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### Authors' Affiliation:

<sup>1</sup>Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland  
<sup>2</sup>PKSO Ophthalmic University Hospital in Warsaw, Józefa Sierakowskiego 13, 03-709 Warszawa, Poland  
<sup>3</sup>Cardinal Stefan Wyszyński University in Warsaw, Kazimierza Wóycickiego 1/3, 01-938 Warsaw, Poland

### \*Corresponding Author

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland  
Email: [Aleks.litwin123@gmail.com](mailto:Aleks.litwin123@gmail.com)

### Contact List

Aleksandra Litwin	<a href="mailto:Aleks.litwin123@gmail.com">Aleks.litwin123@gmail.com</a>
Natalia Dąbrowska	<a href="mailto:nataldabrowska@gmail.com">nataldabrowska@gmail.com</a>
Paweł Nowocin	<a href="mailto:p.nowocin@wp.pl">p.nowocin@wp.pl</a>
Zuzanna Kudas	<a href="mailto:md.zuzannakudas@gmail.com">md.zuzannakudas@gmail.com</a>
Paulina Kumięga	<a href="mailto:paulina.kumięga@wum.edu.pl">paulina.kumięga@wum.edu.pl</a>
Dawid Wiktor Kulczyński	<a href="mailto:dawid.wiktor.kulczynski@gmail.com">dawid.wiktor.kulczynski@gmail.com</a>
Piotr Wasieński	<a href="mailto:p_wasinski@interia.pl">p_wasinski@interia.pl</a>
Karolina Krzywicka	<a href="mailto:karolinakrzywicka08@gmail.com">karolinakrzywicka08@gmail.com</a>
Nikola Perchel	<a href="mailto:nikolaperchel@interia.pl">nikolaperchel@interia.pl</a>
Martyna Koszyk	<a href="mailto:martyna.koszyk@icloud.com">martyna.koszyk@icloud.com</a>

### ORCID List

Nikola Perchel	0009-0005-6489-7480
Natalia Dąbrowska	0009-0009-7170-0614
Paweł Nowocin	0009-0007-2018-6139
Zuzanna Kudas	0009-0009-6750-6886
Paulina Kumięga	0009-0005-1431-0231
Aleksandra Litwin	0009-0004-3221-0085
Piotr Wasieński	0009-0009-3824-3618
Karolina Krzywicka	0009-0001-3248-4674
Dawid Wiktor Kulczyński	0009-0003-3897-1507
Martyna Koszyk	0009-0000-9927-6020

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# The significance of a High-Carbohydrate diet for training efficiency in endurance sports

Aleksandra Litwin<sup>1\*</sup>, Natalia Dąbrowska<sup>1</sup>, Paweł Nowocin<sup>1</sup>, Zuzanna Kudas<sup>1</sup>, Paulina Kumięga<sup>1</sup>, Dawid Wiktor Kulczyński<sup>1</sup>, Piotr Wasieński<sup>1</sup>, Karolina Krzywicka<sup>2</sup>, Nikola Perchel<sup>1</sup>, Martyna Koszyk<sup>3</sup>

## ABSTRACT

Among researchers, there has been much debate about the role of macronutrient composition in optimizing endurance performance. Long-term performance effects of CHO-rich (carbohydrate-rich) muscle-sparing diets in endurance athletes are well known, in part due to their impact on glycogen storage and the availability of energy. This paper summarizes current evidence on the effects of different CHO diets on endurance performance and discusses their physiological, metabolic, and practical aspects. Short-term CHO loading (more), both positive and negative, has been established with these, with implications for GI function and exercise metabolism, for example, to recent work. Lastly, the influence of the glycemic index on performance outcomes is outlined in this review. Insights from this research may lead to dietary periodization and gut training strategies that better harness carbohydrate utilization in applied settings (outdoors, on the road, and in real-world 'hilly' events). Though the carbohydrate diet will most likely remain a crucial link in the extended armor of endurance nutrition, there is a need to shift the mindset among athletes that a uniform carbohydrate recommendation applies to all athletes under all conditions, and research is warranted to identify individual variables among athletes and sport requirements to create specific carbohydrate need guidelines.

