2024, Retos, 60, 1237-1243

Ketogenic diet - A gateway to optimize aerobic and anaerobic athletic performance
Dieta cetogénica: una puerta de entrada para optimizar el rendimiento deportivo aeróbico y anaeróbico

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Abstract. This narrative review aims to highlight the effect of the Ketogenic diet on aerobic and anaerobic athletic performance. This paper adopts a narrative approach exposing the results of approximately 40 earlier studies to define the scope of applying the ketogenic diet as a nutritional therapy, aiming to aid recovery from fatigue or muscle damage caused by exercise and to increase aerobic and anaerobic performance. A ketogenic diet appears better suited for lower-intensity physical activities conducted in a balanced or moderate state of energy demand. However, there is a lack of consensus on its compatibility with strength exercises that require maximal bursts of energy. These investigations should explore its effects on performance, health, and body composition compared to other dietary approaches. Ultimately, a better understanding of the ketogenic diet's benefits and limitations will help athletes and individuals make informed decisions about its adoption for optimizing their health and athletic goals.
Keywords: Injuries, ketogenic, ketosis, aerobic exercises, anaerobic exercises, muscle damage

Resumen. Esta revisión narrativa tiene como objetivo resaltar el efecto de la dieta cetogénica sobre el rendimiento deportivo aeróbico y anaeróbico. Este artículo adopta un enfoque narrativo exponiendo los resultados de aproximadamente 40 estudios anteriores para definir el alcance de la aplicación de la dieta cetogénica como terapia nutricional, con el objetivo de ayudar a la recuperación de la fatiga o daño muscular causado por el ejercicio y aumentar el rendimiento aeróbico y anaeróbico. Una dieta cetogénica parece más adecuada para actividades físicas de menor intensidad realizadas en un estado de demanda energética equilibrado o moderado. Sin embargo, existe una falta de consenso sobre su compatibilidad con ejercicios de fuerza que requieren explosiones máximas de energía. Estas investigaciones deberían explorar sus efectos sobre el rendimiento, la salud y la composición corporal en comparación con otros enfoques dietéticos. En última instancia, una mejor comprensión de los beneficios y limitaciones de la dieta cetogénica ayudará a los atletas y a las personas a tomar decisiones informadas sobre su adopción para optimizar su salud y sus objetivos deportivos.
Palabras clave: Lesiones, cetogénicas, cetosis, ejercicios aeróbicos, ejercicios anaeróbicos, daño muscular.

Fecha recepción: 24-04-24. Fecha de aceptación: 13-09-24
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Introduction

The Ketogenic diet, also known as the ketosis diet, is a "low-carbohydrate" and "high-fat" diet that has gained popularity in recent years. Ketogenic diet has been explored across various health domains including weight management, diabetes control, cardiovascular health, neurological diseases, cancer treatment, and athletic performance. This diet involves reducing carbohydrate intake and increasing fat intake to induce a state of ketosis in the body. The ketosis—a metabolic state where fat is utilized as a primary energy source instead of carbohydrates—leading to significant reductions in body weight and improvements in glycemic control (O'neill & Raggi, 2019). However, concerns have been raised regarding the long-term sustainability of such diets due to potential adverse effects on lipid profiles (Brouns, 2018). Ketogenic diet exhibits strong anti-inflammatory properties that may confer cardioprotective benefits through mechanisms such as reducing inflammation markers and providing an alternative energy source for heart cells during stress conditions (Dyńka et al., 2023). Research indicates that the ketogenic diet may facilitate an increase in fat oxidation during exercise, potentially providing a metabolic advantage for endurance athletes. For instance, studies have shown that adherence to a ketogenic low-carbohydrate high-fat diet can enhance the muscle's ability to utilize fat as a fuel source, thereby sparing glycogen stores for prolonged endurance activities (Cao et al., 2021). However, these benefits may come at the cost of performance during high-intensity efforts. Evidence suggests that while fat oxidation rates can double within a few weeks of adopting a ketogenic low-carbohydrate high-fat diet, the ability to utilize glycogen effectively may diminish, leading to compromised performance in high-intensity scenarios (Wang et al., 2022). Meta-analyses focusing on endurance athletes have yielded mixed results regarding the efficacy of the ketogenic diet on performance metrics such as VO2max and time to exhaustion. A systematic review and meta-analysis encompassing ten studies found no significant improvements in aerobic capacity or exercise performance attributable to ketogenic low-carbohydrate high-fat diets (Cao et al., 2021). Similarly, another review assessing concurrent training combined with ketogenic low-carbohydrate high-fat diets also reported no significant effects on body composition or aerobic performance compared to other dietary strategies (Podlogar & Wallis, 2022).

