BRODA, Aleksandra, HOKSA, Kacper, DUBNIEWICZ, Ewa, MAJEWSKA, Paula, STASZEK, Alicja, ŁOSKOT, Wiktoria, SZWECH, Jan, MATCZAK, Mateusz, JASIŃSKI, Karol and JODŁOWSKI, Krzysztof. The Impact of Diet on Performance in Endurance Sports - Literature Review. Quality in Sport. 2025;38:57917. eISSN 2450-3118.
https://doi.org/10.12775/QS.2025.38.57917
https://apcz.umk.pl/QS/article/view/57917

The journal has been 20 points in the Ministry of Higher Education and Science of Poland parametric evaluation. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024. No. 32553.
Has a Journal's Unique 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 r. 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 declare that there is no conflict of interests regarding the publication of this paper.
Received: 17.01.2025. Revised: 12.02.2025. Accepted: 14.02.2025 Published: 14.02.2025.

The Impact of Diet on Performance in Endurance Sports - Literature Review

AUTHORS

Aleksandra Broda

Hospital of the Ministry of Interior and Administration in Lodz, ul. Północna 42, 91–425 Łódź

ORCID: https://orcid.org/0009-0004-5179-9411

E-mail: aleksandra.d.broda@gmail.com

Kacper Hoksa

Hospital of the Ministry of Interior and Administration in Lodz, ul. Północna 42, 91–425 Łódź

ORCID: https://orcid.org/0009-0007-9832-7093

E-mail: kacper.hoksa98@gmail.com

Ewa Dubniewicz

Central Clinical Hospital of Medical University of Lodz, ul. Pomorska 251, 92-213 Lodz

ORCID: https://orcid.org/0009-0007-4191-6794

E-mail: edubniewicz@gmail.com

Paula Majewska
Central Clinical Hospital of Medical University of Lodz, ul. Pomorska 251, 92-213 Lodz
ORCID: https://orcid.org/0009-0003-7934-397X
E-mail: majewskapaula14@gmail.com

Alicja Staszek
Central Clinical Hospital of Medical University of Lodz, ul. Pomorska 251, 92-213 Lodz
ORCID: https://orcid.org/0009-0007-0323-8697
E-mail: staszekalicja0@gmail.com

Wiktoria Łoskot
University Clinical Hospital No. 2 of the Medical University of Lodz: Łódź, ul. Stefana Żeromskiego 113, 90-549 Łódź, PL
ORCID: https://orcid.org/0009-0001-5392-4835
E-mail: wiktoria.loskot98@gmail.com

Jan Szwech
Masovian Specialist Hospital, ul. Jana Aleksandrowicza 5, 26-617 Radom
ORCID: https://orcid.org/0009-0002-9312-8152
E-mail: szwechjan@gmail.com

Mateusz Matczak
Hospital of the Ministry of Interior and Administration in Lodz, ul. Północna 42, 91–425 Łódź
ORCID: https://orcid.org/0009-0000-9701-406X
E-mail: matczak.mateusz@icloud.com

Karol Jasiński
Provincial Hospital of St. Luke in Tarnów, 33-100 Tarnów, ul. Lwowska 178a
ORCID: https://orcid.org/0009-0004-6845-5199
E-mail: karol.jasinski99@gmail.com

Krzysztof Jodłowski
Hospital of the Ministry of Interior and Administration in Lodz, ul. Północna 42, 91–425 Łódź
ORCID: https://orcid.org/0009-0003-9041-2091
E-mail: lek.krzysztofjodlowski@gmail.com

Abstract

Introduction: The physical performance of athletes in endurance disciplines is the result of a complex process of the body adapting to prolonged and intense exertion. A significant factor influencing the efficiency of this process is an appropriate diet, which ensures optimal conditions for maintaining performance, recovery, and achieving maximum results during competitions. The diet of an athlete, especially in endurance sports, plays a crucial role in providing adequate amounts of energy, micronutrients, and macronutrients, such as carbohydrates, fats, and proteins, which are necessary to maintain energy levels, especially during prolonged efforts. Proper dietary balance, including an adequate supply of carbohydrates, affects the body's ability to utilize stored energy resources and facilitates post-exercise recovery mechanisms.

Objective: To review available studies on the impact of diet on the physical performance of endurance athletes, analyze the findings, and draw practical conclusions that can be used to create dietary plans for athletes.