**Keywords:** High-carbohydrate diet; endurance training; glycogen storage; exercise

## 1. INTRODUCTION

Manipulation of macronutrient intake (most notably carbohydrate (CHO) consumption) has historically been recognized as a key strategy to enhance performance in these suites of tasks. A carbohydrate diet is essential to perform high-intensity exercise and minimize fatigue and recovery by maximizing

glycogen stores. This can be particularly pronounced during long-duration high-intensity efforts when macronutrient contribution is maximized as the primary substrate becomes carbohydrate and fat is unable to satisfy the metabolic (work) demand of the exercise (Melby, 2021; Burke et al., 2021). Over the last few years, the classical view on CHO-sufficient diets has been challenged by alternative nutritional concepts such as low-carbohydrate, high-fat (LCHF) diets.

The aforementioned strategies imply metabolic adaptations that could enhance fat oxidation capacity and reduce reliance on the degradation of intramuscular glycogen. However, the early suggestion that it was fat-induced by exercise to increase overall fat utilization was functionally unsubstantiated: For all major meta-analyses on the relationship between carbohydrate availability and performance, the best evidence found was that carbohydrate availability (via supplementation or implementation) caused a network delaying standard of performance, particularly with endurance-based competition (O'Brien, 2021; Cao et al., 2021). For instance, we need carbohydrates during and after exercise to maintain performance and to speed up recovery, as the stores of glycogen used up during exercise can get depleted comparatively quickly (King et al., 2022; Naderi et al., 2023).

Examples include the introduction of dietary periodization and gut training (i.e., optimizing carbohydrate availability in different phases of training or competition) to sports nutrition. These strategies have been described in studies e.g., Podlogar and Wallis, (2022), showing that they improve the ability to use fat for energy during exercise and enable you to better handle carbohydrates when fed. Additionally, studies from Zdzieblik et al., (2022) highlight the clinical relevance of the glycemia index regarding training adaptations regulation and energy availability, presenting the convincing advantages of a high CHO diet with a low glycemic index concerning adaptations of performance.

CHO-centric approaches have clear benefits, although individual CHO responses and the role of newer strategies such as hybrid fueling are topics worthy of further research. The GI tolerance, metabolism efficiency, and strength/endurance demands for each sport contribute to the complexity of carbohydrate recommendations. More bespoke dietary interventions may be required for athletes that fall on either the spectrum of high-volume/training intensity or long event duration to meet their performance metrics and gut health maintenance (King et al., 2022). In this article, we will summarize what current literature says regarding carbohydrate diets and endurance sports.

It then synthesizes the findings of the latest studies to explore the physiological, metabolic, and pragmatic implications of carbohydrate intake strategies. The areas that will be covered include glycogen metabolism, carbohydrate timing, gut training adaptations, and the role of the glycemic index in performance and recovery. Objective: A summary of suggestions based on evidence for enhancing carbohydrate availability and incorporation in persistence athletes, while taking individual differences and performance context into account. (tab. 1)co

## 2. MATERIALS AND METHODS

The purpose was to provide an overview of the current evidence for the benefits of high-carbohydrate diets for endurance performance. This approach was designed to allow thorough, systematic, and structured reviews of the literature, particularly context-specific, and targeting physiological, metabolic, and operational dimensions of carbohydrate use in endurance athletes.

### Search strategy

A systematic search was performed across the significant scientific databases PubMed, SCOPUS, and Google Scholar to identify relevant studies from 2010–2023. Recent studies (2019–2023) were highlighted in particular. Search terms utilized were combinations of the following terms: "high-carbohydrate diet," "glycogen metabolism," "endurance performance," "sports nutrition," "gut training," "glycemic index". Boolean operators (AND, OR) and filters were used to refine the search from the peer-reviewed literature to studies performed on human participants in endurance sports. In addition, including systematic reviews and meta-analyses, were screened manually for potentially missed studies. This review prioritizes articles in high-impact journals (e.g., *Nutrients*, *Sports Medicine*, and *The Journal of Physiology*), focusing on relevance and methodological rigor.

