



QUALITY IN SPORT

eISSN 2450-3118 · Open Access · Peer-reviewed

apcz.umk.pl/QS Nicolaus Copernicus University in Toruń



OCHMAN, Katarzyna, SZEMIK, Kamil, MALIK, Emilia, KORBAŚ, Miłosz and DREGER, Maja. Physical Activity and the Endothelial Glycocalyx: Acute Responses, Training Adaptations, and the Impact of Exercise Intensity - A Narrative Review. *Quality in Sport*. 2026;77:76272. <https://doi.org/10.12775/QS.2026.77.76272>

ARTICLE TIMELINE

Received: 26.09.2026. Accepted: 01.10.2026. Published: 02.10.2026.

The journal has been awarded 20 points in the parametric evaluation by the Polish Ministry of Higher Education and Science (Annex to the announcement of 05.01.2024, No. 32553). Unique Journal Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).

Punkty Ministerialne z 2019 – aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych). © The Authors 2026.

OPEN ACCESS · CC BY-NC-SA 4.0 This article is published with open access under the License Open Journal Systems of Nicolaus Copernicus University in Toruń, Poland, and is distributed under the terms of the Creative Commons Attribution Non-commercial Share Alike License (<http://creativecommons.org/licenses/by-nc-sa/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the work is properly cited. The authors declare no conflict of interest regarding the publication of this paper.

Physical Activity and the Endothelial Glycocalyx: Acute Responses, Training Adaptations, and the Impact of Exercise Intensity - A Narrative Review

Katarzyna Ochman¹, ORCID <https://orcid.org/0009-0008-8619-7428>

E-mail: ochman.katarzyna9@gmail.com

¹Medical University of Silesia, Katowice, Poland

Kamil Szemik¹, ORCID <https://orcid.org/0009-0007-0178-4168>

E-mail: kszemik70@gmail.com

¹Medical University of Silesia, Katowice, Poland

Emilia Malik¹, ORCID <https://orcid.org/0009-0005-7924-8379>

E-mail: malik.emilia01@gmail.com

¹Medical University of Silesia, Katowice, Poland

Miłosz Korbaś¹, ORCID <https://orcid.org/0009-0006-6232-4862>

E-mail: milosz.korbas@gmail.com

¹Medical University of Silesia, Katowice, Poland

Maja Dreger¹, ORCID <https://orcid.org/0009-0000-2333-4407>

E-mail: majadreger15@gmail.com

¹Medical University of Silesia, Katowice, Poland

Corresponding Author

Kamil Szemik, kszemik70@gmail.com

Abstract

Background. The endothelial glycocalyx is a dynamic layer covering the luminal surface of endothelial cells and contributes to vascular permeability, blood cell–vessel wall interactions, and shear-stress mechanotransduction. Exercise alters hemodynamic conditions, but glycocalyx responses may vary with exercise characteristics and training status.

Aim. To summarize current evidence on the effects of acute exercise and regular training on the endothelial glycocalyx, with emphasis on exercise intensity, modality, and high training load.

Material and methods. A narrative review of PubMed/MEDLINE, Scopus, and Web of Science was conducted, including human studies available up to September 1, 2026.

Results. Glycocalyx responses to exercise were heterogeneous. Acute exercise was associated with either no significant change or increased circulating shedding markers, whereas imaging-derived measures did not consistently change. Chronic training studies reported favorable changes in some markers or no significant group-level effects. High training load and ultra-endurance exercise were also associated with variable glycocalyx-related responses.

Conclusions. The endothelial glycocalyx response to exercise is context-dependent. Acute responses, long-term adaptations, and changes associated with high training load should be considered separately. Standardized studies are needed to clarify the relevance of glycocalyx-related measures for monitoring training adaptation in athletes.

Key words: physical activity; exercise; endothelial glycocalyx; endothelial function; training; vascular adaptation.

1. Introduction

Regular physical activity plays an important role in the prevention of cardiovascular diseases and is associated with beneficial effects on the cardiovascular system (Oćwieja et al., 2026). During exercise, changes in blood flow affect the shear forces acting on the endothelium, which contribute to the regulation of endothelial phenotype and function through mechanotransduction mechanisms (Johnson et al., 2011). One of the important components of the vascular response is nitric oxide (NO), which participates in the regulation of vascular tone and blood flow. The importance of the NO pathway and NO-dependent vasodilation has also been described in the context of exercise physiology and endurance sports (Karoń et al., 2024).