Current Knowledge: Athletic performance is the body's ability to perform physical exertion for an extended period without excessive fatigue while maintaining adequate efficiency. It depends on the cardiovascular, respiratory, and muscular systems' ability to deliver energy and remove metabolic by-products. Diet has a significant impact on the body's performance, and both the number of calories consumed and their primary source are critical for athletic achievements.

Summary: A low-carbohydrate, high-fat diet leads to reduced exercise efficiency because the athlete requires more oxygen to perform the same work. Although reducing carbohydrate intake increases fatty acid oxidation, carbohydrates remain a more efficient energy source for high-intensity efforts, providing more ATP per unit of oxygen. Long-term adaptation to a

high-fat diet reduces exercise capacity, especially during intense activities, due to disruptions in carbohydrate metabolism, despite the availability of glycogen.

Keywords: athletic performance, diet, endurance sports, carbohydrates, fats, dietary recommendations.

Division of Endurance and Its Importance in Endurance Sports

Sports endurance can be divided into two main types:

1. **Aerobic Endurance**
   This refers to the body's ability to generate energy in the presence of oxygen. Aerobic endurance is crucial in endurance disciplines such as marathon running, cycling, or swimming, where the effort lasts longer, and energy is primarily derived from the oxidation of carbohydrates and fats. High aerobic endurance allows for sustained effort over an extended period, delaying fatigue and enabling efficient utilization of energy resources.
2. **Anaerobic Endurance**
   This pertains to the body's ability to produce energy under oxygen-deficient conditions, characteristic of short, intense efforts such as sprinting, weightlifting, or other forms of strength training. Anaerobic endurance enables short but highly intense efforts, utilizing anaerobic processes that provide quick access to energy. However, this leads to the accumulation of lactic acid, which limits the duration of such efforts.

Importance of Sports Endurance

Sports endurance is a critical factor influencing athletic performance, as it determines an athlete's ability to maintain a high level of intensity over time. In endurance disciplines, high aerobic endurance allows athletes to perform intense efforts for extended durations, translating into better times or distances achieved.

Biochemical and Physiological Basics

The individual components of the diet have a crucial impact on sports performance by providing the body with essential substances for maintaining energy, recovery, and optimizing endurance.

Proteins – Essential for the construction and repair of muscles. In strength and endurance sports, protein supports the repair of micro-injuries caused by training and helps maintain muscle mass. A deficiency in protein can lead to muscle weakness and a long-term decrease in endurance.

Carbohydrates – Serve as the main energy source, particularly in endurance sports. They replenish glycogen stores in muscles and the liver, enabling prolonged physical effort. Consuming carbohydrates before, during, and after training enhances endurance and aids recovery.

Fats – Provide energy during prolonged, moderate-intensity effort. An adequate amount of healthy fats, particularly unsaturated fatty acids, affects overall body efficiency and supports the functioning of the hormonal system, which is essential for endurance.

Vitamins and Minerals – Play a crucial role in energy metabolism, support the immune and nervous systems, and accelerate recovery. For example, vitamin D supports bone health, while magnesium and potassium help prevent muscle cramps and maintain electrolyte balance.

Hydration plays a key role in the physical performance of athletes, as water constitutes about 60% of body weight and is essential for the proper functioning of the body during exertion. Optimal hydration ensures electrolyte balance, supports the transport of nutrients and oxygen to muscles, and facilitates the removal of metabolic waste products. Even mild dehydration can lead to reduced performance, increased fatigue, impaired concentration, muscle cramps, and, in extreme cases, heat stroke.

A well-balanced diet, containing the right amounts of these components, is key to achieving optimal sports results, improving endurance, and promoting faster recovery. [1-4]

Selected Nutritional Strategies to Support Endurance

1. Increasing endurance through a carbohydrate-based diet is one of the most effective methods for improving performance in endurance sports such as running, cycling, or swimming. A key element of this strategy is the concept of "carbohydrate loading," which involves increasing carbohydrate intake several days before intense aerobic effort to maximize glycogen stores in muscles and the liver. The benefits of this approach include:
2. **Increased glycogen stores**, which are the main source of energy during high-intensity aerobic exercise, allowing the body to maintain effort at a high level for a longer period before it begins to rely on alternative energy sources such as fats. Increasing glycogen stores delays the onset of fatigue, which is particularly important in endurance disciplines.
3. **Improved endurance**: Higher carbohydrate availability during exercise leads to better energy utilization, resulting in improved sports performance. Research shows that athletes who use the carbohydrate loading strategy achieve better results in prolonged, exhausting aerobic efforts.
4. **Faster recovery**: A carbohydrate-based diet before exercise also aids faster recovery after intense training or competition. Increased carbohydrate intake helps replenish glycogen stores more quickly after exertion, allowing athletes to return to full form more rapidly [6,7].

