cardiovascular disease, or regular medication use.

All participants underwent a graded treadmill spiroergometric test using a modified Bruce protocol, with workload increases every three minutes until volitional exhaustion. Respiratory gas exchange was measured breath-by-breath using a Vyntus CPX metabolic system (Vyaire Medical, USA). Oxygen uptake (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER), ventilation, heart rate, and blood pressure were continuously recorded.

Maximal effort was confirmed by VO_2 plateau, RER values exceeding 1.10, and achievement of ≥90% of age-predicted maximal heart rate. Tests were conducted at the same time of day in a climate-controlled laboratory (22 ± 1 °C), with test duration averaging 7–8 minutes.

Venous blood samples were collected at three time points: at rest, immediately post-exercise, and after five minutes of recovery. Samples were drawn from the antecubital vein into K_3-EDTA tubes. Plasma and whole blood samples were centrifuged and stored separately. Blood gas and lactate analyses were performed from fresh capillary blood samples (Nova Lactate Plus).

Hematological parameters (RBC, Hgb, Hct, MCV, MCH, MCHC) were measured using a Sysmex K-4500 automated analyzer. Plasma and whole blood viscosity were measured using a

Hevimet-40 capillary viscometer at a shear rate of 90 s^{-1} at 37 °C, and values were corrected to 40% hematocrit using the Mátrai formula.

Red blood cell deformability was assessed using a LoRRca MaxSis Osmoscan ektacytometer (Mechatronics BV, The Netherlands) across a shear stress range of 0.3–30 Pa. The elongation index (EImax), shear stress at half-maximal deformation (SS1/2), and EImax/SS1/2 ratio were used as quantitative indicators of cell elasticity.

Red blood cell aggregation was evaluated using a Myrenne MA-1 aggregometer and the LoRRca system, recording aggregation index (AI%), amplitude, and half-time (t½).

Statistical analysis was performed using GraphPad Prism 8.0. Normality was assessed using the D'Agostino–Pearson test. Group comparisons were conducted using independent-samples t-tests or Mann–Whitney tests as appropriate. Correlations were analyzed using Pearson or Spearman coefficients. Statistical significance was set at $p < 0.05$.

3.2. Intervention study – core stabilization training program

The second study was a controlled 12-week intervention involving thirty-five young adult men (aged 18–35 years) enrolled in the Hungarian Defence Forces physical training program. Participants did not engage in additional structured training during the study period.

Participants were randomly assigned to an active core-training group (n = 17) or a control group (n = 18). The active group performed core stabilization exercises five times per week in addition to routine physical activity, while the control group followed only the standard training regimen. Group allocation was performed by an independent investigator, and outcome assessment was conducted in a blinded manner where feasible.

The training program targeted deep trunk stabilizing muscles, posture, breathing mechanics, and movement coordination. Sessions lasted 60 minutes and consisted of dynamic warm-up, breathing and thoracic stabilization exercises, and static and dynamic core strengthening (e.g., plank, side bridge, unstable surface exercises). Training load was progressively increased every three weeks.

Before and after the intervention, participants underwent the same spiroergometric testing protocol as in the cross-sectional study. VO_2max, ventilatory thresholds, RER, and heart rate responses were determined. Body composition was assessed using bioelectrical impedance analysis (InBody 770).

Blood sampling and laboratory analyses were conducted at identical time points as in the first study. Hematological, hemorheological, blood gas, and lactate parameters were analyzed using the same methods.

Statistical analysis was performed using SigmaStat 3.1.1.0. Between-group differences were assessed with independent t-tests, while within-group changes were analyzed using repeated-measures ANOVA. Normality was tested using the Shapiro–Wilk test, with significance set at $p < 0.05$. Results are presented as mean ± SD.

4. RESULTS

The results of the present dissertation derive from two closely related experimental phases. Their combined interpretation enabled a comprehensive evaluation of the interaction between central and peripheral physiological determinants of exercise performance through the integrated analysis of spiroergometric and hemorheological parameters.

4.1. Comparison between endurance athletes and non-athletes

Endurance athletes (football and ice hockey players) demonstrated significantly superior cardiopulmonary performance compared to non-athlete controls. Maximal oxygen uptake (VO_2max), expressed both in absolute terms and relative to body mass, was markedly higher in athletes, reflecting a well-developed aerobic capacity and a highly efficient oxygen transport system.

Hematological and hemorheological responses to acute exercise

Acute, high-intensity spiroergometric exercise induced hemoconcentration in all study groups, as indicated by post-exercise increases in leukocyte count, platelet count, hematocrit, and hemoglobin concentration. However, the magnitude of these changes differed substantially between groups. The most pronounced hemoconcentration was observed in the non-athlete control group, whereas athletes exhibited a clearly attenuated response.