The luminal surface of endothelial cells is covered by the glycocalyx, a dynamic layer composed of proteoglycans, glycoproteins, and associated components, including glycosaminoglycans. It participates, among other functions, in hemostasis, interactions between blood cells and the vascular wall, and mechanotransduction (Reitsma et al., 2007). Due to its location, the glycocalyx is directly exposed to forces generated by flowing blood and may transmit mechanical stimuli to endothelial cells, leading to biochemical responses (Tarbell & Ebong, 2008). This property makes it an important component of the vascular response to hemodynamic changes occurring during physical activity.

Available evidence indicates that both a single bout of exercise and regular training may affect the endothelial glycocalyx. A meta-analysis including 10 studies and 252 healthy adults interpreted the pooled findings as indicating a beneficial acute effect of exercise on the glycocalyx, while also showing considerable variability in exercise protocols and assessment methods (Saz-Lara et al., 2024). In the case of long-term endurance training of moderate intensity, reductions in resting and post-exercise concentrations of markers associated with glycocalyx shedding, including syndecan-1 and heparan sulfate, have been reported (Majerczak et al., 2017). In contrast, female track and field athletes exposed to high training loads showed lower flow-mediated dilation of the brachial artery and higher concentrations of syndecan-1 and hyaluronic acid compared with controls; training load was also correlated with these parameters (Grandys et al., 2023).

The variability of these findings indicates that the effects of physical activity on the glycocalyx should be considered in relation to the characteristics of exercise exposure. The acute response to a single exercise session, long-term adaptation to regular training, and the response associated with high training loads represent distinct but interconnected aspects of this

relationship. Their combined analysis may help to better characterize the association between exercise characteristics and endothelial glycocalyx integrity.

Research Objective. The aim of this review is to synthesize current evidence on the effects of physical activity on the endothelial glycocalyx, with particular emphasis on differences between the acute response to a single bout of exercise, adaptation to regular training, and responses associated with high training loads.

Research Problems. The main research questions are: how does a single bout of physical exercise affect the endothelial glycocalyx and its markers; whether regular training leads to adaptations that support the preservation of glycocalyx integrity; and to what extent the glycocalyx response is associated with exercise intensity, type, and training load.

2. Research materials and methods

2.1. Review design and data sources

A narrative review of the literature was conducted to evaluate the effects of physical activity and training on the endothelial glycocalyx. The literature search was performed in the electronic databases PubMed/MEDLINE, Scopus, and Web of Science from database inception to September 1, 2026. In addition, the reference lists of eligible studies and relevant review articles were screened to identify publications that might not have been retrieved through the electronic search.

The main synthesis included human studies evaluating the effects of a single bout of physical exercise, regular training, or training load on the endothelial glycocalyx or its markers. Review articles and experimental studies addressing the mechanisms and physiological functions of the glycocalyx were used as supplementary sources to provide mechanistic and physiological background.

2.2. Search strategy

The search strategy combined terms related to physical activity and training with terms related to the endothelial glycocalyx and its commonly assessed components and markers. Search terms included “physical activity”, “exercise”, “training”, “athlete”, “endurance training”, “resistance training”, “high-intensity interval training”, “endothelial glycocalyx”,

“glycocalyx”, “syndecan-1”, “heparan sulfate”, “hyaluronan”, and “hyaluronic acid”. Boolean operators were used to combine the terms, and the search syntax was adapted to the requirements of each database.

The searches identified 37 records in PubMed/MEDLINE, 49 records in Scopus, and 26 records in Web of Science.

2.3. Study selection and narrative synthesis

Peer-reviewed human studies were considered eligible for the main synthesis if they assessed the relationship between physical exercise or training and the endothelial glycocalyx. Studies evaluating either direct measures of the glycocalyx or circulating components or markers, including syndecan-1, heparan sulfate, and hyaluronic acid, were included. Eligible studies addressed the acute response to a single exercise session, long-term adaptations to regular training, or the effects of exercise intensity, modality, or training load.

Publications unrelated to physical activity or training were excluded, as were studies assessing only general endothelial function without evaluation of the glycocalyx or its markers. Studies in which glycocalyx alterations were investigated exclusively in the context of severe disease states or non-exercise interventions were also excluded. Conference abstracts, commentaries, letters to the editor, and case reports were not included in the main synthesis.

Titles and abstracts of retrieved publications were initially screened for relevance to the scope of the review, followed by full-text assessment of potentially eligible studies. Following title and abstract screening and full-text assessment, 11 human studies were included in the main narrative synthesis. Data extracted from included studies comprised characteristics of the study population, type and intensity of exercise, duration of the intervention or training exposure, method of glycocalyx assessment, measured markers, timing of measurements, and main findings.

