Proceedings of the 6th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/2026.38401

Research on Skeletal Muscle Glycogen Storage Kinetics, Supercompensation Mechanisms, and Periodized Nutritional Supplementation Strategies in Endurance Exercise

Chenyi Xiong

College of Food Sciences & Technology, Shanghai Ocean University, Shanghai, China
sl_xiongchenyi@163.com

Abstract. In endurance exercise, skeletal muscle glycogen serves as a principal carbohydrate source, especially during high-intensity exercise. The storage, utilization, and replenishment of glycogen in muscles after exercise affect the quality of training, the recovery process, and endurance performance. This paper reviews the dynamic changes in the glycogen status of skeletal muscle and its related regulatory mechanisms, and clarifies how different glycogen levels and carbohydrate availability affect athletes' adaptation to endurance training and their performance. Moreover, it also examines how carbohydrate periodization regulates glycogen availability, influences training adaptation, and preserves exercise performance. In this context, low muscle glycogen may limit high-intensity, high-volume training, while adequate post-exercise carbohydrate intake promotes glycogen resynthesis and may induce glycogen supercompensation. Meanwhile, although low-glycogen training may upregulate signaling proteins involved in cellular adaptation, lipid oxidation, and mitochondrial biogenesis, these metabolic adaptations have not consistently improved competitive performance. Thus, during endurance training, carbohydrate intake should be periodized according to exercise intensity and duration, recovery demands, and individual needs rather than maintained at consistently high or low levels, to balance training quality, metabolic adaptation, and performance.

Keywords: Skeletal muscle glycogen, Endurance exercise, Glycogen availability, Low-glycogen training, Carbohydrate periodization

1. Introduction

During endurance exercise, skeletal muscle glycogen is an important endogenous carbohydrate reserve, especially in moderate to high-intensity exercises, which participates in maintaining energy supply and exercise capacity. As exercise duration increases, muscle glycogen gradually depletes, and the lower glycogen availability may affect carbohydrate oxidation capacity and the quality of high-intensity training. Therefore, the glycogen status before and after exercise influences endurance training quality, recovery, and exercise performance [1, 2]. However, traditional endurance exercise nutrition strategies mainly aim to increase carbohydrate intake to maintain or restore muscle glycogen reserves, thereby meeting the energy requirements during training and competitions.

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2026.38401

Relevant studies have found that muscle glycogen levels regulate energy supply during the exercise process and may influence cellular signaling and metabolic reactions related to endurance training adaptation, such as AMPK and PGC-1α [3, 4]. This has shifted research attention from simply pursuing "maximizing glycogen reserves" to dynamically regulating carbohydrate availability according to different training tasks: maintaining sufficient carbohydrate availability during high-intensity or key training sessions, while also deliberately lowering glycogen availability during selected sessions to enhance metabolic adaptation [5, 6]. Whether such low-glycogen training strategies can further boost endurance exercise performance remains controversial. However, low glycogen availability may reduce training intensity or impair training completion, and findings across studies remain inconsistent [5, 7]. Thus, training intensity, duration, recovery demands, and training quality determine the appropriate glycogen status and carbohydrate intake. This study aims to review muscle glycogen storage and consumption, post-exercise glycogen re-synthesis and supercompensation, the adaptation mechanisms of endurance training under different glycogen availability, and carbohydrate cycle strategies. It further examines their underlying mechanism of action, actual effects, and existing limitations, and provide theoretical basis for carbohydrate nutrition management in endurance exercise.

2. Dynamics of skeletal muscle glycogen and its regulation by exercise

2.1. Characteristics of glycogen storage and metabolism in skeletal muscles

Muscle glycogen is a major endogenous carbohydrate reserve, stored primarily as glycogen granules in the cytoplasm of skeletal muscle cells. The synthesis and breakdown of glycogen are regulated by enzymes like glycogen synthase and glycogen phosphorylase. During exercise, glycogen is degraded to glucose-1-phosphate, which enters glycolytic and oxidative pathways to supply energy for muscle contraction [2, 4]. In addition, the storage level of muscle glycogen in the body is highly dynamic and is shaped by factors like training status, daily carbohydrate intake, recent exercise load, and recovery conditions [2, 8]. Notably, higher intensity and longer duration increase muscle glycogen use during endurance exercise. Under different training and nutritional conditions, pre-exercise muscle glycogen stores vary substantially with training and nutritional conditions. Therefore, muscle glycogen status reflects carbohydrate reserves and influences energy availability during exercise and subsequent training capacity [2, 8].