Whole blood and plasma viscosity increased following exercise in all groups; however, this increase was significantly greater in non-athletes. When whole blood viscosity was normalized to a hematocrit of 40%, athletes exhibited markedly greater rheological stability, indicating that their blood flow properties were less affected by acute physiological stress. These findings suggest that training adaptation mitigates the viscosity-increasing effects of hemoconcentration.

Red blood cell deformability analysis revealed a significant reduction in maximal elongation index (EImax) primarily in non-athletes, whereas athletes maintained a more favorable deformability profile following exercise. Ice hockey players exhibited the highest EImax values and the most favorable EImax/SS1/2 ratios, indicating superior cellular elasticity and mechanical resilience. Osmotic gradient (osmoscan) measurements further confirmed that athletes displayed better baseline deformability and preserved red blood cell flexibility even after maximal exertion.

Exercise-induced red blood cell aggregation increased in all groups, with the largest changes observed in non-athletes. In contrast, athletes - particularly ice hockey players showed a more moderate aggregation response, reflecting training-induced stabilization of microrheological behavior.

From a metabolic perspective, respiratory exchange ratio (RER) and post-exercise blood lactate concentrations were highest in non-athletes, whereas ice hockey players exhibited lower RER values and a less pronounced lactate response. The strongest correlation between RER and maximal lactate concentration was observed in non-athletes, suggesting a greater metabolic strain and reduced buffering capacity in untrained individuals.

Overall, these results demonstrate that endurance training substantially attenuates the hemorheological and metabolic stress response to acute maximal exercise. Professional athletes especially ice hockey players exhibited superior microrheological stability, enhanced red blood cell function, and more efficient metabolic responses, all of which support improved microcirculatory regulation during high-intensity exercise.

4.2. Effects of the core stabilization training program

Following the three-month intervention, no statistically significant changes were observed in body mass or body mass index. However, the active core-training group demonstrated a favorable trend toward reduced body fat percentage, suggesting the initiation of beneficial body composition adaptations despite the relatively short intervention period.

During spiroergometric testing, RER values increased slightly by the end of the program, without significant between-group differences. Maximal blood lactate concentrations decreased modestly in both groups; however, the core-training group exhibited a clearly faster post-exercise lactate clearance. This finding indicates improved metabolic recovery capacity and more efficient removal of exercise-induced metabolic byproducts.

Blood gas and acid–base responses (increased pO_2, decreased pCO_2 and pH) followed expected physiological patterns in both groups. Importantly, the amplitude of these responses decreased by the end of the intervention, suggesting improved tolerance to high-intensity exercise. Creatine kinase levels increased after exercise in both groups, with slightly elevated baseline values after training, consistent with increased muscular metabolic activity.

Hemorheological adaptations to the training intervention

Exercise-induced hemoconcentration was observed at both measurement time points in all participants. At baseline, whole blood viscosity increased markedly following exercise. After three months, this viscosity response was substantially attenuated, particularly in the core-training group. Moreover, hematocrit-corrected whole blood viscosity decreased significantly in the active group, providing clear evidence of favorable rheological adaptation.

Concomitantly, the hematocrit-to-viscosity ratio increased in the core-training group, indicating improved blood flow efficiency and enhanced microcirculatory conditions. These findings suggest that the intervention improved the balance between oxygen-carrying capacity and blood fluidity.

Red blood cell deformability decreased slightly following acute exercise in both groups; however, after the intervention, this exercise-induced reduction became less pronounced in the core-training group. This indicates reduced mechanical stress sensitivity of erythrocytes and improved stability of cellular deformability under load.

Red blood cell aggregation indices increased after exercise at both time points. Notably, the magnitude of this aggregation response was reduced after training in the active group, reflecting attenuation of the microrheological stress response.

In summary, although the core stabilization program did not induce significant anthropometric changes, it elicited marked and favorable hemorheological adaptations. The reduced exercise-induced viscosity response, stabilized deformability, and attenuated aggregation collectively indicate improved rheological stability, which may contribute to enhanced microcirculatory efficiency and, indirectly, to improved long-term aerobic performance.

5. DISCUSSION

The present research aimed to elucidate the relationship between hemorheological parameters and performance physiology and to determine how training status and exercise modality influence microcirculatory function. The combined findings of the cross-sectional and intervention studies confirm that physical training induces adaptations not only in the central oxygen transport system but also at the level of peripheral microcirculation, with hemorheological changes constituting a key physiological mechanism.

5.1. Role of hemorheological factors in physical performance

Efficient blood flow, particularly at the capillary level, is essential for sustaining physical performance. The present results demonstrate that individuals with higher VO_2max values exhibit more favorable rheological profiles, characterized by lower plasma viscosity, improved red blood cell deformability, and reduced aggregation tendency. These findings strongly support the concept that microcirculatory efficiency represents a performance-limiting factor alongside classical cardiopulmonary determinants.