## Eligibility criteria

### *Inclusion criteria*

Established inclusion and exclusion guidelines led the assignment process, ensuring that only studies of high caliber relevant to the research were included.

Humans are considered experimental participants, especially endurance athletes (runners, cyclists, triathletes, and swimmers) — dietary interventions on carbohydrate restriction/cross-overs to low-carbohydrate or other macronutrient manipulations.

The research evaluates endurance ability, time-to-exhaustion, fatigue, and glycogen resynthesis.

Explorations of new carbohydrate approaches, including gut adaptations, carbohydrate periodization, and effects of glycemic index.

### *Exclusion Criteria*

Non-peer-reviewed articles, case reports, conference abstracts, or editorials.

The research includes non-endurance sports or recreationally active individuals without structured endurance training.

Interventions that addressed only other dietary factors (e.g., protein or fat) without possible effects on carbohydrates.

Non-English language articles.

## Data extraction process

Demographic and relevant data were extracted from each study using a predefined extraction template to ensure data consistency and comparability. The extracted data included:

Study Design: RCTs, cross-over trials, observational studies, and systematic reviews.

Demographics of participants: Include age, sex, level of training, and type of sport.

Nutritional One-Offs: Carbohydrate content, timing, and periodization.

Outcome Measures: Markers of endurance performance (e.g., VO<sub>2</sub> max, time-to-fatigue), glycogen status (pre/post-exercise), recovery markers (e.g., muscle soreness, inflammation), and gastrointestinal tolerability.

## Analysis and synthesis

Narrative synthesis was used to assess the results from each included study. Major themes can be grouped into similar areas:

Physiological Consequences: Impact on Exercise Glycogen Stores, Substrate Accessibility, and Efficiency

Recovery Dynamics: Muscle recovery; glycogen resynthesis; exercise-induced fatigue.

Practical aspects of gut training: Influences of glycemic index, timing of meals, and other practical aspects.

High carb vs. low carb approach and performance adaptive experiments

Quantitative findings were presented in a table format that summarized clinical markers or outcomes and influential variables, such as endurance capacity or glycogen content, to summarize trends and the most important differences in dietary interventions. Studies finding contrary results were also critically appraised for potential bias or methodological concerns.

## Ethical Considerations

As a review article, this study does not fall under human or animal studies and hence does not require ethical approval. Nonetheless, studies contributing to reviews were screened concerning the adherence to ethical aspects, such as adhering to the Declaration of Helsinki with human subjects' trials.

## Limitations of the Review

This review recognizes specific limitations since it relies on data obtained from various published studies. Differences in study design, participant demographics, and the methods used in the analyses included may lead to variations in the results. In addition, limiting articles included in this review to only those written in the English language may restrict the breadth of this review. Finally, since the focus is on endurance-based athletes, these results may not apply to other populations, such as athletes engaged in team-based sports or recreational movers.

Data Logic Framework References — Post-date

Critical articles that inspired the structure and foci of this review include:

King et al., (2022) Study: Investigated the short-term effects of a carbohydrate-rich diet on gut tolerance and exercise performance.  
 Podlogar and Wallis, (2022): Explored novel carbohydrate strategies, such as gut training and periodization.  
 Zdzieblik et al., (2022): Examined the impact of low glycemic index diets on endurance adaptations.  
 Burke et al., (2021): A cross-over study comparing high- and low-carbohydrate diets on endurance metabolism and performance.

### 3. RESULT AND DISCUSSION

Here, we describe selected studies on CHO diet and endurance performance that have been performed so far. The results are categorized according to four overarching themes: Glycogen storage and endurance performance, GI tolerance, timing and rationalization of the diet, and comparison with low-carbohydrate and high-fat (LCHF) diets (Table 1).

**Table 1** Results summary

Research Focus	Key Outcomes
Glycogen Storage	High-CHO diets increased glycogen reserves, extending time-to-exhaustion in endurance activities.
GI Tolerance	Gut training reduced GI distress, enabling higher CHO intake during prolonged exercise.
Glycemic Index	Low-GI CHO sources provided sustained energy, reducing fatigue in long-duration sports.
High-CHO vs. LCHF Diets	High-CHO diets supported high-intensity performance; LCHF benefited ultra-endurance athletes.
Carbohydrate Periodization	Improved metabolic flexibility and glycogen utilization across training and competition phases.