2.2. Relationship between glycogen utilization in skeletal muscles and athletic performance

Before exercise, muscle glycogen serves as an important endogenous carbohydrate reserve during endurance activities. Its level directly affects the carbohydrate energy supply capacity during exercise and the maintenance of high-intensity exercise. As exercise duration increases, muscle glycogen is progressively depleted; when the glycogen reserve drops to a lower level, the muscle's carbohydrate oxidation capacity decreases, which may limit the sustained maintenance of exercise intensity [1, 2]. Studies have shown that a relatively sufficient muscle glycogen reserve before exercise helps improve the exercise ability during long-duration and moderate-to-high-intensity endurance activities. The glycogen status before exercise is one of the important factors affecting endurance performance [2, 3].

As shown in Figure 1, there are significant differences in the utilization ratio of energy substrates by the body under different exercise intensities [1]. As the exercise intensity increases, the proportion of carbohydrate energy supply gradually rises, and the contribution of muscle glycogen

DOI: 10.54254/2753-8818/2026.38401

in high-intensity and moderate-intensity endurance activities significantly increases; while in lower-intensity exercise, the proportion of fat oxidation increases relatively [1]. Thus, high-intensity and moderate-intensity endurance activities have a higher dependence on muscle glycogen reserves. When the glycogen level before exercise is insufficient, the ability of athletes to maintain the target intensity and complete training tasks may be limited.

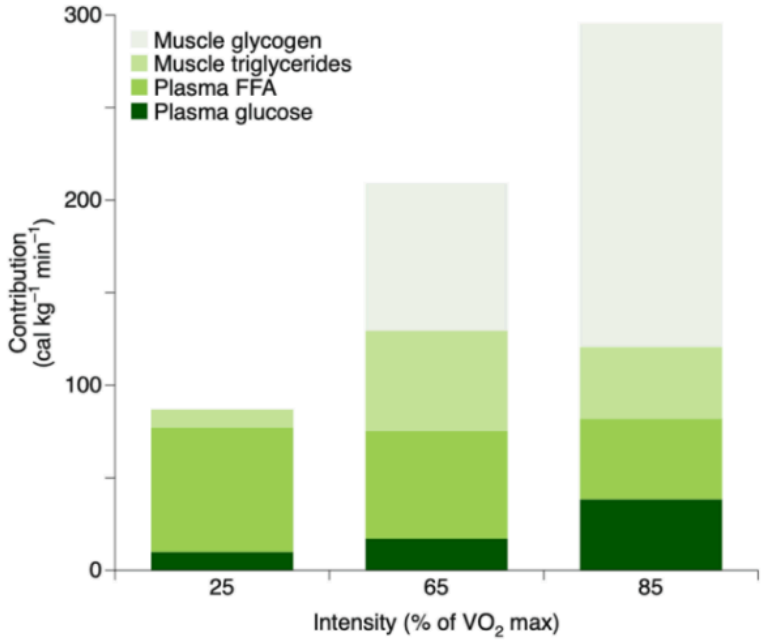


Figure 1. Carbohydrate and fat contributions across exercise intensities

It should be noted that the supply of carbohydrates during exercise also influences the process of glycogen utilization. Intake of exogenous carbohydrates during exercise can maintain blood glucose levels and provide additional oxidative substrates, reducing reliance on muscle glycogen reserves [5, 9]. Thus, endurance exercise performance not only depends on the muscle glycogen level before exercise, but is also jointly influenced by the carbohydrate supply during exercise [3, 9, 10].