Increased Protein Intake in Recovery and Muscle Building

Increased protein intake plays a key role in recovery after training and in muscle mass development. After intense exercise, micro-tears occur in muscle fibers, which require repair and regeneration. Protein provides the essential amino acids that form the foundation of the repair process and the synthesis of new muscle fibers, leading to muscle growth.

Consuming protein in adequate amounts reduces feelings of fatigue and prevents muscle catabolism. For those engaged in strength training, protein contributes to improvements in strength and muscle mass, and its increased intake (compared to standard recommendations) leads to better training results. An adequate amount of protein in the diet (usually between 1.6 and 2.2 g per kilogram of body weight) is essential for optimal muscle growth and recovery [8,9].

Fat-Based Diet in Athletes

A fat-based diet can be beneficial for athletes, but its application depends on the type of sport. In endurance disciplines, such as long-distance running, a ketogenic diet can improve the body's ability to burn fat as fuel, enhancing endurance at low or moderate intensities. Adapting to this diet takes several weeks and may lead to an initial decrease in energy levels before the body adjusts to fat burning. Athletes following a fat-based diet must also ensure adequate electrolyte intake and hydration to prevent mineral imbalances. In practice, a fat-based diet is often used cyclically or in combination with periodic carbohydrate loading to optimize performance and recovery [10,11].

Specifics of Diet in Endurance Sports

The diet of athletes in endurance sports comes with several challenges that can impact performance, recovery, and overall health. Key challenges include:

1. **Adequate Energy Intake**: Endurance sports require a high caloric intake, which can be difficult to meet, especially during prolonged physical effort. Inadequate calorie consumption leads to fatigue, muscle mass loss, and a decline in performance.
2. **Macronutrient Balance**: Ensuring an appropriate amount of carbohydrates, which are the main energy source during intense exercise, is crucial. At the same time, athletes must maintain a balance between carbohydrates, protein (for muscle recovery), and fats (as an alternative energy source).
3. **Hydration and Electrolytes**: During prolonged exertion, the body loses a significant amount of water and electrolytes (sodium, potassium, magnesium). A deficiency in these can lead to dehydration, muscle cramps, and reduced performance. Planning hydration strategies is critical, especially in extreme conditions.
4. **Recovery**: After exertion, the body requires proper nutrients for muscle recovery, glycogen replenishment, and reducing inflammation. Poor nutrition can lengthen recovery time and contribute to overtraining.
5. **Diet Individualization**: Every body is different, and universal nutrition plans may not meet individual needs. Athletes must experiment with various strategies during training to find the optimal nutrition combination tailored to their requirements and tolerances [12,13].

Diet-Related Disorders in Athletes

Hormonal disturbances in endurance athletes caused by improper diet result from energy, macro-, and micronutrient deficiencies that disrupt the hormonal system. These issues vary by gender, as hormones play different key roles in the bodies of women and men [17].

Women

1. The Female Athlete Triad: This is a set of three interrelated pathological conditions that can occur in women involved in sports, particularly endurance sports or those that require weight control. It consists of the following elements:
    a. **Relative Energy Deficiency in Sport (RED-S):** This is the central component of the female athlete triad. Due to intense physical activity, poor diet, excessive training, or insufficient calorie intake relative to energy expenditure, the woman's body does not receive enough energy to meet both metabolic needs and those resulting from physical activity. As a result, the body enters an energy conservation mode.
    b. **Menstrual Disorders (Amenorrhea, Hypogonadism):** Chronic energy deficiency in the body leads to suppression of the hypothalamic-pituitary-gonadal axis, which causes a decrease in the secretion of sex hormones, including estrogen. Estrogen plays a crucial role in regulating the menstrual cycle and maintaining bone health. A low level of estrogen leads to menstrual disturbances.
    c. **Bone Metabolism Disorders (Osteopenia, Osteoporosis):** The decrease in estrogen levels, associated with menstrual disorders and chronic energy deficiency, significantly affects bone metabolism. Estrogens are essential in regulating bone metabolism because they stimulate osteoblast activity (cells responsible for bone formation) and inhibit osteoclasts (cells responsible for bone resorption). Their deficiency disrupts bone remodeling processes and accelerates bone resorption, leading to a decrease in bone mineral density, which can result in osteopenia or osteoporosis. Women with the female athlete triad are significantly more prone to fractures, especially in long bones (e.g., femur, wrist bones) [14,15].

