Journal of Physical Education and Sport ® (JPES), Vol. 25 (issue 11), Art 254, pp. 2303-2310, November 2025
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Structural and functional organization of the blood microcirculation system in students with different levels of physical activity

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Published online: November 30, 2025
Accepted for publication: November 15, 2025
DOI:10.7752/jpes.2025.11254

Abstract:
Human physical activity induces adaptive changes in the blood microcirculation system, particularly in muscle tissue. **Purpose:** To investigate the characteristics of tissue blood flow and identify the phenotypes of blood microcirculation in students with different levels of physical activity. **Materials and Methods:** The study involved 57 male university students (mean age 19.2 ± 1.3 years), including those engaged in martial arts as part of academic electives (n = 34) and athletes from the national team (n = 23). The functional state of the blood microcirculation system was evaluated using the LAZMA hardware–software complex (Russia), which allows for measurement of blood flow perfusion levels. The study investigated the contribution of various factors to the regulation of vascular tone and tissue metabolic activity. Cluster analysis was performed using the K-means method, while correlation analysis was performed using Spearman's method. **Results:** The findings suggest that the level of physical activity shapes the functional organization of the microcirculation system. Cluster analysis revealed distinct microcirculation phenotypes, reflecting varying degrees of adaptation to physical activity. Correlation analysis indicated that in students without athletic training, regulation of microcirculation was primarily mediated by local mechanisms, whereas in student–athletes, central mechanisms dominated, enhancing energy efficiency and maintaining stable blood flow. **Conclusions:** Regular moderate- and high-intensity physical activity promotes the development of an energy-efficient microcirculation system, characterized by more stable vascular and metabolic regulation. These findings should be considered when designing physical training programs and strategies to prevent vascular tone dysfunction in university students.
Keywords: physical activity, sports training, martial arts, blood microcirculation, metabolic processes

Introduction

Regular physical exercise has a profound effect on the functional characteristics of blood microcirculation. It enhances the ability of blood vessels to respond to fluctuations in tissue oxygen demand (Ma et al., 2022), improves oxygen delivery, and activates metabolic processes (Hong, & Park, 2024). Evidence from systematic reviews and empirical studies indicates that aerobic and combined aerobic–strength training programs improve coronary circulation and stimulate cutaneous microcirculatory reactivity, as reflected in changes in hyperemia, endothelial sensitivity, and vascular responses to local stimuli (Haunhorst, 2025). Additionally, a key component of adaptation involves changes in mitochondrial function and substrate metabolism, which can be assessed using nicotinamide adenine dinucleotide (NADH) fluorescence. Recent evidence shows that both short-term and long-term training lead to increases in basal and stimulated NADH fluorescence in the skin, reflecting enhanced mitochondrial function and greater tissue readiness for oxidative metabolism (Garcia-Roves et al., 2025). Training not only improves baseline perfusion but also modulates various regulatory oscillations in microcirculation, including those related to respiration and heart rate, ultimately contributing to better overall health. Studies have demonstrated that regular physical activity increases the amplitude of blood flow oscillations, which are associated with cardiorespiratory components and indicate a greater systemic involvement in vascular control. This also reflects a restructuring of hemodynamic relationships in response to training stress.

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Therefore, different forms of physical activity induce multiple beneficial adaptive changes in blood microcirculation, particularly in muscle tissue.

Microcirculation can be effectively studied using laser Doppler flowmetry (LDF), a method that assesses spectral components of blood flow as well as skin NADH fluorescence. These techniques provide sensitive and informative, noninvasive tools for evaluating perfusion, blood flow variability, and the relationship between hemodynamics and tissue metabolism. Application of these methods in studies of exercise adaptation has demonstrated their high sensitivity to changes in microcirculatory reactivity.

However, evidence suggests that the skin's response to training can be heterogeneous, depending on factors such as exercise type, training duration, and the tissue under investigation. Recording NADH fluorescence provides a means to assess oxidative metabolism in tissues, offering additional insights into mitochondrial activity and redox status.