2.3. Regeneration and regulatory mechanisms of muscle glycogen

Post-exercise muscle glycogen recovery is regulated by exercise-induced metabolic changes and nutritional intake during recovery. Exercise depletes muscle glycogen and increases its use for ATP production; after exercise, increased glycogen synthase activity, GLUT4-mediated glucose transport, and insulin sensitivity promote glucose uptake by muscle cells and glycogen resynthesis [8, 11]. The extent of exercise-induced glycogen depletion also affects the rate of recovery, with greater glycogen depletion generally associated with increased glucose uptake and glycogen synthesis [8, 11].

During the recovery process, carbohydrate intake provides substrates for glycogen re-synthesis, and its recovery effect is influenced by the time of intake, the amount of intake, and the interval between two training sessions. When the training interval is short and a rapid recovery is needed for the next training session, early supplementation of carbohydrates after exercise can help increase the rate of glycogen re-synthesis [12, 13]. However, with longer recovery periods, daily carbohydrate

DOI: 10.54254/2753-8818/2026.38401

and total energy intake become more important for glycogen recovery, which depends on glycogen depletion, metabolic regulation, nutritional intake, and recovery conditions [2].

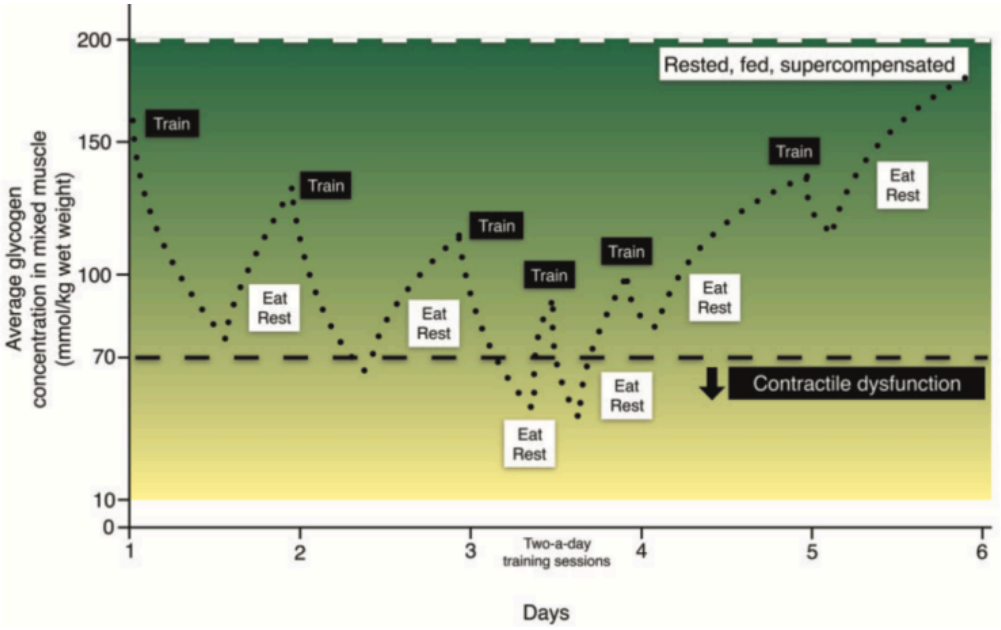


Figure 2. Changes in muscle glycogen during training periods

As shown in Figure 2, muscle glycogen levels fluctuate with training load and recovery conditions [1]. Repeated training depletes muscle glycogen, whereas adequate recovery and carbohydrate intake promote glycogen replenishment and may increase glycogen stores above baseline [2]. However, the extent of glycogen supercompensation depends on the degree of glycogen depletion, carbohydrate intake, and recovery duration, and does not occur consistently [8, 14].