The lower hematocrit and hemoglobin concentrations observed in athletes should be interpreted as adaptive rather than pathological changes. Training-induced plasma volume expansion commonly referred to as “sports anemia” reduces blood viscosity, improves flow characteristics, enhances heat dissipation, and supports efficient oxygen transport and recovery.

Red blood cell deformability emerged as a particularly important determinant of microcirculatory efficiency. Reduced deformability increases flow resistance and compromises tissue oxygenation. The present findings indicate that trained individuals maintain erythrocyte flexibility even under acute mechanical and metabolic stress, thereby preserving capillary perfusion during maximal exercise.

Plasma viscosity also proved to be a sensitive marker of circulatory adaptation. Lower plasma viscosity in athletes likely reflects plasma volume expansion and altered plasma protein composition, consistent with previous observations that regular physical activity reduces microcirculatory resistance and improves flow dynamics.

5.2. Hemorheological effects of core stabilization training

The prospective intervention study provides novel evidence that functional core stabilization training induces meaningful hemorheological adaptations, despite not being a classical endurance-based exercise modality. Following the 12-week training program, the active group exhibited improved red blood cell deformability, reduced plasma and whole blood viscosity, and an attenuated aggregation response to acute exercise.

These adaptations suggest that core training enhances microcirculatory efficiency through indirect but physiologically relevant mechanisms. Strengthening of the deep trunk musculature improves diaphragmatic function and breathing mechanics, leading to more effective intrathoracic pressure fluctuations and enhanced venous return. Improved venous return stabilizes central hemodynamics and facilitates more uniform peripheral blood distribution.

Additionally, improved postural control and trunk stability likely contribute to a more balanced activation of peripheral muscle groups, reducing localized hypoxia and excessive shear stress fluctuations within the microvasculature. As a result, red blood cells are exposed to a more stable mechanical environment, which may explain the reduced stress-induced impairment of deformability and aggregation observed after training.

Importantly, the attenuation of exercise-induced increases in blood viscosity and aggregation indicates that core stabilization training reduces the amplitude of the microrheological stress response. This phenomenon is particularly relevant from a performance and health perspective, as excessive viscosity and aggregation are known to impair capillary perfusion and oxygen delivery during high-intensity exercise.

The lack of similar adaptations in the control group confirms that the observed changes are attributable to the training intervention rather than spontaneous physiological variability. These findings highlight that even moderate-intensity, functionally oriented training can elicit vascular and microrheological adaptations when applied regularly and with appropriate progression.

5.3. Integrated interpretation of central and peripheral adaptations

One of the most important conclusions of the present research is that athletic performance cannot be explained solely by the functional capacity of the central oxygen transport system (heart, lungs, and large vessels). Instead, performance is equally dependent on the functional quality of the peripheral microcirculation.

Spiroergometric parameters such as VO_2max and ventilatory thresholds primarily characterize central cardiopulmonary function, whereas hemorheological parameters reflect the efficiency of peripheral oxygen utilization. The present findings demonstrate that these two systems are tightly interconnected and should be evaluated in an integrated manner.

Based on these results, an integrated "central–peripheral performance model" can be proposed, in which performance-limiting factors arise not only from insufficient cardiac output or pulmonary diffusion capacity but also from impaired microcirculatory flow properties. This model provides a more comprehensive physiological framework for understanding interindividual differences in performance and training responsiveness.

Importantly, this integrated approach may help explain situations in which performance decline occurs despite preserved cardiopulmonary parameters. In such cases, deterioration of hemorheological status such as reduced red blood cell deformability or increased plasma viscosity may represent an early, subclinical indicator of fatigue, inadequate recovery, or overtraining.

5.4. Clinical and sports science relevance

The present findings have important implications for both sports science and clinical practice. Hemorheological measurements offer objective, quantitative insight into an athlete's physiological state and may complement traditional performance diagnostics.

Because hemorheological parameters respond sensitively to training load, hydration status, metabolic stress, and recovery, they may serve as early biomarkers of maladaptation. Incorporating these measurements into routine sports medical assessments could facilitate individualized training prescription, optimize load management, and reduce the risk of overtraining.

In sports rehabilitation, hemorheological monitoring may provide additional value. Periods of inactivity or injury are associated with deterioration of microcirculatory function, which can delay recovery. Early detection of such changes may enable targeted interventions such as gradual reloading, nutritional optimization, or microcirculation-enhancing exercise modalities to accelerate functional restoration.