2. **Increased Risk of Chronic Inflammation**

Chronic strain associated with frequent and intense training can lead to a state of chronic inflammation, resulting from excessive production of pro-inflammatory cytokines and inflammatory markers. Additionally, fluctuating levels of estrogen and progesterone can influence the immune response, increasing the levels of inflammatory markers. High-intensity endurance training can also lead to depletion of energy resources, weakening the body's defense mechanisms, which further promotes chronic inflammation.

3. **Impact on the Thyroid**

One of the most common issues is hypothyroidism (underactive thyroid), characterized by a low level of thyroid hormones in the blood. Chronic high-intensity physical exertion combined with insufficient recovery can lead to reduced thyroid activity. This results from various factors, such as chronic stress, energy depletion, and changes in leptin levels and other hormones regulating metabolism. Hypothyroidism in athletes may manifest as reduced energy, difficulty maintaining body weight, decreased performance, weakness, depression, and menstrual cycle disturbances [16].

Men

Testosterone Deficiency – This is a complex issue with multiple contributing factors:

1. **Intense and prolonged physical exertion** increases cortisol levels, which contributes to muscle tissue breakdown and inhibits testosterone production. Excess cortisol can also alter the secretion of gonadotropins (LH and FSH) from the pituitary gland, which regulate testosterone production in the testes. Prolonged endurance training can lead to a condition known as "exercise-induced hypogonadism," where testosterone levels decrease, while cortisol levels rise.
2. **Impact of Energy Depletion** – In situations of chronic energy deficiency, the body allocates available energy resources to basic life functions, leading to reduced testosterone production. Energy depletion, especially in athletes on restrictive diets, can disrupt the hypothalamic-pituitary-gonadal axis, resulting in decreased secretion of gonadotropins and, consequently, testosterone.

3. **Disruptions in Hormonal Regulation** – Chronic endurance exercise, especially without proper rest and recovery, can lead to an imbalance between testosterone and estrogen levels, which in extreme cases may result in lowered testosterone levels. This occurs through the increased secretion of hormones that inhibit testosterone production, such as prolactin and cortisol [18,19,29,31].

Impact on the Thyroid: Similar to women, malnutrition reduces thyroid activity, leading to hypothyroidism, which can result in reduced endurance and chronic fatigue [16].

Common Consequences for Both Genders

1. **Relative Energy Deficiency in Sport (RED-S):** RED-S occurs when an athlete's body expends more energy than it can provide through diet. In response to this energy deficit, the body adapts its functions to conserve energy, which can lead to disruptions in multiple physiological systems. Energy deficiency may arise from excessive training intensity, insufficient calorie intake, or an improper macronutrient distribution (e.g., low carbohydrate intake). The pathophysiology of the syndrome is multifactorial, and the following are the main disorders associated with it:
    a. **Hormonal Disturbances:** Chronic energy deficiency causes the body to react to metabolic stress, leading to decreased levels of hormones responsible for reproductive functions, metabolism, and bone health. Leptin (a hormone that regulates hunger and metabolism) and insulin levels often drop, reducing the body's ability to utilize energy. Additionally, reduced levels of estrogen in women and testosterone in men may lead to menstrual cycle disturbances in women and fertility issues in both genders.
    b. **Muscle Weakness, Decreased Aerobic Capacity, Muscle Mass Loss, and General Decreased Ability for Intense Effort:** This results in poor athletic performance, lower endurance, and muscle deterioration.
    c. **Reduced Bone Mineral Density:** Disruptions in estrogen or testosterone levels can decrease bone density, increasing the risk of fractures and osteoporosis. High physical stress combined with energy deficiency and hormonal disruptions can lead to osteopenia and other bone-related issues, such as stress fractures.

d. **Immune System Impact:** Energy deficit weakens the immune system's ability to defend against infections. Reduced calorie intake can lower white blood cell count, increasing vulnerability to infections, colds, and other diseases.
e. **Lower Blood Pressure, Reduced Blood Volume, and Bradycardia:** In severe cases, this can be dangerous for health. A lower number of red blood cells (due to decreased erythropoietin production) diminishes the body's ability to transport oxygen, which impairs aerobic performance.
f. **Psychological Issues:** Energy deficiency is often accompanied by increased risk of mental health disorders such as depression, anxiety, eating disorders, sleep disturbances, and concentration problems [17,20,21].