3. Regulation of glycogen availability and adaptation to endurance training

3.1. The impact of glycogen levels on training load

Endurance training adaptation relies on the ability to consistently maintain the target training intensity and volume. Pre-exercise muscle glycogen levels can therefore influence the ability to complete the prescribed training load. In particular, adequate muscle glycogen reserves can support long-duration or high-intensity exercise, helping the athlete maintain the planned training intensity and duration [2, 6]. Especially during high-intensity interval training and long-duration endurance training, a higher glycogen reserve helps reduce the decline in exercise capacity caused by insufficient carbohydrate supply, thereby ensuring the quality of training [5, 6].

Conversely, when the pre-exercise muscle glycogen level is low, the ability to maintain the target intensity during exercise may be limited. Studies have shown that lower glycogen availability may reduce the duration of exercise and the actual completed training volume, causing the training load to be lower than the expected level [5, 6]. Impey et al. pointed out that a low glycogen state may affect muscle contraction function, thereby limiting the completion ability of high-intensity training [5]. Therefore, low-glycogen training should be implemented without compromising key training loads, as reductions in training volume or intensity may attenuate its potential benefits [5, 6].

DOI: 10.54254/2753-8818/2026.38401

3.2. Metabolic adaptation through regulation of glycogen availability

The glycogen level in skeletal muscle determines the energy supply during exercise and participates in regulating metabolic signaling after exercise. Prior studies have shown that compared to a normal glycogen state, endurance exercise performed under a lower glycogen state may enhance the activity of energy-sensing pathways such as AMPK and p38MAPK, and further affect factors like PGC-1α and p53 involved in mitochondrial biogenesis and oxidative metabolism regulation [4, 5]. Among them, AMPK, a major sensor of cellular energy status, regulates glucose uptake, lipid metabolism, and exercise-induced skeletal muscle adaptation [15]. However, the impact of low glycogen state on related signal responses is not consistent in all studies. Thus, it is more likely to act as a regulatory factor for enhancing the metabolic stimulation induced by exercise rather than directly determining the conditions for stronger training adaptation, as shown in Figure 3 [4].

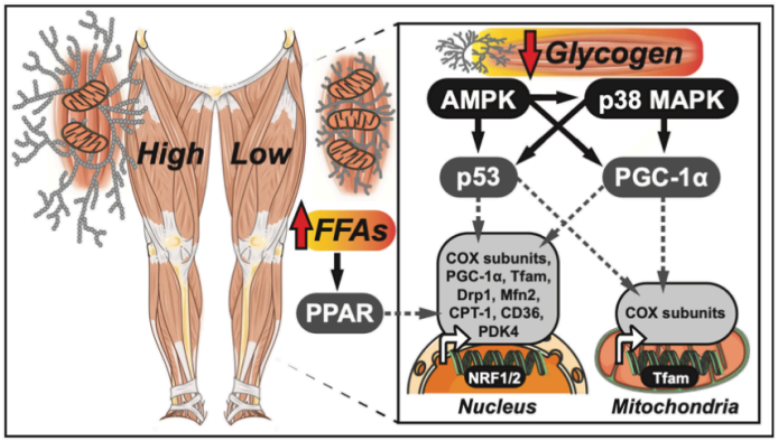


Figure 3. Metabolic signal regulation in the context of low glycogen levels

3.3. Training adaptation differences under different glycogen states

The high and low muscle glycogen states have different effects on endurance training, as shown in Table 1. Higher muscle glycogen stores help maintain training intensity, duration, and overall volume and are particularly beneficial for high-intensity interval training, long-duration endurance training, and competition simulation. In contrast, a lower glycogen state may enhance some metabolic signal responses and promote lipid utilization-related adaptations, but its effect depends on the training load arrangement, and an excessively low glycogen level may affect the quality of training completion. Therefore, different glycogen states do not have absolute superiority or inferiority; they should be adjusted according to the training goals and training stages.

Table 1. Comparison of adaptation to endurance training under different muscle glycogen levels

Comparison aspects	High glycogen state	Low glycogen state
Training quality	Conducive to maintaining a high training intensity, duration and total training volume [5, 6]	May reduce the completion rate of high-intensity training and the actual training volume [5, 6].
Metabolic adaptation	Supporting the normal adaptation process of endurance training [4]	Some studies have observed stronger metabolic signals and mitochondrial-related adaptations [4, 5].