Given the narrative nature of the review, the findings were synthesized qualitatively. The available evidence was organized into the following thematic areas: acute glycocalyx responses to a single bout of exercise, adaptations to regular training, the influence of exercise type and intensity, and the association between high training load and endothelial glycocalyx integrity. No meta-analysis or formal risk-of-bias assessment was performed.

2.4. AI.

Generative artificial intelligence tools were used as supportive instruments during manuscript structuring, development of the search strategy, and language editing. Decisions regarding study eligibility, interpretation of scientific evidence, and final conclusions remained under the responsibility of the authors. All scientific information and bibliographic data obtained with the assistance of AI tools were verified by the authors against the original sources.

3. Research results

3.1. Endothelial Glycocalyx and Exercise-Induced Shear Stress

The endothelial glycocalyx forms an important interface between blood flow and endothelial cells and participates in the mechanotransduction of shear stress. Its components, including heparan sulfate, hyaluronan, and membrane-associated proteoglycans, contribute to the transmission of mechanical forces generated by blood flow. Experimental studies summarized by Power et al. indicate that glycocalyx-dependent mechanotransduction contributes to endothelial nitric oxide production and flow-mediated vasodilation (Power et al., 2024).

Physical exercise alters the magnitude, duration, and pattern of shear stress acting on the vascular wall. Regular exercise training is generally associated with increased antegrade shear stress and reduced retrograde or oscillatory shear, which has been linked to anti-inflammatory, antioxidant, and antithrombotic endothelial responses (Qi et al., 2026). Different exercise modalities and durations generate distinct shear-stress profiles, and the endothelial glycocalyx has been proposed as a key interface through which these hemodynamic stimuli are transmitted to endothelial cells (Qi et al., 2026).

The characteristics of the included human studies, exercise protocols, methods of glycocalyx assessment, and their main findings are summarized in Table 1.

Table 1. Characteristics and main findings of human studies evaluating the endothelial glycocalyx in relation to physical exercise and training.

Study	Participants	Exercise/ protocol	training Glycocalyx assessment	Main findings
Majerczak et al., 2016	21 healthy, young, untrained men	Maximal incremental cycling exercise to exhaustion; workload increased by 30 W every 3 min	Serum SDC-1, HS and HA	No significant post-exercise changes in SDC-1 or HS.

Lee et al., 2019	26 sedentary men; 13 with and 13 without dysglycemia	45-min cycling exercise at 70% VO ₂ max; acute tests performed before and after a 12-week exercise intervention	Serum SDC-1 and SDC-4	Acute ↑ SDC-1 and SDC-4; no baseline change after 12-week training.
Sapp et al., 2019	10 young, healthy men	30-min moderate-intensity continuous cycling at 60% PPO vs. workload-matched high-intensity interval cycling	Serum SDC-1 and other circulating endothelial markers; FMD	SDC-1 increased after both moderate and high-intensity exercise.
Kröpfl et al., 2021	18 well-trained male runners and cyclists	Four 4-min high-intensity bouts at approximately 84% PPO, separated by 3-min low-intensity recovery	Serum SDC-1, HS and HA	↑ SDC-1, HS and HA; no difference between running and cycling.
Fuchs et al., 2022	14 healthy adults	Single 10-km running trial	Sublingual SDF imaging; PBR and RBC filling	No significant immediate changes in PBR or RBC filling.
Steinach et al., 2022	13 finishers of the Yukon Arctic Ultra; additional control group	Ultra-endurance footrace of up to 690 km under extreme cold conditions	Serum HS, HA and syndecan CD138/SDC-1	↑ HA, ↓ syndecan CD138; no significant temporal change in HS.
Majerczak et al., 2017	11 healthy, young, previously untrained men; age-matched control group	20 weeks of moderate-intensity endurance training; 4 sessions/week	Serum SDC-1, HS and HA	↓ resting SDC-1 and HS after training; HA unchanged.
Schmitz et al., 2019	50 healthy, young, moderately trained adults	4-week running-based HIIT; 4 × 30-s all-out bouts, twice weekly	Sublingual SDF imaging; PBR and microvascular parameters	Improved exercise capacity was associated with reduced PBR.
Grandys et al., 2023	15 female track and field athletes vs. 15 age-matched controls	High-volume professional training, approximately 13 h/week	Serum SDC-1 and HA; brachial artery FMD	Lower FMD and higher HA/SDC-1 in athletes; associations with training load.
Pranskūnienė et al., 2020	18 healthy, recreationally active men	High-intensity sprint interval cycling; measurements repeated after a 2-week pomegranate extract or control intervention	Sublingual microcirculatory and glycocalyx-related assessment; SDC-1	No significant changes in SDC-1, PBR or microcirculatory parameters.
Schwalm et al., 2022	21 healthy adult sport and running beginners	10-week polarized and periodized running training program	SBT-mini and vascular function parameters	No group-level change in SBT-mini after training.