2. **Leptin Deficiency and Its Impact-** Leptin is known as the "hunger hormone" and is produced primarily by adipocytes (fat cells). It plays a crucial role in regulating appetite, metabolism, and the body's energy balance. Its levels are closely correlated with body fat percentage. Leptin functions to influence the hunger and satiety centers in the brain and regulate the secretion of other metabolic hormones.
    a. In the context of energy deficiency, such as from excessive physical activity or restrictive diets, leptin levels decrease. This drop signals the brain that there is insufficient energy, triggering hunger mechanisms that aim to restore energy balance by increasing appetite and lowering metabolic rate. In endurance athletes who consistently perform prolonged training, leptin levels may remain low due to chronic energy deficiency.
    b. Aside from regulating appetite, leptin affects processes like thermogenesis and reproductive function. In cases of prolonged energy deficiency and low leptin levels, the body attempts to conserve energy, which can reduce thermogenesis, decrease performance, and slow metabolism. Moreover, low leptin levels are linked to hormonal disruptions, such as reduced estrogen in women and testosterone in men, which can negatively impact reproductive functions and bone health.
    c. The body compensates for leptin deficiency by increasing the production of other hormones like ghrelin (which stimulates appetite) and reducing insulin-like growth factor 1 (IGF-1), which is essential in anabolic processes. These hormonal changes can disturb metabolic balance, leading to reduced physical performance and slower recovery.

d. Over time, persistently low leptin levels can lead to significant negative health effects, such as muscle mass loss, exhaustion, and an increased risk of injuries [22].

Analysis of Available Studies

Numerous athletes, dietitians, strength and conditioning coaches, and researchers are trying to determine which dietary strategy has the most beneficial effect on the health and performance of endurance athletes. A review of scientific studies indicates that a high-carbohydrate diet is the best choice, as supported by the following research findings.

According to Hawley JA et al. [23], increasing muscle glycogen levels through a high-carbohydrate diet, above normal resting levels prior to exercise, has a negligible or no effect on performance in moderate-intensity efforts lasting 60 to 90 minutes. In these types of efforts, significant amounts of glycogen remain in the muscles after exercise. However, a higher initial muscle glycogen level may delay fatigue by approximately 20% during endurance efforts lasting over 90 minutes. Glycogen supercompensation can also improve performance in efforts where the goal is to cover the distance as quickly as possible. In such cases, high-carbohydrate diets have been shown to improve results by 2-3%.

A study conducted on cyclists by researchers from South Africa demonstrated that a low-carbohydrate, high-fat diet led to adaptations that supported fat metabolism but hindered carbohydrate metabolism in the body. Despite the increased fat metabolism, it did not translate into improved exercise efficiency, even after carbohydrate loading prior to the event. Sprint performance, a key component in cycling races, was worse in the low-carbohydrate diet group [24].

Another study from the Australian Institute of Sport, involving race walkers, confirmed that no additional benefits in athletic performance were observed from following a high-fat, low-carbohydrate dietary model compared to a high-carbohydrate diet. It was noted that exercise performance at high intensities did not improve after three weeks of training in the ketogenic group, whereas athletes consuming a high-carbohydrate diet showed significant improvements in their athletic performance [25].

These findings consistently support the idea that high-carbohydrate diets enhance endurance performance and lead to better overall athletic outcomes, particularly in sports requiring high-intensity efforts or prolonged durations.

Nutritional Recommendations Regarding Carbohydrate Intake for Athletes

The recommended daily carbohydrate intake depends on the type and intensity of physical activity performed.

1. For individuals performing technical exercises or low-intensity activities, such as light training, it is recommended to consume 3–5 grams of carbohydrates per kilogram of body weight daily.
2. For moderate training loads, approximately one hour of exercise per day, the intake should be 5–7 grams per kilogram of body weight.
3. For athletes performing endurance training (1–3 hours daily at moderate or high intensity), it is recommended to consume 6–10 grams of carbohydrates per kilogram of body weight.
4. In cases of extreme sport involvement, such as training sessions lasting over 4–5 hours per day at moderate or high intensity, the carbohydrate intake may increase to 8–12 grams per kilogram of body weight daily.