Several systematic reviews have been conducted to assess the impact of ketogenic diet on strength and endurance performance. For instance, one systematic review found that while ketogenic diet may enhance fat oxidation during exer-

cise, its effects on overall physical performance remain contentious. In endurance activities, results have been mixed; some studies report no significant differences in performance between those on a ketogenic diet and those consuming a mixed macronutrient diet (Murphy et al., 2021). In contrast, other studies suggest that prolonged adherence to a ketogenic diet could lead to impairments in high-intensity exercise performance due to reduced muscle glycogen availability (Ashtary-Larky et al., 2022).

When examining anaerobic performance, particularly in resistance training contexts, the evidence suggests that ketogenic diet does not significantly hinder strength gains in trained individuals. A systematic review highlighted that while there were no notable differences in one-repetition maximum (1-RM) strength tests between ketogenic and control groups, there was a tendency for slight improvements in favor of the ketogenic group (Koerich et al., 2022). However, concerns about potential reductions in fat-free mass when following a ketogenic diet persist, especially among resistance-trained athletes (Vargas-Molina et al., 2022). Paoli, (2014) described ketosis as a natural metabolic state where, instead of carbohydrates, ingested glucose acts as the key energy resource for the body. Here, the body reallocates fat as the primary energy source and breaks it down into ketone bodies, enabling it to be utilized as the main energy by most tissues, including muscles and the brain (McSwiney et al., 2019). The impacts of ketogenic diet across different health contexts necessitating personalized approaches considering athletes characteristics alongside existing clinical guidelines ensuring balanced considerations around potential risks versus benefits tailored accordingly. Ketogenic diet has been proposed as a strategy to enhance sports performance by augmenting fat oxidation during prolonged exercise. This metabolic adaptation is hypothesized to preserve glycogen stores, potentially extending endurance performance capacity (Burke, 2021; Burke et al., 2021). However, the effect of ketogenic diet on sports performance remains contentious due to mixed findings across various athletic disciplines. Thus, this narrative review aims to describe the effects of the ketosis diet on aerobic and anaerobic athletic performance.

Material and Methods

A literature search was achieved using PubMed, Medline, and Google Scholar databases to achieve this purpose. The search items consisted of related terms such as 'ketogenic', 'ketosis diet', 'performance', 'keto', 'ketone bodies', 'low-carbohydrate', 'low-fat', 'high-carbohydrate', 'high-fat', 'aerobic exercises', 'anaerobic exercises', 'fatty acids', 'body-composition', 'endurance athlete', 'weight loss', 'lactic acid', etc. Manual searches of undigitized journals, papers, and articles were also undertaken, focusing on meta-analysis re-evaluations of the ketosis diet and its role in performance optimization. We included only studies which is directly related to aerobic or anaerobic sports performance. Any study related to any other issue except sports performance was excluded form this review.

Interpretation

Recapitulation of the ketogenic diet

Research has proved that the ketogenic diet works on various mechanisms simultaneously to generate certain maximal benefits compared to other dietary regimes.

The basic function of the ketosis diet is to curb carbohydrates to produce improved insulin sensitivity (reduce insulin resistance) while lowering the risk for some chronic diseases, such as cancer, cardiovascular diseases, and diabetes. However, in the absence of the carbohydrates needed to provide the body's energy requirements, fat becomes the substitute fuel. This change is of more assistance in producing comparatively early weight loss than the loss of body mass caused by other dietary regimes. The ketogenic diet relies on using accumulated body fat and any fat derived from the food intake. The liver is active in breaking down fat to produce the three ketone bodies, one of which is BHB. Conversely, the energy molecules derived from ketone bodies provide a 'pure' source of high energy for the brain, which reduces inflammation in the central nervous system and improves mental clarity.