Source: Authors' own compilation.

Notes: FMD, flow-mediated dilation; HA, hyaluronic acid; HIIT, high-intensity interval training; HS, heparan sulfate; PBR, perfused boundary region; PPO, peak power output; RBC, red blood cell; SBT-mini, salt blood test-mini; SDC, syndecan; SDF, sidestream dark-field imaging. Increased circulating concentrations of glycocalyx components such as SDC-1, HS and HA generally reflect increased shedding and should not be interpreted as direct measurements of glycocalyx thickness. Imaging-derived indices such as PBR represent a different approach to glycocalyx assessment.

3.2. Acute Effects of Physical Exercise on the Endothelial Glycocalyx

Across the included studies, the acute response of the endothelial glycocalyx to physical exercise was heterogeneous. Majerczak et al. observed no significant changes in SDC-1 or HS after maximal incremental cycling in young, healthy men, providing no evidence of increased glycocalyx shedding based on these circulating markers (Majerczak et al., 2016). In contrast, Lee et al. reported increased serum SDC-1 and SDC-4 after 45 min of cycling, consistent with enhanced syndecan shedding (Lee et al., 2019).

Similar post-exercise increases in glycocalyx-related markers were reported by Sapp et al., who observed elevated SDC-1 after both moderate continuous and high-intensity interval cycling, and by Kröpfl et al., who demonstrated increases in SDC-1, HS, and HA after high-intensity exercise in trained runners and cyclists (Sapp et al., 2019; Kröpfl et al., 2021).

However, imaging-derived measures did not consistently demonstrate acute changes. Fuchs et al. found no significant immediate change in PBR or RBC filling after a 10-km run, while Pranskūnienė et al. reported no significant changes in SDC-1 or PBR across assessments involving high-intensity sprint interval cycling (Fuchs et al., 2022; Pranskūnienė et al., 2020).

3.3. Chronic Training Adaptations

Across the included studies, chronic training-related glycocalyx responses were variable. After 20 weeks of moderate-intensity endurance training, Majerczak et al. reported significant reductions in resting SDC-1 and HS concentrations, consistent with reduced glycocalyx shedding (Majerczak et al., 2017).

In Schmitz et al., improvement in exercise capacity following a four-week HIIT intervention was associated with a reduction in PBR, an imaging-derived change compatible with a more favorable glycocalyx-related profile (Schmitz et al., 2019).

However, not all interventions produced group-level changes in glycocalyx-related measures. Lee et al. observed no significant changes in baseline SDC-1 or SDC-4 after 12 weeks of exercise training. Similarly, Schwalm et al. reported no change in SBT-mini for the overall cohort after a 10-week running program, although greater performance gains were associated with improved SBT-mini values in participants younger than 45 years (Lee et al., 2019; Schwalm et al., 2022).

Overall, chronic training effects on glycocalyx-related measures were not uniform, with favorable changes or associations observed in some studies and no group-level changes in others.

3.4. The Role of Exercise Intensity and Modality

Available studies do not demonstrate a consistent relationship between exercise intensity and glycocalyx-related responses. Sapp et al. reported similar increases in SDC-1 after both moderate continuous and high-intensity interval cycling, while the high-intensity protocol produced changes in selected additional endothelial markers (Sapp et al., 2019).

In a direct comparison of exercise modalities, Kröpfl et al. observed increases in SDC-1, HS, and HA after high-intensity exercise without significant differences between running and cycling (Kröpfl et al., 2021). Pranskūnienė et al. reported no significant changes in SDC-1 or PBR across assessments involving high-intensity sprint interval cycling (Pranskūnienė et al., 2020).

Schmitz et al. also found no significant differences in microvascular parameters between two HIIT protocols differing in recovery duration (Schmitz et al., 2019). Overall, the included studies did not demonstrate a clear intensity- or modality-dependent pattern in glycocalyx-related responses.

3.5. High Training Load and Endothelial Glycocalyx Integrity

In the available athlete-specific evidence, high training load was associated with a less favorable endothelial and glycocalyx-related profile. Grandys et al. found that female track and field athletes had lower FMD and higher resting concentrations of HA and SDC-1 than age-matched controls. Training load was negatively correlated with FMD and positively correlated with both HA and SDC-1, consistent with an association between greater training exposure and increased glycocalyx shedding (Grandys et al., 2023).