In such situations, to ensure adequate carbohydrate availability during training, it is recommended to consume carbohydrates before, during, and after physical activity, especially during the recovery period. Once all energy needs are met, carbohydrate intake can be adjusted according to comfort and individual dietary preferences. Additionally, athletes should choose carbohydrate-rich foods that are also nutrient-dense.

In the recommendations from the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine, we can also find aggressive nutritional strategies aimed at ensuring adequate carbohydrate availability during key training sessions and competitions, which can improve athletic performance. These recommendations are as follows:

- General guidelines for preparation for an event lasting less than 90 minutes suggest consuming 7–12 grams of carbohydrates per kilogram of body weight daily to meet energy needs.
- For long-duration efforts lasting over 90 minutes, whether continuous or intermittent, it is recommended to follow a carbohydrate loading strategy. In this case, carbohydrate intake should be 10–12 grams per kilogram of body weight daily for 36–48 hours before the event.
- Athletes should choose carbohydrate-rich foods that are low in fiber and easy to digest, which will help ensure gastrointestinal comfort and assist in maintaining proper body weight before the event.
- During the recovery period between intense training sessions that are spaced closely together (up to 8 hours), a rapid carbohydrate replenishment strategy is recommended. This involves consuming 1–1.2 grams of carbohydrates per kilogram of body weight per hour for the first four hours after exercise, and then continuing to consume according to daily requirements. In this case, sports foods and drinks that provide carbohydrates can help fulfill nutritional goals. Regular consumption of small snacks can also be beneficial. [26,27]

Conclusions

The key conclusions regarding the impact of diet on the performance of endurance athletes are as follows:

1. Low-carbohydrate, high-fat diets lead to a deterioration in exercise efficiency, meaning that the athlete requires more oxygen to perform the same amount of work.
2. Based on the results of all previous studies on endurance and ultra-endurance exercises, it can be concluded that a reduction in carbohydrate intake leads to an increase in fatty acid oxidation. However, even at the highest exercise intensity, carbohydrates have an advantage over fats as an energy substrate because they provide more ATP molecules per unit of oxygen available for mitochondria.
3. Long-term adaptation to a high-fat, low-carbohydrate diet, which results in increased fatty acid oxidation rates, negatively impacts exercise capacity, particularly during high-intensity exercise.
4. The adverse metabolic changes observed in high-fat, low-carbohydrate diets appear to be due to disturbances in carbohydrate metabolism, even when glycogen is available.

Therefore, in elite sports, it would be unreasonable to adhere to a high-fat diet at the expense of the ability to perform demanding training sessions or high-intensity efforts during competitions, which would undoubtedly affect the final performance outcome. [27,28,30]

Disclosure

Authors do not report any disclosures

Author's contribution:

Conceptualization: Aleksandra Broda, Mateusz Matczak, Kacper Hoksa,

Methodology: Krzysztof Jodłowski, Jan Szwech, Ewa Dubniewicz

Formal analysis: Paula Majewska, Wiktoria Łoskot, Alicja Staszek, Karol Jasiński

Investigation: Jan Szwech, Ewa Dubniewicz, Aleksandra Broda

Supervision: Krzysztof Jodłowski, Alicja Staszek, Karol Jasiński

Writing – Original Draft: Aleksandra Broda, Mateusz Matczak, Wiktoria Łoskot

Writing - Review and Editing: Kacper Hoksa, Paula Majewska

All authors have read and agreed with the published version of the manuscript.

Funding Statement

Study did not receive special funding

Institutional Review Board Statement

Not applicable

Informed Consent Statement

Not applicable

Data Availability Statement

Not applicable

Acknowledgments

Not applicable

Conflict of Interest Statement

The authors of the paper report no conflicts of interest.