DOI: 10.54254/2753-8818/2026.38401

Table 1. (continued)

Lipid utilization	Has a higher dependence on carbohydrates during exercise	Low glycogen or low-carbohydrate strategies may enhance lipid utilization ability [4, 6].
Sport performance	More beneficial for maintaining high-intensity training and competition capabilities [5, 6]	The metabolic adaptation advantage has not yet been steadily converted into performance improvement [7].
Applicable scenarios	Competition, high-intensity intervals and key training	It can be used for some low to moderate-intensity training and is not suitable for long-term continuous use [5, 6]

However, current research has not demonstrated that low-glycogen training consistently improves endurance performance. Gejl and Nybo conducted a meta-analysis of related studies and found that intermittent carbohydrate restriction did not significantly improve the overall performance of trained endurance athletes compared to normal or higher carbohydrate supply [11]. In practical applications, the glycogen state should be adjusted according to the training task, load requirements, and recovery conditions, rather than maintaining a single high-glycogen or low-glycogen pattern for a long time.

4. Carbohydrate cycle strategy and its impact on endurance training

4.1. From glycogen regulation to carbohydrate cycle strategy

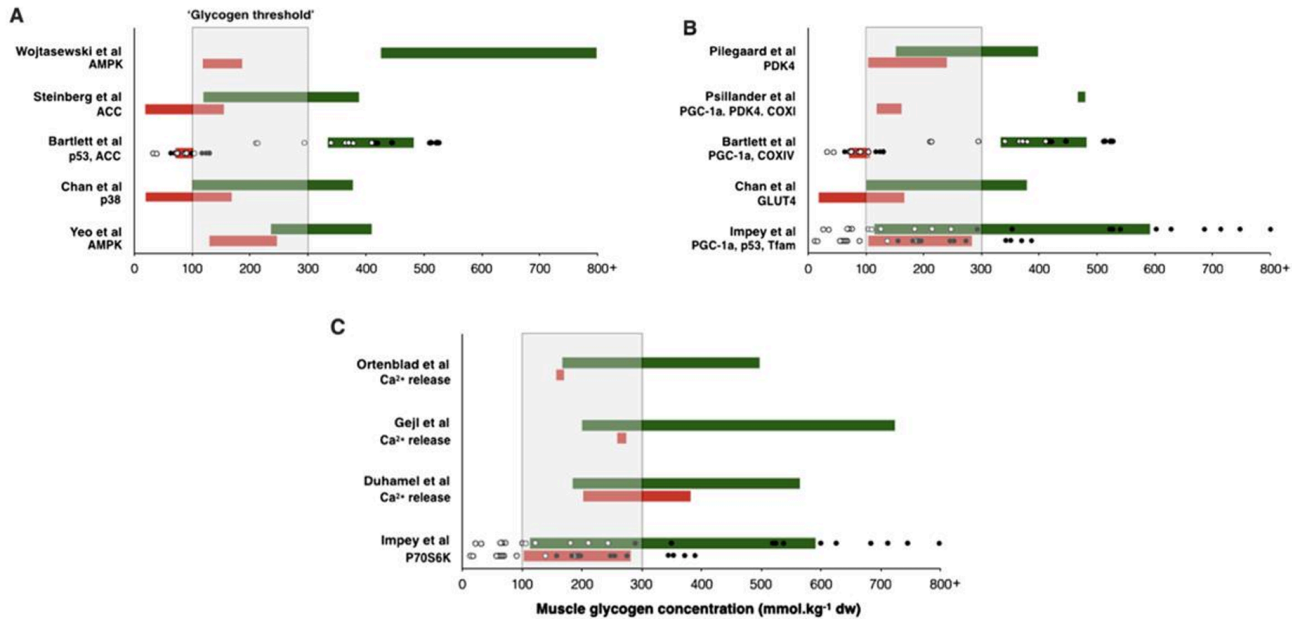


Figure 4. Metabolic and exercise adaptation responses at different muscle glycogen levels (a: changes in cellular signaling pathways; b: changes in metabolic-related gene expression; c: muscle contractile function and exercise adaptation responses)