Studies have shown that athletes exhibit increases in both basal and post-exercise levels of skin NADH fluorescence after training, reflecting a restructuring of tissue metabolism in response to systematic exercise. These findings highlight the potential of integrating these measurements into a single hardware–software system for studying microcirculatory adaptation to exercise. Evidence also suggests that NADH levels can be modulated through exercise, nutrition, and a healthy lifestyle (Poljsak et al., 2020). Despite these insights, questions remain regarding the variability of interstitial and shunt perfusion components in young students engaged in regular physical activity of differing intensities. It is also important to investigate hemodynamic changes in relation to oxidative metabolism parameters. Moreover, identifying correlations between these parameters and performing cluster analyses based on blood microcirculation characteristics is of practical interest because this approach could provide a reliable biomarker for the degree of adaptation to training loads. Testing these hypotheses allows for assessment of how the regularity and intensity of training influence these relationships.

Research aim: The study aimed to analyze tissue blood flow characteristics and identify microcirculation phenotypes in students with different levels of physical activity.

Materials and methods

The study included 57 male students from Privolzhsky Research Medical University (Russia), with a mean age of 19.2 ± 1.3 years. Participants were divided into two groups. Group 1 (n = 34) comprised students practicing aikido as part of optional physical education classes, while Group 2 (n = 23) consisted of university martial arts team members who engaged in high-intensity physical training. Students in Group 1 participated in the described physical activity no more than once per week, whereas those in Group 2 trained at least twice per week. All participants in both experimental groups provided informed consent to participate in the study. The study was conducted in accordance with the principles of the 2008 Helsinki Declaration on Biomedical Research. The project was performed in collaboration with researchers and specialists from universities in Russia, Kyrgyzstan, and Kazakhstan.

The functional state of the blood microcirculation system was assessed using a portable hardware–software system, the LAZMA-PF Microcirculation Analyzer (Moscow, Russia). The device emits laser radiation onto the surface under examination, which is then reflected by red blood cells and returned to the device for photometric detection and signal analysis. LDF results are displayed on a personal computer using specialized software, presenting a signal whose amplitude is proportional to both blood flow velocity and red blood cell count. The LDF diagram generated by the device is derived from the analysis of perfusion fluctuations and provides a quantitative assessment of the state of blood microcirculation. During measurements, subjects were seated, and the sensor was applied to the skin of the index finger on the left hand. Recordings were performed for a minimum of 5 min. The functional state of the LDF was evaluated using the microcirculation index (M), the standard deviation of blood flow oscillation amplitude from the mean (σ, "flux"), the ratio of blood perfusion to its variability (coefficient of variation, Cv), and the oxidative metabolism index (OMI). OMI was calculated based on the relationship between the nutritive component of blood perfusion and the fluorescence amplitude of the coenzyme NADH. During data processing, statistical analysis of wavelet oscillations was performed to determine the amplitudes of blood flow oscillations.

Oscillation amplitudes corresponding to the endothelium-dependent component of vascular tone (Ed), neurogenic tone (Nt), and myogenic tone (Mt) were analyzed to assess mechanisms of vascular regulation. Passive wavelet oscillations were represented by respiratory (Rt) and cardiac (Ct) components, associated with breathing and heart rate, respectively. The measured parameters were compared with the standard reference values provided by the device manufacturer.

The data were analyzed using variation statistics methods in Statistica 10.1 (StatSoft, Oklahoma) and Microsoft Excel 2016 (Microsoft, Redmond). The arithmetic mean perfusion index (M) and standard error of the mean (m) were calculated. The Shapiro–Wilk test was applied to assess the normality of the data distribution. Because the data deviated from normality, the nonparametric Kruskal–Wallis test was used to evaluate the statistical significance of differences between study groups. Cluster analysis was performed using the K-means method, with centroids and distances between value clusters determined. Correlation analysis was performed

using Spearman's rank-order method, with relationships assessed separately for students participating in physical education electives and for athletes. Differences were considered statistically significant at $p < 0.05$.

Results

Analysis of microcirculation parameters revealed several characteristic features in students with different patterns of physical activity (Table 1).