References

1. Hargreaves M. The metabolic systems: carbohydrate metabolism. In: Farrell PA, Joyner MJ, Caiozzo VJ, editors. Advanced exercise physiology. 2nd ed. Philadelphia: Lippincott, Williams and Wilkins; 2012. p. 3–391.
2. Spriet LL. The metabolic systems: lipid metabolism. In: Farrell PA, Joyner MJ, Caiozzo VJ, editors. Advanced exercise physiology. 2nd ed. Philadelphia: Lippincott, Williams and Wilkins; 2012. p. 392–407
3. Ormsbee M.J., Bach C.W., Baur D.A.: Pre-exercise nutrition: the role of macronutrients, modified starches and supplements on metabolism and endurance performance. Nutrients. 2014; 6 (5): 1782–1808. doi: 10.3390/nu6051782.
4. Papadopoulou SK. Rehabilitation Nutrition for Injury Recovery of Athletes: The Role of Macronutrient Intake. Nutrients. 2020 Aug 14;12(8):2449. doi: 10.3390/nu12082449. PMID: 32824034; PMCID: PMC7468744.
5. Burke L.M., Hawley J.A., Jeukendrup A. i wsp.: Toward a Common Understanding of Diet-Exercise Strategies to Manipulate Fuel Availability for Training and Competition Preparation in Endurance Sport. Int. J. Sport Nutr. Exerc. Metab. 2018; 28 (5): 451–463. doi: 10.1123/ijsnem.2018-0289
6. Cermak N.M., van Loon L.J.: The use of carbohydrates during exercise as an ergogenic aid. Sports Med. 2013; 43 (11): 1139–1155. doi: 10.1007/s40279-013-0079-0.
7. Colombani P.C., Mannhart C., Mettler S.: Carbohydrates and exercise performance in non-fasted athletes: a systematic review of studies mimicking real-life. Nutr. J. 2013; 12: 16. doi: 10.1186/1475-2891-12-16.
8. Kerksick CM, Arent S, Schoenfeld BJ, Stout JR, Campbell B, Wilborn CD, Taylor L, Kalman D, Smith-Ryan AE, Kreider RB, Willoughby D, Arciero PJ, VanDusseldorp TA, Ormsbee MJ, Wildman R, Greenwood M, Ziegenfuss TN, Aragon AA, Antonio J. International society of sports nutrition position stand: nutrient timing. J Int Soc Sports Nutr. 2017 Aug 29;14:33. doi: 10.1186/s12970-017-0189-4. PMID: 28919842; PMCID: PMC5596471.

9. Nieman DC, Zwetsloot KA, Simonson AJ, Hoyle AT, Wang X, Nelson HK, Lefranc-Millot C, Guérin-Deremaux L. Effects of Whey and Pea Protein Supplementation on Post-Eccentric Exercise Muscle Damage: A Randomized Trial. Nutrients. 2020 Aug 9;12(8):2382. doi: 10.3390/nu12082382. PMID: 32784847; PMCID: PMC7468723.
10. Volek J.S., Noakes T., Phinney S.D.: Rethinking fat as a fuel for endurance exercise. Eur J Sport Sci. 2015; 15 (1):13–20. doi: 10.1080/17461391.2014.959564.
11. McSwiney F.T., Wardrop B., Hyde P.N. i wsp.: Keto-adaptation enhances exercise performance and body composition responses to training in endurance athletes. Metabolism. 2018; 81: 25–34. doi: 10.1016/j.metabol.2017.10.010.
12. Vitale K, Getzin A. Nutrition and Supplement Update for the Endurance Athlete: Review and Recommendations. Nutrients. 2019 Jun 7;11(6):1289. doi: 10.3390/nu11061289. PMID: 31181616; PMCID: PMC6628334.
13. Malsagova KA, Kopylov AT, Sinitsyna AA, Stepanov AA, Izotov AA, Butkova TV, Chingin K, Klyuchnikov MS, Kaysheva AL. Sports Nutrition: Diets, Selection Factors, Recommendations. Nutrients. 2021 Oct 25;13(11):3771. doi: 10.3390/nu13113771. PMID: 34836029; PMCID: PMC8619485.
14. Daily JP, Stumbo JR. Female Athlete Triad. Prim Care. 2018 Dec;45(4):615-624. doi: 10.1016/j.pop.2018.07.004. Epub 2018 Oct 4. PMID: 30401345.
15. Carlson JL, Golden NH. The female athlete triad. The Female Patient 2012;37: 16–24.
16. Larson-Meyer DE, Gostas DE. Thyroid Function and Nutrient Status in the Athlete. Curr Sports Med Rep. 2020 Feb;19(2):84-94. doi: 10.1249/JSR.0000000000000689. PMID: 32028353.
17. Goolsby MA, Boniquit N. Bone health in athletes: the role of exercise, nutrition, and hormones. Sports Health 2017;9(2):108–17.
18. Cupka M, Sedliak M. Hungry runners - low energy availability in male endurance athletes and its impact on performance and testosterone: mini-review. Eur J Transl Myol. 2023 Apr 11;33(2):11104. doi: 10.4081/ejtm.2023.11104. PMID: 37052052; PMCID: PMC10388605.
19. Hooper DR, Tenforde AS, Hackney AC. Treating exercise-associated low testosterone and its related symptoms. Phys Sportsmed. 2018 Nov;46(4):427-434. doi: 10.1080/00913847.2018.1507234. Epub 2018 Aug 27. PMID: 30063407.
20. Torstveit MK, Fahrenholtz I, Stenqvist TB, Sylta Ø, Melin A. Within-Day Energy Deficiency and Metabolic Perturbation in Male Endurance Athletes. Int J Sport Nutr