In response to training demands, carbohydrate cycling adjusts carbohydrate intake across training phases rather than maintaining a fixed high- or low-carbohydrate state [6, 16]. Fuel for the Work Required suggests that the availability of carbohydrates should be adjusted according to the upcoming training tasks: high-intensity training requires sufficient carbohydrate support, while some training can be conducted at a lower carbohydrate level to obtain the corresponding metabolic stimulation [5]. On this basis, Impey et al. proposed the Glycogen Threshold Hypothesis, suggesting

DOI: 10.54254/2753-8818/2026.38401

that an optimal muscle glycogen range may provide metabolic stimulation while maintaining training quality [5]. It should be noted that this view is still a theoretical hypothesis and not yet a determined physiological threshold. As shown in Figure 4, muscle glycogen levels may influence signaling responses involving AMPK, p38MAPK, and PGC-1α, as well as muscle contractile function, suggesting that excessively low glycogen levels may not necessarily promote greater training adaptation [5].

4.2. Carbon source allocation for different training tasks

The supply of carbohydrates should be adjusted according to the intensity, duration, training goals, and subsequent recovery requirements rather than maintaining a fixed high-carbohydrate or low-carbohydrate state over the long term. For glycogen-dependent tasks, like high-intensity interval training, long-duration endurance training, and competitions, greater carbohydrate availability helps maintain the target intensity, complete the planned training volume, and support subsequent recovery. On the contrary, in some low to moderate-intensity training, if the training quality can be guaranteed, moderately reducing the carbohydrate supply may help increase metabolic stimulation and promote related adaptations [6, 16]. In practice, Train High refers to performing key training sessions with high carbohydrate availability to achieve the target intensity and volume. In contrast, Train Low involves strategies such as training with low glycogen on consecutive days, fasting training, and sleep low [5, 16]. The double-training-day strategy reduces muscle glycogen during the first session and completes the subsequent session under low glycogen availability, while fasting training mainly alters the metabolic environment by reducing pre-exercise exogenous carbohydrate intake or modifying liver glycogen stores and does not necessarily substantially reduce muscle glycogen. Therefore, the physiological stimuli produced by different Train Low strategies are not exactly the same, and their application should be selected based on training goals, exercise load, and recovery conditions, rather than simply understanding it as long-term low-carbohydrate intake [5].

4.3. Periodized carbohydrate strategy and training adaptation to changes

The cyclical carbohydrate strategy adjusts the availability of carbohydrates during different training phases, enabling athletes to select the appropriate nutritional state to complete their training according to their training goals. Evidence suggests that several weeks of Train Low may enhance skeletal muscle oxidative enzyme activity, lipid oxidation capacity, and mitochondrial adaptations [5, 16]. In addition, reduced carbohydrate availability may promote lipid metabolism-related adaptations during exercise and improve skeletal muscle flexibility in using different energy substrates. However, these adaptations are not consistently observed in all studies, and their effects are influenced by factors like training level, intervention period, glycogen depletion degree, and overall energy intake [5, 7]. As a result, the training adaptations induced by carbohydrate cycling should be viewed as complementary to different training stimuli rather than as a simple reduction in carbohydrate intake. In high-intensity interval training, competition simulation, and other training requiring high glycogen availability, higher carbohydrate availability helps maintain training quality. In contrast, some low- to moderate-intensity training may benefit from reduced carbohydrate availability to provide additional metabolic stimulation. The key is to strategically match carbohydrate availability to different training demands while maintaining the overall training load and meeting recovery needs, thereby balancing training quality and metabolic adaptation [5, 16].