Table 1. Blood microcirculation parameters in students with different physical activity patterns (n = 57), mean ± standard error (M ± m)

Parameter	Observation group		p < 0.05
	Group No. 1 (elective classes, n = 34)	**Group No. 2 (athletes, n = 23)**	
M, perfusion units	18.9 ± 10.2	20.0 ± 8.3	
M_{nutr}, perfusion units	10.4 ± 6.0	8.9 ± 3.0	1–2
M_{shunt}, perfusion units	8.5 ± 6.5	11.1 ± 6.0	1–2
SD (σ), perfusion units	2.54 ± 2.53	3.06 ± 1.27	1–2
Cv, %	13.2 ± 6.1	16.8 ± 6.5	1–2
Ed, c.u.	0.92 ± 0.67	1.00 ± 0.43	
Nt, c.u.	0.93 ± 0.67	1.07 ± 0.55	
Mt, c.u.	0.85 ± 0.61	0.76 ± 0.26	
Rt, c.u.	0.52 ± 0.38	0.42 ± 0.14	1–2
Ct, c.u.	0.57 ± 0.33	0.63 ± 0.31	1–2
NADH, c.u.	0.7 ± 0.19	0.7 ± 0.31	
OMI, c.u.	8.37 ± 5.81	12.4 ± 25.7	

Note: p indicates the significance of differences between groups, assessed using the Kruskal–Wallis test (p < 0.05)

The average microcirculation index was similar in both study groups (18.9 ± 10.2 perfusion units (PU) in the first group and 20.0 ± 8.3 perf. units in the second group, $p > 0.05$), indicating that overall perfusion levels were maintained regardless of training intensity. This suggests that basal blood flow in a state of relative physiological rest remains comparable in both moderately trained students and those engaged in intense physical activity. At the same time, significant changes were observed in the blood flow structure of the study groups. In the first group, the nutritive perfusion index (M_{nutr}) increased by 16.8%, from 8.9 ± 3.0 to 10.4 ± 6.0 c.u. ($p < 0.05$), reflecting a more uniform distribution of blood flow across the capillary network in students attending elective classes. In contrast, national team athletes showed a 30.6% higher shunt blood flow (from 8.5 ± 6.5 to 11.1 ± 6.0 PU, $p < 0.05$), indicating activation of mechanisms that redistribute perfusion toward arteriovenous shunts.

The standard deviation of microcirculatory blood flow fluctuations was significantly higher by 20.5% in the second group of students (3.06 ± 1.27 vs. 2.54 ± 2.53 PU, $p < 0.05$), indicating a greater activity of vascular tone regulation mechanisms in this group. This finding is further supported by the Cv, which was also significantly higher in the athlete group ($p < 0.05$).

Analysis of microcirculatory bed amplitude fluctuations revealed significant differences between the experimental groups in parameters associated with respiratory and cardiac regulation. The amplitude of respiratory fluctuations was significantly higher by 23.8% in students attending elective classes (0.52 ± 0.38 in the first group vs. 0.42 ± 0.14 in the second group, $p < 0.05$), suggesting more pronounced respiratory modulation of microcirculation during moderate training. In contrast, national team athletes exhibited a significantly higher amplitude of cardiac fluctuations, by 10.5% (0.63 ± 0.31 in the second group vs. 0.57 ± 0.33 in the first group, $p < 0.05$). Cluster analysis in each group revealed distinctive features of microcirculatory responses, differing in both perfusion levels and the structure of interstitial blood flow and metabolic activity (Table 2).

Table 2. Cluster analysis of blood microcirculation indicators in students with varying physical activity levels (n = 57), mean ± standard error (M ± m)

Group No. 1 (elective classes, n = 34)				
Cluster/Indicator	**1 Cluster**	**2 Cluster**	**3 Cluster**	**p < 0.05**
M, perfusion units	21.3 ± 3.4	36.4 ± 6.3	9.7 ± 3.1	1–2; 1–3; 2–3
M_{nutr}, perfusion units	13.1 ± 4.3	16.5 ± 6.6	5.3 ± 2.0	1–2; 1–3; 2–3
M_{shunt}, perfusion units	8.2 ± 3.7	19.9 ± 7.3	4.4 ± 1.5	1–2; 1–3; 2–3
σ, perfusion units	3.8 ± 3.7	2.1 ± 0.9	2.0 ± 1.5	1–2; 1–3
Cv, %	20.3 ± 4.1	6.4 ± 0.9	14.6 ± 3.9	1–2; 1–3; 2–3
Ed, c.u.	1.48 ± 0.6	0.77 ± 0.4	0.64 ± 0.3	1–2; 1–3