Exerc Metab. 2018 Jul 1;28(4):419-427. doi: 10.1123/ijsnem.2017-0337. Epub 2018 Jun 26. PMID: 29405793.

21. Torstveit MK, Fahrenholtz I, Stenqvist TB, Sylta Ø, Melin A. Within-Day Energy Deficiency and Metabolic Perturbation in Male Endurance Athletes. Int J Sport Nutr Exerc Metab. 2018 Jul 1;28(4):419-427. doi: 10.1123/ijsnem.2017-0337. Epub 2018 Jun 26. PMID: 29405793.
22. Leal-Cerro A, Garcia-Luna PP, Astorga R, Parejo J, Peino R, Dieguez C, Casanueva FF. Serum leptin levels in male marathon athletes before and after the marathon run. J Clin Endocrinol Metab. 1998 Jul;83(7):2376-9. doi: 10.1210/jcem.83.7.4959. PMID: 9661612.
23. Hawley JA, Schabort EJ, Noakes TD, Dennis SC. Carbohydrate-loading and exercise performance. An update. Sports Med. 1997 Aug;24(2):73-81. doi: 10.2165/00007256-199724020-00001. PMID: 9291549.
24. Havemann L., West S.J., Goedecke J.H. i wsp.: Fat adaptation followed by carbohydrate loading compromises high-intensity sprint performance. J. Appl. Physiol. (1985) 2006; 100 (1): 194–202. doi: 10.1152/japplphysiol.00813.2005.
25. Burke L.M., Ross M.L., Garvican-Lewis L.A. i wsp.: Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefit from intensified training in elite race walkers. J. Physiol. 2017; 595 (9): 2785–2807. doi: 10.1113/JP273230.
26. Burke L.M., Hawley J.A., Wong S.H., Jeukendrup A.E.: Carbohydrates for training and competition. J. Sports Sci. 2011; 29 (Suppl 1): S17–27. doi: 10.1080/02640414.2011.585473.
27. Thomas D.T., Erdman K.A., Burke L.M.: Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and Athletic Performance. J. Acad. Nutr. Diet. 2016; 116 (3): 501–528. doi: 10.1016/j.jand.2015.12.006.
28. Tiller NB, Roberts JD, Beasley L, Chapman S, Pinto JM, Smith L, Wiffin M, Russell M, Sparks SA, Duckworth L, O'Hara J, Sutton L, Antonio J, Willoughby DS, Tarpey MD, Smith-Ryan AE, Ormsbee MJ, Astorino TA, Kreider RB, McGinnis GR, Stout JR, Smith JW, Arent SM, Campbell BI, Bannock L. International Society of Sports Nutrition Position Stand: nutritional considerations for single-stage ultra-marathon

training and racing. J Int Soc Sports Nutr. 2019 Nov 7;16(1):50. doi: 10.1186/s12970-019-0312-9. PMID: 31699159; PMCID: PMC6839090.

29. Hackney A.C., Aggon E.: Chronic Low Testosterone Levels in Endurance Trained Men: The Exercise- Hypogonadal Male Condition. J. Biochem. Physiol. 2018; 1 (1). pii: 103. Epub 2018 Feb 28.
30. Rothschild JA, Kilding AE, Plews DJ. What Should I Eat before Exercise? Pre-Exercise Nutrition and the Response to Endurance Exercise: Current Prospective and Future Directions. Nutrients. 2020 Nov 12;12(11):3473. doi: 10.3390/nu12113473. PMID: 33198277; PMCID: PMC7696145.
31. Zekarias K., Shrestha R.T.: Role of Relative Malnutrition in Exercise-Hypogonadal Male Condition. Med. Sci. Sports Exerc. 2018; 2. doi: 10.1249/MSS.0000000000001783.