DOI: 10.54254/2753-8818/2026.38401

4.4. Performance and limitations of the periodized carbohydrate strategy

Periodized carbohydrate strategies adjust carbohydrate availability across training phases to maintain key training quality and provide metabolic stimulation. Whether these metabolic adaptations improve endurance performance remains controversial. Evidence on the effects of periodized carbohydrate strategies on athletic performance remains inconsistent. Gejl and Nybo conducted a meta-analysis of nine endurance training studies and found that periodic carbohydrate restriction did not significantly improve overall endurance performance compared with normal or high carbohydrate availability [7]. As illustrated in Figure 5, the effects varied across studies, but the overall pooled effect size was not statistically significant, hence indicating insufficient evidence that periodized carbohydrate strategies consistently improve endurance performance [7].

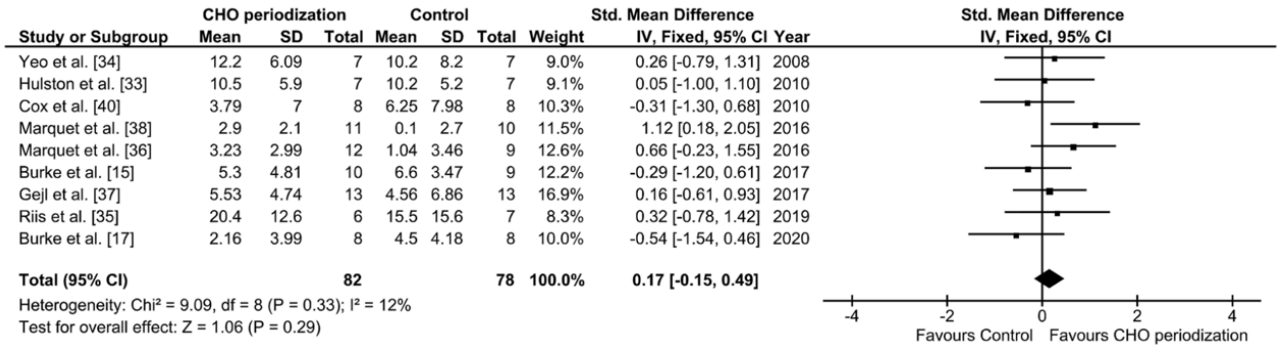


Figure 5. Meta-analysis results of the impact of periodic carbohydrate restriction on endurance performance

The actual effectiveness of the periodic carbohydrate strategy may be influenced by factors such as the athlete's training level, training cycle arrangement, degree of carbohydrate restriction, training type, and total energy intake [7, 16]. For instance, high-level endurance athletes typically undergo glycogen adaptations during long-term training, so further reducing carbohydrate availability may provide limited additional benefits. If carbohydrate restriction reduces training intensity or volume or impairs recovery, it may also diminish its potential benefits. Thus, periodized carbohydrate strategies are better used as a regulatory approach within training plans, tailored to specific training tasks, rather than as a complete replacement for high-carbohydrate strategies.

5. Conclusion

This study reviews the storage, utilization and recovery processes of skeletal muscle glycogen during endurance exercise, as well as the impact of different glycogen availability on training adaptation and athletic performance. The results indicate that the level of muscle glycogen changes dynamically with exercise load and nutritional supply. Adequate glycogen reserves are helpful for completing high-intensity and large-volume training, and reasonable post-exercise carbohydrate supplementation can promote glycogen re-synthesis and achieve supercompensation under specific conditions. In contrast, low glycogen or low-carbohydrate availability training may promote metabolic adaptations such as lipid utilization and mitochondrial function, but these changes have not been fully confirmed to be able to stably translate into endurance performance advantages. Therefore, the carbohydrate cycling strategy is not simply about pursuing high or low glycogen states, but rather adjusting carbohydrate supply reasonably according to training tasks, while ensuring training quality and obtaining potential adaptations. However, previous studies have

DOI: 10.54254/2753-8818/2026.38401

differed in carbohydrate restriction protocols, training loads, intervention duration, and participant training status. Future research should integrate sport-specific demands and individual responses to optimize carbohydrate strategies and better balance training quality, metabolic adaptation, recovery, and athletic performance.