Nt, c.u.	1.43 ± 0.6	0.7 ± 0.3	0.66 ± 0.2	1–2; 1–3
Mt, c.u.	1.32 ± 0.7	0.72 ± 0.5	0.54 ± 0.3	1–2; 1–3; 2–3
Rt, c.u.	0.71 ± 0.3	0.81 ± 0.3	0.3 ± 0.2	1–3; 2–3
Ct, c.u.	0.67 ± 0.2	0.87 ± 0.2	0.39 ± 0.2	1–3; 2–3
NADH c.u.	0.58 ± 0.17	0.86 ± 0.2	0.76 ± 0.12	1–2; 1–3
IOM, c.u.	12.5 ± 5.8	9.8 ± 3.6	3.7 ± 1.8	1–2; 1–3; 2–3
Group No. 2 (athletes, n = 23)				
Cluster/Indicator	**1 Cluster**	**2 Cluster**	**3 Cluster**	**p < 0.05**
M, perfusion units	16.4 ± 5.3	31.0	33.0 ± 0.7	1–2; 1–3; 2–3
M_{nutr}, perfusion units	7.7 ± 2.1	13.3	12.8 ± 2.3	1–2; 1–3; 2–3
M_{shunt}, perfusion units	8.7 ± 3.7	4.1	2.7 ± 0.6	1–2; 1–3; 2–3
σ, perfusion units	3.1 ± 1.3	4.1	2.7 ± 0.6	1–2; 1–3; 2–3
Cv, %	17.8 ± 5.0	13.1	7.9 ± 2.5	1–2; 1–3; 2–3
Ed, c.u.	1.09 ± 0.3	1.46	0.49 ± 0.1	1–2; 1–3; 2–3
Nt, c.u.	1.14 ± 0.4	1.19	0.65 ± 0.2	1–3; 2–3
Mt, c.u.	0.82 ± 0.2	0.8	0.54 ± 0.1	1–3; 2–3
Rt, c.u.	0.4 ± 0.1	0.61	0.53 ± 0.1	
Ct, c.u.	0.62 ± 0.3	0.67	0.66 ± 0.4	
NADH c.u.	0.74 ± 0.27	0.06	0.66 ± 0.2	1–2; 1–3
IOM, c.u.	5.8 ± 2.4	115.0	9.5 ± 2.9	1–2; 1–3; 2–3

*Note: p indicates the significance of differences between groups, assessed using the Kruskal–Wallis test (p < 0.05; * mean error (m) is not shown owing to an insufficient number of observations.*

Cluster analysis identified several typical microcirculation phenotypes in each group, reflecting different levels of peripheral blood flow functional activity.

In Group 1, analysis identified three clusters differing in perfusion level, spectral oscillation activity, and metabolic parameters. The first cluster consisted of young men with moderate microcirculation (21.3 ± 3.4 PU) and an increased Cv (20.3% ± 4.1%), suggesting considerable lability of cardiac tone and relative instability of microcirculatory regulation. This cluster likely reflects functional instability of microvessels during physical activity, characterized by fluctuations in blood flow under moderate exercise. The IOM value (12.5 ± 5.8 c.u.) was within the moderate range, indicating preservation of basic tissue oxygenation, albeit with relatively low efficiency of oxygen utilization.

The second cluster was characterized by high perfusion values (36.4 ± 6.3 PU) and a low Cv (6.4% ± 0.9%), indicating a more stable type of microcirculation. Students in this cluster likely exhibit effective vascular control and optimal blood flow distribution in the microcirculatory bed. Additionally, a moderate increase in metabolic activity (9.8 ± 3.6 c.u.) was observed, reflecting activation of tissue respiration. This microcirculatory profile suggests a sufficient level of functional adaptation of vascular regulation in these students, despite the absence of intensive athletic training.