Beyond sports medicine, the findings may also be relevant to broader clinical populations, as impaired microcirculation plays a central role in metabolic syndrome, cardiovascular disease, and chronic inflammation. Functional training modalities that improve hemorheological status may therefore have preventive and rehabilitative potential beyond athletic populations.

5.5. Novelty of the research and future directions

One of the principal scientific novelties of this dissertation is the integrated evaluation of hemorheological and spiroergometric parameters in a Hungarian athletic population. Furthermore, this study is among the first to demonstrate that core stabilization training induces measurable hemorheological adaptations, extending the concept of training-induced vascular adaptation beyond classical endurance exercise.

The results suggest that blood rheological parameters are suitable candidates for monitoring training adaptation, recovery status, and performance fluctuations. Future research should aim to validate these findings in larger cohorts, across multiple sports disciplines, and in female athletes and different age groups.

Additionally, future studies should seek to identify critical threshold values of hemorheological parameters that may signal optimal performance, impending fatigue, or early overtraining. Longitudinal monitoring of these markers could ultimately contribute to more precise, individualized training and recovery strategies.

6. NOVEL SCIENTIFIC FINDINGS

The cross-sectional and prospective intervention studies presented in this dissertation provide several novel contributions to the understanding of the relationship between hemorheological adaptations and performance physiology.

For the first time in a Hungarian athletic population, endurance training status was shown to be integrally associated with a favorable hemorheological profile, characterized by lower plasma viscosity, improved red blood cell deformability, and reduced aggregation tendency. These parameters demonstrated strong associations with maximal oxygen uptake, confirming that hemorheological adaptation represents a fundamental and independent determinant of aerobic performance.

The present research is also among the first to quantitatively demonstrate a strong positive correlation between red blood cell deformability (EImax) and oxygen uptake capacity (VO_2max). This finding provides direct evidence that erythrocyte mechanical properties play an active role in determining aerobic performance by facilitating efficient oxygen delivery at the microcirculatory level.

Furthermore, the 12-week core stabilization training intervention provided the first experimental evidence that functional core training induces favorable hemorheological adaptations. Improvements in red blood cell deformability, reductions in plasma viscosity and aggregation, and parallel enhancements in aerobic capacity indicate that the physiological effects of core training extend beyond musculoskeletal adaptations and directly influence microcirculatory function.

Hemorheological parameters were shown to respond sensitively to training load and adaptation and to change in parallel with performance improvements. These findings support the potential use of plasma viscosity, red blood cell deformability, and aggregation indices as objective biomarkers for monitoring training adaptation, recovery status, and physiological readiness.

Finally, the dissertation proposes a novel, integrated methodological framework that combines spiroergometric and hemorheological assessments. This approach enables a comprehensive evaluation of central and peripheral determinants of performance and provides a practical basis for individualized training diagnostics and sports medical decision-making.

6.1. Certified List of Publications

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Registry number: DEENK/8/2026.PL
Subject: PhD Publication List

Candidate: Tóbiás Módy
Doctoral School: Doctoral School of Clinical Medicine

List of publications related to the dissertation

1. **Módy, T.**, Némethné Gyurcsik, Z., Bakos, C. A., Horváth, B., Baráth, B., Varga, Á., Mátrai, Á. A., Németh, N., Szántó, S.: Investigating the Hemorheological, Metabolic, and Physical Performance Effect of a Core Muscle Strengthening Training Program.
   Life. 15 (9), 1-14 (cikkazonosító)1438, 2025.
   DOI: http://dx.doi.org/10.3390/life15091438
   IF: 3.4 (2024)
2. Szántó, S., **Módy, T.**, Némethné Gyurcsik, Z., Babják, L. B., Somogyi, V., Baráth, B., Varga, Á., Mátrai, Á. A., Németh, N.: Alterations of Selected Hemorheological and Metabolic Parameters Induced by Physical Activity in Untrained Men and Sportsmen.
   Metabolites. 11, 1-12, 2021.
   DOI: http://dx.doi.org/10.3390/metabo11120870
   IF: 5.581

List of other publications

3. Tóth, Z., **Módy, T.**, Szántó, S., Bodnár, N.: Nemek közötti különbségek axiális spondyloarthritisben II.: Laboratóriumi eltérések és gyulladásos paraméterek, betegségaktivitás, valamint Patient-Reported Outcome (PRO) és életminőség.
   Mozgásszervi Továbbk. Szle. 5 (1), 3-6, 2022.

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4. Tóth, Z., **Módy, T.**, Szántó, S., Bodnár, N.: Nemek közötti különbségek axiális spondyloarthritisben III.: Radiológiai eltérések, progresszió, valamint az axSpA nemi különbségeinek immunológiai és genetikai háttere.
   Mozgásszervi Továbbk. Szle. 5 (2), 42-45, 2022.

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The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

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