#### Emerging Trends, Limitations, and Applications: A Comparative, Critical Review

##### *Maximum Endurance Performance – Diets High in Carbohydrate*

We have previously demonstrated that high-CHO diets maximize glycogen stores, the main energy substrate during high-intensity prolonged exercise [47]. Studies like Zdzieblik et al., (2022) found that high-glycemic index carbohydrate intake blunted training adaptations in female endurance athletes compared to a low-glycemic index, high-carbohydrate diet during both exercise and recovery, with greater glycogen storage following exercise. This resonates with the observation of Mattsson et al., (2019) (doi:10.1038/s41598-018-35444-8) (NIH), who analyzed the role of carbohydrate loading with exercising for supplying energy continuously, in long-duration exercise.

More specific studies evaluating moderate carbohydrate (for example Henselmans et al., (2022)) improved strength and endurance performance acutely in this phase. The results suggested the basic importance of total carbohydrate intake, in that more carbohydrate intake is better in terms of glycogen storage and utilization. Furthermore, Wachsmuth et al., (2022) confirmed that the former preserved glycogen stores to increase endurance capacity in a comparison of high or low CHO, low-fat vs. low-CHO, high-fat (LCHF) diets (2022). The high-carbohydrate (CHO) diet improved recovery parameters and time to depletion in extended endurance tasks in fit subjects, demonstrating the efficacy of the diet for prolonged endurance efforts.

### *Common Practices of CHO Consumers: Gastrointestinal Tolerance of Diet*

While high-CHO diets have the most positive effects, these also vary in their impact on GI health. King et al., (2022) examined the short-term effects of ultra-massive carbohydrate intake and gut training. They found that GI status and performance outcomes were significantly influenced by this intervention. Athletes had anecdotally reported mild GI discomfort, corroborated by this with the increased GI symptoms, which may suggest gut training strategies may assist with reducing the negative effects elicited for both pre-performance substrate loading (carbohydrate) (naive gut function) to be performant. In contrast, Burke et al., (2021) found that rapid adjustment to LCHF diets caused more profound gastrointestinal symptomatology due to the lower volume of consumed carbohydrates. Yet that came at a large performance cost, highlighting that metabolic GI tolerance alone cannot account for the cessation of CHO-heavy strategies for endurance-based athletes.

### *Individualizing the Diet and Timing*

Increasing evidence about endurance nutrition advocates eating carbohydrates at the right time but also notes that personalized strategies must be utilized to improve performance. Carbohydrate periodization and gut training are some of the methods that are useful at the individual level to improve metabolic flexibility and energy requirements for the diversity of endurance events.

### **Carbohydrate Periodization**

Podlogar and Wallis, (2022) assessed the validity of carbohydrate periodization, which represents an approach to the periodic adaptation of carbohydrate availability and intake to the demands of training. This predictably allows athletes to use glycogen and fat efficiently as energy substrates during prolonged efforts, as the final results illustrate. While fat oxidation is elevated on low-intensity workout or recovery days. This dynamic adjustment not only boosts performance but also reduces metabolic alterations in the extended term.

### **Emphasis on Glycemic Index**

In a world where there is so much focus on the glycemic index and euglycemic energy release, Zdzieblik et al., (2022) have shown that exercise duration during endurance events could be improved by including carbohydrate sources with a low glycemic index (GI) as the carbohydrate source. Low-GI foods are slowly absorbed and can be particularly effective for training or events requiring an energy release over a long time. They may show better performance capacity during protracted exercise while reducing the risk of being energy slug.

In contrast, the study performed by Cao et al., (2021) has found that higher-GI carbohydrate sources are superior for low-duration, high-intensity efforts (2021). This quick refilling of glycogen stores and supply of instantly accessible energy can be especially advantageous in its own right for activities involving repeatedly high-intensity efforts. Carbohydrate approaches should be task-specific to competition demands, underscoring the relevance of these findings.