These students likely developed an efficient microvascular function, indicating a balance between vasomotor regulation and tissue metabolic demands, consistent with a normoergic adaptation pattern. In the third cluster, students exhibited reduced perfusion (9.7 ± 3.1 PU), a moderately elevated Cv (14.6 ± 3.9%), and a low OMI value (3.7 ± 1.8 units).

In Group 2, three clusters were also identified, although their structure differed from Group 1, likely reflecting adaptations of microcirculatory mechanisms to intensive physical activity. Cluster 1 included the majority of athletes and was characterized by moderate perfusion values (16.4 ± 5.3 PU) and an increased Cv (17.8 ± 5.0), suggesting preservation of vascular tone lability with effective compensation for metabolic demands. The IOM value (5.8 ± 2.4) indicated a balance between perfusion and tissue metabolism. Overall, these characteristics correspond to a normoergic microcirculation phenotype, demonstrating hemodynamic stability during training.

The second cluster included a single individual and can be considered an outlier in the athlete group, exhibiting an extremely high oxidative metabolism rate and elevated perfusion. This likely reflects a post-exercise effect, characterized by a surge in tissue oxygen consumption. The third cluster was distinguished by high perfusion values (36.4 ± 6.3 PU) and a low Cv (7.9 ± 2.5%), indicating a highly organized microcirculatory regulatory system. The IOM value (9.5 ± 2.9 c.u.) reflects activation of oxidative processes and high metabolic efficiency.

This pattern is typical of athletes with optimal vascular reactivity and reflects a hyperergic type, providing an excess reserve of blood supply even during routine physical activity.

Correlation analysis was performed to examine the relationships between parameters in the experimental student groups. The correlation matrices for each group are presented in Tables 3 and 4.

Table 3. Correlation relationships between microcirculation parameters in students attending physical education elective classes (n = 34)

	M	M_{nutr}	M_{shunt}	σ	Cv	Ed	Nt	Mt	Rt	Ct	NADH	OMI
M	1.0											
M_{nutr}	0.8	1.0										
M_{shunt}	0.83	0.33	1.0									
σ	0.23	0.31	0.09	1.0								
Cv	-0.45	−0.22	-0.52	0.45	1.0							
Ed	0.23	0.34	0.06	0.82	0.64	1.0						
Nt	0.23	0.37	0.01	0.8	0.62	0.96	1.0					
Mt	0.3	0.58	0.07	0.66	0.55	0.84	0.91	1.0				
Rt	0.64	0.65	0.41	0.44	0.04	0.49	0.54	0.67	1.0			
Ct	0.6	0.49	0.5	0.34	0.17	0.54	0.54	0.63	0.85	1.0		
NADH	−0.05	−0.08	−0.01	−0.31	−0.09	−0.24	−0.27	−0.22	−0.07	−0.02	1.0	
OMI	0.58	0.77	0.21	0.35	−0.13	0.33	0.38	0.53	0.47	0.32	−0.62	1,0

Table 4. Correlation relationships between microcirculation parameters in student–athletes (n = 23)

	M	M_{nutr}	M_{shunt}	σ	Kv	Ed	Nt	Mt	Rt	Ct	NADH	OMI
M	1.0											
M_{nutr}	0.83	1.0										
M_{shunt}	0.96	0.65	1.0									
σ	0.38	0.13	0.46	1.0								
Cv	−0.57	−0.68	−0.44	0.46	1.0							
Ed	−0.25	−0.32	−0.19	0.57	0.71	1.0						
Nt	−0.02	−0.12	0.04	0.59	0.43	0.79	1.0					
Mt	−0.04	0.04	−0.07	0.44	0.25	0.66	0.90	1.0				
Rt	0.82	0.72	0.77	0.44	−0.46	0.01	0.34	0.34	1.0			
Ct	0.55	0.22	0.64	0.53	−0.11	0.16	0.47	0.44	0.64	1.0		
NADH	−0.14	0.01	−0.2	−0.12	0.07	−0.28	-0.24	−0.15	−0.23	−0.17	1.0	
OMI	0.39	0.42	0.33	0.20	−0.19	0.23	0.06	0.05	0.39	0.07	−0.58	1.0