A heterogeneous response was also observed during ultra-endurance exercise. During the Yukon Arctic Ultra, performed under extreme cold conditions, Steinach et al. reported an increase in HA, a decrease in syndecan CD-138, and no significant temporal change in HS. Glycocalyx-related responses were additionally associated with sex, age, BMI, and covered distance (Steinach et al., 2022).

Overall, high-volume training and ultra-endurance exposure were associated with

alterations in glycocalyx-related markers, but the limited available evidence does not indicate a uniform pattern of response.

4. Discussion

The findings of this review indicate that the relationship between physical exercise and the endothelial glycocalyx is not uniform. Acute exercise was associated with responses ranging from no detectable change to transient increases in circulating glycocalyx components, whereas chronic training studies reported either favorable changes or no significant group-level effects. High-volume training and ultra-endurance exercise were associated with further heterogeneous responses. These differences may partly reflect distinct patterns of exercise-induced shear stress, which contribute to endothelial adaptation and vascular remodeling (Tinken et al., 2010; Green et al., 2017). Such mechanisms are consistent with the broader cardiovascular benefits of regular aerobic exercise (Koman et al., 2024), although direct evidence linking them to glycocalyx remodeling remains limited.

Interpretation of acute glycocalyx responses is particularly challenging. Saz-Lara et al. interpreted pooled findings as indicating an overall beneficial acute effect of exercise (Saz-Lara et al., 2024), whereas Bolger et al. subsequently emphasized that increases in circulating SDC-1, HS, and HA generally indicate shedding and should not be interpreted as direct evidence of improved glycocalyx integrity (Bolger et al., 2025). Circulating markers provide indirect information on glycocalyx degradation or turnover, while PBR and other imaging-derived indices assess different properties of the endothelial surface layer and are not interchangeable with serum biomarkers (Tomita et al., 2026). Consequently, post-exercise increases in circulating glycocalyx components cannot be classified automatically as either beneficial adaptation or endothelial damage. Measurement timing may further influence interpretation, as other indices of endothelial function, including FMD, also demonstrate time-dependent responses after acute exercise (Dawson et al., 2013).

Redox balance may contribute to this variability. Kröpfl et al. reported an association between glycocalyx shedding and total antioxidative capacity after high-intensity exercise (Kröpfl et al., 2021). Exercise-induced ROS participate in physiological signaling and training adaptation, whereas excessive oxidative stress may contribute to tissue injury (Powers et al., 2016; Korohod et al., 2026). Transient glycocalyx shedding could therefore occur within a broader adaptive response, but its physiological significance remains uncertain, and no threshold separating normal turnover from detrimental degradation has been established. This

uncertainty is also relevant to the findings of Steinach et al., who suggested that changes in circulating glycocalyx components during ultra-endurance exercise may partly reflect reorganization or physiological release rather than exclusively destructive shedding (Steinach et al., 2022).

The chronic training studies further emphasize the distinction between acute responses and long-term adaptation. Moderate-intensity endurance training was associated with reductions in resting SDC-1 and HS in Majerczak et al., while improvement in exercise capacity following HIIT was associated with lower PBR in Schmitz et al. (Majerczak et al., 2017; Schmitz et al., 2019). However, other interventions produced no significant group-level changes in baseline syndecan concentrations or SBT-mini values (Lee et al., 2019; Schwalm et al., 2022). Thus, the available evidence does not support a uniform chronic training response, and the absence of change in a single glycocalyx-related measure should not necessarily be interpreted as an absence of vascular adaptation.

From a sports medicine perspective, the findings related to high training load require particular caution. Grandys et al. reported lower FMD and higher HA and SDC-1 in female track and field athletes, with these measures associated with training volume (Grandys et al., 2023). Sex-related differences may also influence the interpretation of endothelial function, as associations between flow-mediated dilation and metabolic cardiovascular risk factors have been reported to differ between women and men (Gozhenko et al., 2025). These findings should not be equated with overtraining syndrome, but they can be considered within the broader concept of the balance between training stress and recovery. Current literature emphasizes that excessive training exposure combined with insufficient recovery may be associated with maladaptation and that no single biomarker is sufficient to identify overtraining-related states (Meeusen et al., 2013; Wajerowska et al., 2026). Glycocalyx-related measures may therefore warrant further investigation as components of multidimensional athlete monitoring, but they are not currently validated for this purpose.

Ultra-endurance exercise represents an even more complex setting. During the Yukon Arctic Ultra, individual glycocalyx components changed in different directions, and the results may have been influenced by cold exposure, hydration status, renal elimination, sex, age, BMI, and covered distance (Steinach et al., 2022). Marathon and ultramarathon participation can also be accompanied by broad transient biochemical and metabolic changes involving multiple organ systems (Uzdicki et al., 2018). Glycocalyx-related changes observed under such

conditions should therefore be interpreted as part of a complex systemic response rather than as isolated evidence of endothelial injury.