### *Gut Microbiome Health Journey*

This ultimately led to gut microbiome health being decentralized by providing personalized, custom-tailored gut training and gut-directed protocols. Gut training, a third recent strategy, that aims to enhance the GI tolerance of athletes to increased CHO delivery during exercise, has recently been investigated by (Podlogar and Wallis, 2022). Increasing tolerance to larger carbohydrate loads means glucose can be absorbed and used for energy without GI distress. It needs confirmation on how this will have a direct effect on performance, but this bodes well for those who use carbohydrates in high amounts over longer endeavors.

### **High-CHO vs. LCHF Diets: What's the Difference?**

There are a few studies that help explain the longstanding debate between high-CHO and low-CHO (LCHF) diets. While athletes experience fast adaptations to LCHF diets, Burke et al., (2021) process restricted glycogen access and impaired performance during high-intensity endurance exercise (Wachsmuth et al., 2022). These findings are supported by other research (2022), where a high-CHO diet resulted in better performance outcomes alongside higher glycogen stores compared to lower-CHO diets, diversity results observed in endurance challenges.

Conversely, Cao et al., (2021) and that low-carbohydrate, high-fat diets could lead to upregulated fat oxidation, which may benefit ultra-endurance athletes (Bailey and Hennessy, 2020). But this third advantage is only relevant during low-intensity exercise when fat serves as the primary fuel. Exercise of higher intensity leads to high CHO contributing to an energy-giving effect that is magnified for higher-intensity sources yielding a context where high-CHO approaches are favorable during many endurance sport modalities.

### ***Gut Training and Stepwise Periodization***

A concept arising in the context of high-CHO strategies is gut training, an attractive concept arising under high-CHO strategies to promote maximal human carbohydrate absorption and GI tolerance. King et al., (2022) took a look at the idea that proposed gut training protocols may allow for higher carbohydrate volumes to be consumed by athletes with lower GI symptoms. Podlogar and Wallis, (2022) suggested that athletes could maintain more favorable long-term metabolic adaptations through a pattern of high CHO intakes on high-intensity training days and moderate CHO intakes on recovery days.

The evidence suggests the important potential benefits of high-CHO diets in maximizing glycogen stores and improving endurance performance and post-exercise recovery. Cooling LCHF will yield better results in ultra-endurance and low-intensity sports, yet cooling LCHF cannot sustain high-intensity performance. Gut training and carbohydrate periodization are novel strategies that have the potential to refine the efficacy of certain CHO-based approaches and highlight the need to individualize nutritional strategies to the individual's competing profile and needs.

### **Discussion**

The findings of the current review underscore the power of high-CHO diets on endurance performance. In this section, we will critically review the evidence, compare high-CHO vs. LCHF dietary approaches, and describe emerging practices such as dietary periodization and gut-training approaches.

### **Use and Effectiveness of High-Carbohydrate Diets**

High-CHO diets remain a cornerstone of endurance nutrition, enabling maximal glycogen stores, high intensities, and recovery. This was evident in the study by that demonstrated a lower glycemic index of carbohydrates offered improved training adaptations and extended energy release in addition to reducing fatigue during prolonged exercises. Similarly, Wachsmuth et al., (2022) reported superior performance outcomes for physically active individuals consuming high-CHO diets, particularly for the time of exhaustion and recovery metrics.

In contrast, in a highly recent investigation, King et al., (2022) reported an absolute threshold for the CHO effect (meaning that according to gut training protocols, very high CHO diets between 9 and 12 g/kg/d have little effect on performance), as well as a threshold that depends upon individual differences in metabolic and gastrointestinal factors (2022). These findings mirror that of previous works by Henselmans et al., (2022), where only minor performance benefits were noted for resistance training contexts at moderate carbohydrate intakes. Hence, the full meeting needs of usage tasks for CHO intakes are sustained.