In students attending elective classes, the correlation structure between microcirculation parameters suggested a relatively balanced, though less specialized, type of peripheral blood flow regulation. The overall perfusion parameter M correlated strongly with both the nutritive component (M_{nutr}, $r = 0.80$, $p < 0.05$) and shunt blood flow (M_{shunt}, $r = 0.83$, $p < 0.05$), reflecting coordinated involvement of both branches of the microcirculatory bed in maintaining microcirculatory function.

Additionally, a negative correlation between M and the Cv ($r = −0.45$, $p < 0.05$) indicated that higher tissue perfusion was associated with reduced blood flow instability. In athletes, strong correlations between flux, Ed, Nt, and Mt parameters reflect coordinated activity of endothelial, neurogenic, and myogenic regulatory mechanisms, characteristic of a compensatory type of regulation with a high degree of centralization.

Moderate correlations between respiratory and cardiac-range fluctuations and perfusion suggest a significant contribution of systemic hemodynamics to microcirculatory modulation. Notably, a negative correlation between IOM and NADH fluorescence ($r = −0.62$) highlights the relationship between tissue metabolic activity and energy supply: higher oxidative metabolism corresponds to lower NADH reduction, indicating more active utilization of respiratory chain substrates. Positive correlations between IOM and M ($r = 0.58$, $p < 0.05$), M_{nutr} ($r = 0.77$, $p < 0.05$), and Mt ($r = 0.53$, $p < 0.05$) further demonstrate a close link between metabolic processes and microcirculatory efficiency.

The negative correlations between Cv and M ($r = −0.57$, $p < 0.05$) and between Cv and M_{nutr} ($r = −0.68$, $p < 0.05$) indicate that in trained individuals, higher perfusion is accompanied by reduced blood flow variability, reflecting more stable neurovegetative control of vascular tone. Unlike Group 1, athletes exhibited weaker connections between endothelial and neurogenic components. However, correlations between perfusion and respiratory (Rt, $r = 0.82$, $p < 0.05$) and cardiac (Ct, $r = 0.55$, $p < 0.05$) oscillations were stronger, suggesting adaptation of microcirculation to rhythmic systemic influences.

This restructuring is characteristic of trained individuals, in whom blood flow regulation shifts from local to central mechanisms. In student–athletes, the IOM indicator was positively correlated with overall perfusion ($r = 0.39$, $p < 0.05$) and nutritive blood flow ($r = 0.42$, $p < 0.05$), reflecting a direct link between tissue metabolism and microcirculatory efficiency. Simultaneously, the negative correlation of IOM with NADH ($r = −0.58$, $p < 0.05$) indicates more active utilization of this coenzyme in mitochondrial oxidative processes, consistent with high aerobic fitness and metabolic efficiency.

Discussion

Physical activity during physical education or sports causes profound morphofunctional changes in the human body (Tiwari et al., 2021; Kolokoltsev et al., 2021; Martusevich et al., 2023; Bocharin et al., 2025). Numerous scientific observations indicate changes in blood microcirculation in tissues and organs under the influence of training loads (Ma et al., 2022; Koller et al., 2022). Changes in oxidative metabolism in muscle tissue are also recorded, which may impact the effectiveness of human physical performance (Hong, & Park, 2024). However, the state of blood microcirculation in male students during various physical activity regimens during physical education classes remains incompletely understood. Therefore, there is a need to study the issues of blood microcirculation during the exposure to training loads of varying intensity during the physical education course.

It was found that students who were members of the university martial arts team had shunt blood flow values that were 30.6% higher than those of young men attending elective physical education classes. We suggest that this phenomenon can be interpreted as an adaptive mechanism that ensures a rapid response of the vascular system to changing metabolic needs during intense physical activity. Student athletes had a 20.5% higher level of microcirculation fluctuations and a 20.5% higher coefficient of variation. Such pronounced blood flow fluctuations may indicate a higher involvement and refinement of vascular tone regulation mechanisms in more trained individuals, reflecting a higher level of activity of vascular tone regulation mechanisms among this group of subjects.