References

[1] Hargreaves, M., & Spriet, L. L. (2020). Skeletal muscle energy metabolism during exercise. *Nature Metabolism, 2*, 817–828. https://doi.org/10.1038/s42255-020-0251-4

[2] Murray, B., & Rosenbloom, C. (2018). Fundamentals of glycogen metabolism for coaches and athletes. *Nutrition Reviews, 76*(4), 243–259. https://doi.org/10.1093/nutrit/nuy001

[3] Mata, F., Valenzuela, P. L., Gimenez, J., Tur, C., Ferreira, D., Domínguez, R., Sanchez-Oliver, A. J., & Martínez Sanz, J. M. (2019). Carbohydrate availability and physical performance: Physiological overview and practical recommendations. *Nutrients, 11*(5), 1084. https://doi.org/10.3390/nu11051084

[4] Hawley, J. A., Lundby, C., Cotter, J. D., & Burke, L. M. (2018). Maximizing cellular adaptation to endurance exercise in skeletal muscle. *Cell Metabolism, 27*(5), 962–976. https://doi.org/10.1016/j.cmet.2018.04.014

[5] Impey, S. G., Hearris, M. A., Hammond, K. M., Bartlett, J. D., Louis, J., Close, G. L., & Morton, J. P. (2018). Fuel for the work required: A theoretical framework for carbohydrate periodization and the glycogen threshold hypothesis. *Sports Medicine, 48*(5), 1031–1048. https://doi.org/10.1007/s40279-018-0867-7

[6] Podlogar, T., & Wallis, G. A. (2022). New horizons in carbohydrate research and application for endurance athletes. *Sports Medicine, 52*(Suppl 1), 5–23.

[7] Gejl, K. D., & Nybo, L. (2021). Performance effects of periodized carbohydrate restriction in endurance trained athletes: A systematic review and meta-analysis. *Journal of the International Society of Sports Nutrition, 18*, 37. https://doi.org/10.1186/s12970-021-00435-3

[8] Burke, L. M., van Loon, L. J. C., & Hawley, J. A. (2017). Postexercise muscle glycogen resynthesis in humans. *Journal of Applied Physiology, 122*(5), 1055–1067. https://doi.org/10.1152/japplphysiol.00860.2016

[9] Thomas, D. T., Erdman, K. A., & Burke, L. M. (2016). Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. *Journal of the Academy of Nutrition and Dietetics, 116*(3), 501–528. https://doi.org/10.1016/j.jand.2015.12.006

[10] Naderi, A., Gobbi, N., Ali, A., Berjisian, E., Hamidvand, A., Forbes, S. C., Koozehchian, M. S., Karayigit, R., & Saunders, B. (2023). Carbohydrates and endurance exercise: A narrative review of a food first approach. *Nutrients, 15*(6), 1367

[11] Li, L., & Su, H. (2015). Research progress on the effects of combined carbohydrate and protein supplementation on muscle glycogen synthesis after exercise. *China Sport Science, 35*(9), 84–89.

[12] Betts, J. A., & Williams, C. (2010). Short-term recovery from prolonged exercise: Exploring the potential for protein ingestion to accentuate the benefits of carbohydrate supplements. *Sports Medicine, 40*(11), 941–959.

[13] Ivy, J. L. (2004). Regulation of muscle glycogen repletion, muscle protein synthesis and repair following exercise. *Journal of Sports Science & Medicine, 3*(3), 131–138.

[14] Solem, K., Clauss, M., & Jensen, J. (2025). Glycogen supercompensation in skeletal muscle after cycling or running followed by a high carbohydrate intake the following days: A systematic review and meta-analysis. *Frontiers in Physiology, 16*, 1620943. https://doi.org/10.3389/fphys.2025.1620943

[15] Zhang, G. H. (2007). AMPK/PGC-1α pathway and exercise-induced mitochondrial biogenesis in skeletal muscle. *Journal of Guangzhou Sport University, 27*(6), 100–104.

[16] Che, K. X., Li, Q. L., Yang, J. C., & Qiu, J. Q. (2023). Nutritional strategies for optimizing exercise performance—Periodized nutrition. *Chinese Journal of Sports Medicine, 42*, 739–748.