However, as in many other cases of dietary restriction, the ketogenic diet also has some side effects in the preliminary stages, such as fatigue, headache, dizziness, sleep disturbances, cramps, heart palpitations, and diarrhoea or constipation [1-29]. Furthermore, it is considered by some authorities in the field that reliance on a diet loaded with animal fats and proteins can lead to the risk of developing cardiovascular disease, with elevated cholesterol levels and high blood pressure (hypertension). In this context, Paoli et al. (2012) reported that most ketogenic diets have low magnesium, vitamin D, calcium, and folic acid levels. If the diet is not carefully planned, this could lead to nutrient insufficiencies. Thus, nutritionists and clinicians advocate detailed planning for optimum benefits from the ketogenic diet.

Gateway to enhanced sports performance

The purpose of the ketogenic diet has changed in the last twenty years, and it is no longer only a therapeutic procedure for treating patients. It is gaining popularity as a weight-loss regime but has also received some recognition as a performance-optimization tool for athletes. Many researchers have tried recently to confirm the positive aspects of the ketogenic diet for optimizing sports performance by boosting athletes' strength and endurance. Several studies have reported substantial increases in fat oxidation rates

among elite athletes following a ketogenic diet regimen. Burke et al. highlighted that even within elite endurance athletes, adherence to a ketogenic diet could double exercise fat use to approximately 1.5 g min^-1 (Burke, 2021). Despite these metabolic shifts favoring increased lipid utilization during submaximal exercise intensities (~70% maximal aerobic capacity), concerns arise regarding the diet's impact on higher-intensity efforts (>80% maximal aerobic capacity). Herein lies a critical limitation: keto-adaptation may impair muscle glycogen utilization during high-intensity bouts where carbohydrates are more efficiently metabolized than fats (Burke et al., 2021). Some athletes may experience enhanced endurance capabilities post-adaptation, others report deteriorated performance outcomes (Burke et al., 2021). Burke et al.'s (2017) study involving elite race walkers found that while both dietary approaches improved peak aerobic capacity (VO2 peak), only those adhering to high-carbohydrate protocols demonstrated improvements in race times—a stark contrast against their LCHF counterparts who showed no such benefit despite heightened fat oxidation capacities. Moreover, short-term adaptations to ketogenic diet can rapidly enhance fat oxidation but fail to improve or even impair endurance exercise metabolism and performance despite increased glycogen availability (Devrim-Lanpir et al., 2021). The Ketogenic diet has been shown to have numerous health benefits, including weight loss, improved blood sugar control, and reduced risk of heart disease. However, this diet has also gained attention in the athletic community as a way to optimize both aerobic and anaerobic performance. Research has shown that the Ketogenic diet can improve aerobic and anaerobic athletic performance.

Ketogenic and anaerobic exercise

Sports activities requiring intense energy expenditure for short bursts are considered anaerobic exercises. The physiological process in these exercises involves breaking down glucose for energy without using oxygen. These activities release energy within a small period but with high intensity when oxygen demand surpasses oxygen supply. The relationship between ketogenic diets and anaerobic exercise performance presents a complex interplay influenced by adaptations in fuel utilization, body composition changes, and potential impacts on high-intensity exercise capabilities. The critical examination of recent literature reveals nuanced findings that challenge traditional paradigms surrounding carbohydrate dependency for peak athletic performance.

Several studies demonstrate that adaptation to Low Crab and High Fat (LCHF) diets results in significantly enhanced fat oxidation rates during exercise (Noakes et al., 2023), with one study documenting peak fat oxidation rates over 1.5 g/min at intensities exceeding 85% VO2max (Noakes et al., 2023). This shift potentially allows for sustained energy production from fat stores even during higher intensity efforts traditionally believed to rely predominantly on carbohydrate metabolism. However, it's essential to acknowledge the variability in individual responses to such dietary interventions, as highlighted by Prins et al., who noted record-high peak fat oxidation rates alongside maintained high-intensity performance at ~85%VO2max following LCHF diet adaptation (Prins et al., 2023). Contrasting these positive outcomes are findings suggesting impairments in anaerobic performance metrics post-adaptation to ketogenic diets. Wroble et al.'s (2019) randomized-sequence crossover trial reported significant reductions in both peak power output and mean power during Wingate tests following a short-term low-carbohydrate ketogenic diet intervention compared to a high-carbohydrate diet among trained individuals. These results underscore potential limitations of ketogenic diets concerning immediate energy requirements characteristic of anaerobic activities. Moreover, Burke et al.'s investigation into elite race walkers revealed an increased oxygen cost associated with speeds pertinent to competitive events after brief keto-adaptation periods despite enhanced glycogen availability (Burke et al., 2017). Such observations suggest that while LCHF diets may improve substrate availability through elevated fat oxidation rates and glycogen conservation/storage mechanisms, they might concurrently impair exercise economy—potentially negating benefits derived from altered fueling strategies during actual competition scenarios (Tiller et al., 2019). Additionally, McSwiney et al.'s (2019) longitudinal study involving endurance athletes indicated no decrement in moderate-to-vigorous intensity exercise performance following keto-adaptation; however, decreases in exercise economy were observed above 70% VO2max. This aligns with concerns regarding the efficiency of energy utilization under ketosis at higher intensities where rapid ATP turnover is crucial. It's also noteworthy that several investigations have pointed out improvements or neutral effects on specific aspects of physical performance (e.g., sprint times) alongside favorable body composition alterations subsequent to transitioning towards lower carbohydrate intakes (Prins et al., 2019; Volek et al., 2016). Yet questions remain about long-term sustainability and broader applicability across different athletic populations given inherent study limitations including small sample sizes and short-duration interventions. In synthesizing available evidence within this contextually rich landscape fraught with contradictory findings and methodological disparities among studies (ranging from acute dietary manipulations spanning days weeks months), it becomes evident there exists no one-size-fits-all nutritional strategy suitable across all modalities intensity domains within sport-specific settings particularly when considering anaerobic versus aerobic demands distinct physiological bases underlying each mode exertion.