The students on the martial arts team had a significantly higher amplitude of cardiac oscillations that was 10.5% higher. Considering that this parameter reflects the influence of the severity of pulse oscillation transmission to the peripheral bloodstream, a higher value among the national team students indicates the result of the cardiovascular system's adaptation to intense physical activity, and heart contractions have a more significant effect on the microcirculatory system. Interestingly, both groups of students showed a slight predominance of active mechanisms regulating vascular tone, which determines the influence of physical activity on the variability and adaptation of vasoconstriction and vasodilation regulatory mechanisms, emphasizing the need for physical activity. Similar results have been obtained by other researchers (Ma et al., 2022; Marcinek et al., 2025; Kryzhevsky et al., 2022).

Cluster analysis of the study materials revealed that hypoperfusion microcirculation with signs of tissue energy deficiency can be accompanied by activation of vascular vasoconstriction processes and decreased capillary blood flow. This may be due to low levels of physical activity or a pronounced vascular response to physical exertion. Students with a voluntary level of physical activity exhibit significant heterogeneity in microcirculatory responses, indicating varying degrees of activation of regulatory mechanisms and unequal effectiveness of peripheral adaptation. Student-athletes with optimal vascular reactivity exhibit a hyperergic type, which provides an excess reserve of blood supply even during standard physical activity. Overall, the athlete group exhibits a shift in microcirculation phenotypes toward higher perfusion and metabolic activity, consistent with the concept of structural and functional adaptation of the vascular bed to regular exercise (Garcia-Roves et al., 2025). The identified microcirculation types allow us to differentiate the degree of adaptation of the peripheral circulation to physical activity, identifying neurovascular and metabolic regulatory links in individuals with different levels of physical activity. Among the athletes, the correlation structure is physiologically differentiated. An extremely high correlation is observed between the microcirculation indicator and nutritional and shunt blood flow, indicating a high functional coordination of the microcirculatory system and ensuring stable blood flow distribution during physical activity.

In the group of students attending elective classes, microcirculatory regulation is more variable, with active participation of the endothelial and neurogenic components. In athletes, a more organized system is developed, in which respiratory-hemodynamic mechanisms play a leading role, with energy coupling between blood flow and oxidative metabolism. This indicates the development and formation of an energy-efficient type of microcirculatory adaptation. Our research results confirm the findings of other authors (Khalova et al., 2022; Guryanov et al., 2023; Hong, & Park, 2024; Garcia-Roves et al., 2025).

Thus, regular moderate- and high-intensity physical activity promotes the development of an energy-efficient microcirculation pattern with more stable vascular and metabolic regulation mechanisms. These findings should be considered when developing physical training programs and preventing vascular tone dysfunction among students enrolled in higher education programs.

Conclusions

Students' level of physical fitness influences the functional organization of their microcirculation. Trained individuals exhibit a more integrated and stable system of blood flow regulation, whereas students participating in elective physical education classes tend to show fragmented and highly variable control mechanisms.

Cluster analysis identified distinct microcirculation phenotypes corresponding to different levels of adaptation to physical activity. Students participating in elective physical education exhibited predominantly hypoperfusion and labile blood flow patterns, whereas athletes displayed normo- and hyperergic patterns with

high metabolic activity. Correlation analysis showed that in students without athletic training, microcirculation regulation was mainly mediated by local mechanisms, while in male athletes, central mechanisms dominated, supporting energy efficiency and stable blood flow.

These findings suggest the development of a balanced and adapted microcirculation pattern that optimizes tissue perfusion and oxidative metabolism under regular physical activity. Such insights should be considered when designing physical training programs and strategies to prevent vascular tone dysfunction in higher education students.

Conflicts of interest. The authors declare no conflict of interest.

Acknowledgments. The authors would like to thank Falcon Scientific Editing (https://falconediting.com) for proofreading the English language in this paper.

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