4.1. Limitations

Several limitations of the available evidence should be acknowledged. Most studies included small samples and differed in sex distribution, training status, exercise modality, intensity, duration, and measurement timing. Men predominated in most experimental studies, while the main study of high training load in competitive athletes included only women.

Methodological heterogeneity is another important limitation. Circulating SDC-1, HS, and HA are indirect markers of glycocalyx shedding or turnover and do not directly measure glycocalyx thickness or function. Likewise, PBR, SBT-mini, and other approaches assess different aspects of glycocalyx-related physiology and should not be interpreted interchangeably. These differences may partly explain conflicting findings across studies.

The present review is also limited by its narrative design, with no formal risk-of-bias assessment or quantitative synthesis. Future studies should use larger and more diverse cohorts, standardized exercise protocols, and complementary glycocalyx measurements combined with established markers of endothelial function. At present, glycocalyx-related measures should be considered research tools rather than established standalone markers of training adaptation in athletes.

5. Conclusions

Current evidence indicates that the endothelial glycocalyx responds to both acute exercise and repeated training, but the direction and magnitude of these responses are not uniform. Acute exercise may be accompanied by changes in circulating glycocalyx-related markers without consistent alterations in imaging-derived measures, while chronic training studies have reported both favorable associations and no detectable group-level changes. High training load and ultra-endurance exercise have also been associated with alterations in glycocalyx-related markers, although the available evidence does not demonstrate a consistent pattern of glycocalyx disruption.

Interpretation of these findings is limited by small study populations, heterogeneous exercise protocols, differences in training status, and substantial variability in glycocalyx assessment methods. Circulating shedding markers and imaging-derived indices should therefore not be interpreted interchangeably. Further prospective studies using standardized and

complementary assessment methods are needed to clarify how exercise intensity, duration, modality, and training load influence the endothelial glycocalyx and to determine whether glycocalyx-related measures may have future value in the assessment of training adaptation in athletes.

Disclosure

Supplementary Materials

None.

Author Contributions

Conceptualization, K.O. and K.S.; methodology, K.O., K.S., and M.K.; investigation, K.O., K.S., E.M., and M.K.; data curation, K.O., K.S., E.M., and M.K.; writing - original draft preparation, K.O., K.S., E.M., and M.K.; writing - review and editing, K.O., K.S., E.M., M.K., and M.D.; visualization, K.S. and E.M.; project administration, K.S. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Acknowledgements

None.

Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) and Claude (Anthropic) to support manuscript structuring, language editing, and improvement of clarity and readability. All scientific content, interpretations, and cited references were subsequently reviewed and verified by the authors. The authors take full responsibility for the accuracy, integrity, and substantive content of the manuscript.

References

1. Bolger, C., Pyne, D. B., & McKune, A. J. (2025). Concerns regarding interpretation in systematic review of exercise and endothelial glycocalyx. *European Journal of Clinical Investigation*, 55(8), e70048. <https://doi.org/10.1111/eci.70048>
2. Dawson, E. A., Green, D. J., Cable, N. T., & Thijssen, D. H. J. (2013). Effects of acute exercise on flow-mediated dilatation in healthy humans. *Journal of Applied Physiology*, 115(11), 1589-1598. <https://doi.org/10.1152/japplphysiol.00450.2013>
3. Fuchs, A., Neumann, T., Drinhaus, H., Herrmann, A., Vink, H., & Annecke, T. (2022). Effects of a single aerobic exercise on perfused boundary region and microvascular perfusion: A field study. *Journal of Clinical Monitoring and Computing*, 36(2), 37-377. <https://doi.org/10.1007/s10877-021-00660-w>
4. Grandys, M., Majerczak, J., Frolow, M., Chlopicki, S., & Zoladz, J. A. (2023). Training-induced impairment of endothelial function in track and field female athletes. *Scientific Reports*, 13, 3502. <https://doi.org/10.1038/s41598-023-30165-2>
5. Green, D. J., Hopman, M. T. E., Padilla, J., Laughlin, M. H., & Thijssen, D. H. J. (2017). Vascular adaptation to exercise in humans: Role of hemodynamic stimuli. *Physiological Reviews*, 97(2), 495-528. <https://doi.org/10.1152/physrev.00014.2016>
6. Gozhenko A, Pavlega H, Savytskyi I, Zukow W. Sexual dimorphism in relationships between flow-mediated vasodilation and metabolic cardiovascular risk factors. *Pedagogy and Psychology of Sport*. 2025;24:64864. <https://doi.org/10.12775/PPS.2025.24.64864>
7. Johnson, B. D., Mather, K. J., & Wallace, J. P. (2011). Mechanotransduction of shear in the endothelium: Basic studies and clinical implications. *Vascular Medicine*, 16(5), 365-377. <https://doi.org/10.1177/1358863X11422109>
8. Karoń, Ł., Zygmunt, A. E., Karoń, K., Grabowski, W., Drapała, G., Pedrycz, E., & Pedrycz, D. (2024). L-arginine supplementation in endurance athletes: A systematic review of recovery mechanisms and performance enhancement. *Quality in Sport*, 33, 55867. <https://doi.org/10.12775/QS.2024.33.55867>
9. Koman, A. M., Chamera-Cyrek, K., Pliszka, M., Janik, I., Gadzała, K., Palacz, K. A., Kułak, K. B., & Sztybór, I. (2024). The beneficial effects of aerobic exercise on human systems and organs: A literature review. *Journal of Education, Health and Sport*, 73, 51710. <https://doi.org/10.12775/JEHS.2024.73.51710>