In this context, several studies have assessed the impact

of the Ketogenic diet on athletes' performance during anaerobic exercise in various populations. While considering various factors among endurance game players (McSwiney et al., 2018), Cross-Fit contestants (Gregory, 2017), gymnastic players (Paoli, Grimaldi, D'Agostino, et al., 2012), and power-lifters (Greene et al., 2018). Recently, a significantly increased relative power, instead of absolute or total power, has been revealed, resulting from reduced body weight among subjects (McSwiney et al., 2018) in athletes performing endurance exercises. Other studies demonstrated a reduced thickness of skeletal muscle or lean body mass (Kephart et al., 2018). A study published in the International Journal of Sports and Exercise Medicine found that athletes on a Ketogenic diet had significantly higher peak power output during high-intensity exercise than those on a high-carbohydrate diet (Gregory, 2017).

The integration of current research suggests that while ketogenic or LCHF diets can enhance fat oxidation capacity possibly offering metabolic advantages under certain conditions their application as universal ergogenic aids especially concerning anaerobic sports disciplines remains questionable due complexities surrounding individual variability metabolic flexibility impact on exercise economy overall implications for high-intensity performances requiring immediate explosive energy outputs Hence further rigorous long-term investigations are warranted better elucidate optimal dietary frameworks conducive maximizing athlete health functional capacities across diverse sporting endeavors.

Ketogenic diet and aerobic exercise

Aerobic exercise, popularly known as 'cardio', provides cardiovascular conditioning. The amount of oxygen available to the muscles for burning fuel and movement is controlled by breathing. Aerobic activity, including swimming and running, strengthens the respiratory system and increases lung capacity while maintaining a healthy heart**.** Unlike anaerobic exercises, performed using the greatest effort over a lesser time, aerobic exercises are performed at a lower intensity for a comparatively longer period. The intensity and duration of aerobic exercise (Egan & Zierath, 2013) determine the role of fatty acids in the oxidation process. In activities requiring only a moderate amount of strength, exogenic fatty acids' oxidation provides a great energy source. However, including fatty acid production increases activity duration during low-intensity activities. Continuous availability of fatty acids is required for optimal performance during endurance exercise.