### **With Low-Carb, High-Fat Diets**

Another argument that has been popularized in the LCHF debate is that they improve fat oxidation and lower reliance on glycogen stores. A debate on LCHF pros and cons (Terink et al., 2021; Burke et al., 2021). Published data on glycogen content which were accepted and included in the (Table 2). Table 2 summarized the effects of LCHF and high-CHO diets during exercise; it was concluded that LCHF diets more prefer fatty acid oxidation, however, markedly prohibited glycogen availability as well as high-intensity exercise. For endurance sports, where bursts of high-intensity energy are the norm, the reliance on carbohydrates as the fuel of choice is universal.

In comparison, LCHF has been associated with beneficial adaptations in ultra-endurance or lower-intensity exercise settings. Cao et al., (2021) keto effects, such as greater fat oxidation, and lower enjoyable exertion during long-duration, steady-state exercises. Due to a decrease in glycogen-based energy reserves, this effect is wiped out O'Brien, (2021), making the LCHF diets unfitting for competitive athletes competing at a high intensity or mixed intensity.

**Table 2** Key findings summary

Key focus	Highlights
Glycogen Storage	High-CHO diets optimize glycogen stores, critical for sustained high-intensity performance.
GI Tolerance	Gut training minimizes gastrointestinal distress, improving carbohydrate absorption.
Glycemic Index	Low-GI carbohydrates ensure sustained energy release, reducing fatigue during prolonged efforts.
Diet Comparisons	High-CHO diets outperform LCHF diets for high-intensity events but suit fewer ultra-endurance scenarios.
Personalized Strategies	Carbohydrate periodization and gut training tailor CHO intake to individual athlete needs.

### Trends and Strategies: What's Coming Next

The scientific literature on sports nutrition has increasingly seen carbohydrate strategies tailored to the individual. Alternative approaches (e.g., carbohydrate periodization and gut training) were reviewed and their potential implications for meeting carbohydrate metabolism and GI tolerance were discussed (Podlogar and Wallis, 2022). Therefore, alternate periods of increased carbohydrate availability with periods of low carbohydrate availability during specific training periods to enhance metabolic flexibility and glycogen availability storage for specific bouts of performance. These methods could offer a preventative framework for those in the sport trying to find a balance between fuel needs and gut comfort.

As King et al., (2022) laid out in my piece in 2022, gut training is the progressive adaptation of the gastrointestinal (GI) tract to digest and absorb greater amounts of carbohydrates when exercising. While this strategy does do a good job of mitigating GI upset, there remains conflicting data on the effects on overall performance. Merging gut training protocols with more traditional CHO approaches may provide a compromise for endurance athletes who are prone to experience indigestion or other GI sensitivities.

### Practical Implications

Diets with high CHO in athletes doing endurance workouts should be tailored to individual sport, intensity of training, and individual metabolism responsiveness. Periodized carbohydrate intake, as suggested by Podlogar and Wallis, (2022), is a flexible approach that can be applied to different phases of training. To illustrate:

High-CHO intakes around training or competition during high-intensity exercise have been suggested to optimize glycogen availability and performance.

Moderate to low carb intake may be enough to prevent excess calorie intake and repair muscle tissue when recovering from exercise, or exercising at a low intensity.

In line with Zdzieblik et al., (2022), including low-GI carbohydrate sources will also enhance performance through a gradual supply of energy, a film of fatigue, and a reduction in the following exercise hypoglycemia.

### Limitations and Future Research Directions

Although this review demonstrates the beneficial impact of high-CHO diets, some limitations need to be addressed:

Examples: King et al., (2022) individual variability (2022), underscoring how individual metabolic and GI function directly calibrate carbohydrate tolerance and utilization. More studies should explore personalized diets about these factors.

Consequences in the long term: The long-term metabolic and health impacts of sustained high-CHO and LCHF diets which differ in compositions have not been evaluated, particularly in elite athletes who follow these dietary regimens for extended periods.

Hybrid approaches: Novel dual-CHO+fat strategies may offer a compromise for mixed-intensity events but warrant exploration.