10. Korohod, T., Pietrzak-Chmiel, M., Ramanekaitė, P., Binkiewicz, A., & Ślesik, M. (2026). Antioxidants in sport: Exercise-induced oxidative stress, dietary strategies, and performance outcomes – A review. *Quality in Sport*, 50, 68197. <https://doi.org/10.12775/QS.2026.50.68197>
11. Kröpfl, J. M., Beltrami, F. G., Rehm, M., Gruber, H. J., Stelzer, I., & Spengler, C. M. (2021). Acute exercise-induced glycocalyx shedding does not differ between exercise modalities, but is associated with total antioxidative capacity. *Journal of Science and Medicine in Sport*, 24(7), 689-695. <https://doi.org/10.1016/j.jsams.2021.01.010>
12. Lee, S., Kolset, S. O., Birkeland, K. I., Drevon, C. A., & Reine, T. M. (2019). Acute exercise increases syndecan-1 and -4 serum concentrations. *Glycoconjugate Journal*, 36(2), 113-125. <https://doi.org/10.1007/s10719-019-09869-z>
13. Majerczak, J., Duda, K., Chlopicki, S., Bartosz, G., Zakrzewska, A., Balcerzyk, A., Smoleński, R. T., & Zoladz, J. A. (2016). Endothelial glycocalyx integrity is preserved in young, healthy men during a single bout of strenuous physical exercise. *Physiological Research*, 65(2), 281-291. <https://doi.org/10.33549/physiolres.933049>
14. Majerczak, J., Grandys, M., Duda, K., Zakrzewska, A., Balcerzyk, A., Kolodziejski, L., Szymoniak-Chochol, D., Smolenski, R. T., Bartosz, G., Chlopicki, S., & Zoladz, J. A. (2017). Moderate-intensity endurance training improves endothelial glycocalyx layer integrity in healthy young men. *Experimental Physiology*, 102(1), 70-85. <https://doi.org/10.1113/EP085887>
15. Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J., & Urhausen, A. (2013). Prevention, diagnosis, and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Medicine & Science in Sports & Exercise*, 45(1), 186-205. <https://doi.org/10.1249/MSS.0b013e318279a10a>
16. Oćwieja, Z., Wyborska, A., Fengler, K., Jakubowska, O., Pietrzak, K., Gascon Carreno, M., Urbanik, A., Mińkowski, M., Kominiak, D., & Solecka, K. (2026). Physical activity in cardiovascular disease prevention: A narrative review. *Quality in Sport*, 55, 71615. <https://doi.org/10.12775/QS.2026.55.71615>
17. Power, G., Ferreira-Santos, L., Martinez-Lemus, L. A., & Padilla, J. (2024). Integrating molecular and cellular components of endothelial shear stress mechanotransduction. *American Journal of Physiology-Heart and Circulatory Physiology*, 327(4), H989–H1003. <https://doi.org/10.1152/ajpheart.00431.2024>
18. Powers, S. K., Radak, Z., & Ji, L. L. (2016). Exercise-induced oxidative stress: Past, present and future. *The Journal of Physiology*, 594(18), 5081-5092. <https://doi.org/10.1113/JP270646>
19. Pranskūnienė, Z., Belousovienė, E., Baranauskienė, N., Eimantas, N., Vaitkaitienė, E., Bernatoniene, J., Brazaitis, M., & Pranskūnas, A. (2020). Modulation of endothelial glycocalyx and microcirculation in healthy young men during high-intensity sprint interval cycling-exercise by supplementation with pomegranate extract: A randomized controlled trial. *International Journal of Environmental Research and Public Health*, 17(12), 4405. <https://doi.org/10.3390/ijerph17124405>

20. Qi, Z., Zhang, C., Shi, H., Li, W., Xia, Y., Yan, X., Zhou, X., Ling, J., & Liu, G. (2026). Exercise-induced shear stress, endothelial glycocalyx remodeling, and atherosclerotic plaque stability: A mechanistic review. *Journal of Cardiovascular Development and Disease*, 13(6), 265. <https://doi.org/10.3390/jcdd13060265>
21. Reitsma, S., Slaaf, D. W., Vink, H., van Zandvoort, M. A. M. J., & oude Egbrink, M. G. A. (2007). The endothelial glycocalyx: Composition, functions, and visualization. *Pflügers Archiv - European Journal of Physiology*, 454(3), 345-359. <https://doi.org/10.1007/s00424-007-0212-8>
22. Sapp, R. M., Evans, W. S., Eagan, L. E., Chesney, C. A., Zietowski, E. M., Prior, S. J., Ranadive, S. M., & Hagberg, J. M. (2019). The effects of moderate and high-intensity exercise on circulating markers of endothelial integrity and activation in young, healthy men. *Journal of Applied Physiology*, 127(5), 1245-1256. <https://doi.org/10.1152/japplphysiol.00477.2019>
23. Saz-Lara, A., Cavero-Redondo, I., Del Saz-Lara, A., Rodríguez-Gutiérrez, E., Bizzozero-Peroni, B., & Pascual-Morena, C. (2024). The acute effect of exercise on the endothelial glycocalyx in healthy adults: A systematic review and meta-analysis. *European Journal of Clinical Investigation*, 54(9), e14240. <https://doi.org/10.1111/eci.14240>
24. Schmitz, B., Niehues, H., Lenders, M., Thorwesten, L., Klose, A., Krüger, M., Brand, E., & Brand, S. M. (2019). Effects of high-intensity interval training on microvascular glycocalyx and associated microRNAs. *American Journal of Physiology-Heart and Circulatory Physiology*, 316(6), H1538-H1551. <https://doi.org/10.1152/ajpheart.00751.2018>
25. Schwalm, L. C., Bäcker, S., Weisser, B., & Kusche-Vihrog, K. (2022). Effects of improved cardiovascular performance on vascular function – a pilot study. *German Journal of Sports Medicine*, 73(7), 241-250. <https://doi.org/10.5960/dzsm.2022.547>
26. Steinach, M., Biere, K., Coker, R. H., Gaul, A. L., Hoerl, M., Jorres, M., Kienast, C., Mascarell-Maricic, L., Schalt, A., Gunga, H. C., Chouker, A., & Rehm, M. (2022). Influences on glycocalyx shedding during the Yukon Arctic Ultra: The longest and the coldest ultramarathon. *Journal of Applied Physiology*, 133(5), 1119-1135. <https://doi.org/10.1152/japplphysiol.00180.2022>
27. Tarbell, J. M., & Ebong, E. E. (2008). The endothelial glycocalyx: A mechano-sensor and -transducer. *Science Signaling*, 1(40), pt8. <https://doi.org/10.1126/scisignal.140pt8>
28. Tinken, T. M., Thijssen, D. H. J., Hopkins, N. D., Dawson, E. A., Cable, N. T., & Green, D. J. (2010). Shear stress mediates endothelial adaptations to exercise training in humans. *Hypertension*, 55(2), 312–318. <https://doi.org/10.1161/HYPERTENSIONAHA.109.146282>
29. Tomita, H., Suzuki, A., & Okada, H. (2026). Evaluating the endothelial glycocalyx from bench to bedside: A translational framework for microvascular assessment. *Angiogenesis*, 29, 65. <https://doi.org/10.1007/s10456-026-10084-2>

30. Uździcki, A., Małas, M., Przybylski, T., Turoń-Skrzypińska, A., Szylińska, A., Ciosek, Ż., Ptak, M., Dutkiewicz, G., & Rotter, I. (2018). Selected metabolic changes after extreme endurance physical exercise by the example of marathon and ultra-marathon runners. *Journal of Education, Health and Sport*, 8(9), 662-672. <https://doi.org/10.5281/zenodo.1412496>
31. Wajerowska, W., Nawracaj, B., Browarny, S., Dubniański, B., Fudali, K., Hejnowicz, M., Tymec, J., & Stawińska, K. (2026). Assessing overtraining syndrome in competitive athletes: Biomarkers, screening tools, and clinical correlates – A narrative review. *Quality in Sport*, 55, 71097. <https://doi.org/10.12775/QS.2026.55.71097>