### Summary

We review existing evidence indicating that high-carbohydrate (CHO) diets are indispensable for optimizing the training response in endurance-based exercise modalities across a broad spectrum of sports. The most notable use of glycogen detail is for its most common energy substrate used for episodes of prolonged and high-intensity exercise. It is instrumental for the best performance and recovery. The data is clear that CHO strategies (as opposed to low-carbohydrate high-fat (LCHF) diets) lead to better performance during prolonged high-intensity endurance exercise. Athletes using high-CHO diets can perform high amounts of work in long-duration, high-intensity efforts.

For instance, the importance of glycogen re-synthesis is well-established in prolonging time to exhaustion and aiding recovery. Moreover, in confirmation of this, mucosal immunity, another parameter often lost in many reviews, is the continued delivery of carbohydrates. This illustrates the institutional benefits of CHO approaches. Although similar diets did increase fat oxidation, their application is restricted to ultra-endurance events performed at low intensity. However, at higher exercise intensities where glycogen becomes the main player in energy provision, the adaptations gained through LCHF do not meet the energetic needs that allow performance at full capacity.

Rosenberg elaborates that while LCHF diets can improve hormonal responses (i.e., reduce cortisol), they are insufficient to maintain endurance capacity during high-energy demand situations (endurance capacity correlates to glucose availability in skeletal muscles). New approaches, such as carbohydrate periodization and gut training, offer great promise to enhance carbohydrate utilization: CHO periodization aligns with other phases of training. It enhances glycogen reserves and metabolic flexibility during demanding training sessions and rehab, and helps athletes in mixed-intensity competitions by maximizing the use of glycogen and fats for energy. Protocols for gut training assist athletes in enhancing their gastrointestinal tolerance to high CHO intakes during extended exercise. While there is some debate on the direct performance benefits obtained from gut training, for those who are prone to GI distress during prolonged exercise, being able to increase the number of carbohydrates in the diet whilst experiencing less GI discomfort can be the key to enabling athletes to stick with the rigors of training in an elite environment.

But by adding low GI (glycemic index) carbs, you get a slow release of energy, which enhances your staying power, averting fatigue when you work out for long durations. However, for short, high-intensity work or immediate post-exercise, high-GI carbohydrates can still be useful. To maximize their effectiveness, these methods should be individualized to athletes' distinctive metabolic needs and competition schedules. To maintain performance, tailored carbohydrate methods should be created based on the athlete's sport, training phase, and acuity to GI discomfort. Integration of periodization and gut training:

The combined approach maximizes glycogen availability at reduced GI stress incidence, thereby optimizing performance.

Qualitative methodology: Create a methodology for identifying hindrances: "As qualitative research typically deals with 'why' and 'how', it can provide a systematic method of identifying barriers to dietary adaptations and performance outcomes".

While much evidence supports HCHO diets, several key gaps in knowledge warrant further study:

Genetic variation: The rogue carbohydrate breaks the metabolism, examine the genetics that compete with carbs.

Hybrid approach: A mix of CHO and moderate fat combined for optimal endurance performance.

Chronic effects: Presentation and discussion of potential differences in health and performance outcomes following chronic CHO-dominant strategies, particularly in elite volumes.

## 4. CONCLUSION

CHO diets make constancy performance through enhanced glycogen storage, improved healing, and sustained high-intensity activities. The carbohydrate periodization and core training methods provide functional tools to individualize CHO intake, ensuring optimal performance tailored to exact requirements and conditions. While low-carbohydrate, high-fat (LCHF) diets may encounter limited application in ultra-endurance sports, they fail to meet the energy demands of high-intensity activities. High-CHO approaches, when personalized and periodized, remain the gold standard in endurance nutrition, delivering a foundation for achieving peak athletic performance across diverse disciplines.

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### Author's Contributions

Aleksandra Litwin: Conceptualization; writing - rough preparation; supervision

Zuzanna Kudas, Paweł Nowocin, Martyna Koszyk, Dawid Wiktor Kulczyński, Karolina Krzywicka, Nikola Perchel: Writing - rough preparation

Natalia Dąbrowska, Paulina Kumiega: Writing - review and editing

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### Informed consent

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### Conflict of interest

The authors declare that there is no conflict of interests.

### Data and materials availability

All data sets collected during this study are available upon reasonable request from the corresponding author.

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