For aerobic endurance activity, the ketogenic diet may be more beneficial than other diets since it encourages using fat as an energy source rather than carbohydrates. While adipose tissue fat provides an endless energy supply, internal carbohydrate storage via glucose in the liver and tissues is limited. The raised ketones from the Ketogenic diet may offer an alternative fuel source for sustaining exercise performance. Cao et al., (2021) found no significant effect of KD on aerobic capacity or exercise performance among endurance athletes through their systematic review and meta-analysis. This is echoed by Burke et al.'study (2017), where adaptation to an LCHF diet impaired performance in elite endurance athletes despite improvements in peak aerobic capacity—a result attributed to reduced exercise economy under a ketogenic state. Many studies in the past two decades observed the consequence of a low carbohydrate diet on the athlete's performance. The studies focused primarily on endurance-trained male athletes. The caloric intake from fat ranged up to 80%, with protein between 15 and 29%, and that from carbohydrates being the least, at 3.5 to 15%. Periods under study they were varied from a level of three weeks to twenty months (Burke et al., 2017; Greene et al., 2018). As a result, serum ketone body beta-hydroxybutyrate concentrations increased from 0.5 to 1.2 mmol/L. Most of the research highlighted considerable decline in body weight (Burke et al., 2021; Cao et al., 2021; Egan & Zierath, 2013; Gregory, 2017; McSwiney et al., 2019; Wroble et al., 2019). The results supported the use of the KETOGENIC DIET as an efficient dietary plan for reducing weight and balancing a sports person's physique. Although positive changes had been shown in body and fat mass in these studies, the low carbohydrate Ketogenic diet had failed effectively and significantly to improve the performance of athletes, even with a considerable decrease in respiratory exchange ratio (RER) and an increase in fatty acid oxidation. However, after examining five separate studies, it was concluded that the metabolic state of ketogenic had improved physical endurance among 39 high-performance athletes due to the ability of the body to utilize fat as a substitute source of energy for oxidative respiration (Cox et al., 2016). Muscle catabolism and plasma-lactate concentration decreased through ketogenic, providing an alternate substrate oxidation procedure. Ketogenic enhances intra-muscular triacylglycerol lipase function while exercising, in the occurrence of carbohydrates, muscle glycogen, and a raised glucose level. Another study of 20 endurance athletes had similarly noticed improved performance, with fat loss, compared to a high carbohydrate contrast group, after 12 weeks on the Ketogenic diet (McSwiney et al., 2018). Researchers found that athletes on a Ketogenic diet had significantly higher VO2 max levels than those on a high-carbohydrate diet. VO2 max measures an athlete's maximal oxygen uptake and indicates aerobic fitness (McSwiney et al., 2018). Nevertheless, clinical assessment and observational experiences from time to time have shown divergent results regarding the performance-optimization abilities of the Ketogenic diet. One review observed that increased levels of ketone bodies due to supplements may speed up muscle recovery and reduce protein

break ketogenic diet following endurance exercise (Sansone et al., 2018). Thus, using ketone esters to bring about nutritional ketogenic without restraining carbohydrate ingestion was proposed. Exogenous ketones (a class of ketone bodies ingested via nutritional supplements) correspond to an unconventional anabolism fuel resource and spare carbohydrates. They may amplify post-exercise glycogen replacement, decrease protein hydrolysis, and perform as a modulator for metabolism.

Many studies have found that the Ketogenic diet could help speed up post-workout muscle recovery. One study established self-reported improvement at the end in well-being, recovery, skin condition, and level of inflammation among five athletes following a non-calorie controlled Ketogenic diet for ten weeks (Paoli, Grimaldi, Toniolo, et al., 2012). Although, on the other hand, they experienced reductions in some other measures of performance, they did show an increased capability to consume fat as an energy source, even at high workout intensities. Mean body mass declined significantly by 4±3.1 kg, and the sum of eight skinfolds by 25.9±6.9 mm, but mean time to exhaustion showed a significant reduction of 2±0.7 minutes. Other performance parameters also showed mean reductions, but with some increases and some unchanged results in two of the five individuals: VO_2max fell by 1.69±3.4 ml.kg.min^{-} 1peak power by 18±16.4 W, and VT2 by 6±44.5 W. Interviews took place at five and ten weeks. The athletes initially reported reduced energy levels, but high levels returned, particularly throughout exercise, but there remained a lack of ability to carry out bouts of intense exercise easily.

Another study on eight competition-experienced off-road cyclists (Zajac et al., 2014) measured the long-term effects of a polyunsaturated fatty acid-rich Ketogenic diet on aerobic performance and exercise metabolism over two months. The Ketogenic diet caused a beneficial variation in physique, body mass, and lipid profile. Significantly increased maximal oxygen consumption (VO_2 max) and oxygen uptake at lactate adaptation (VO_2 LT) were attributable to increased adipose tissue oxidation or improved vasodilation. The RER was notably reduced at rest and during some phases of the test exercise protocol. Heart rate and oxygen consumption were significantly higher at rest and through the initial three stages of the test exercise protocol but lower during the last stage, carried out at maximal intensity. The results showed that, at rest and at particular stages of the test exercise protocol, there were decreased levels of creatine kinase and dehydrogenized lactate activity, which indicate muscular damage during exercise.

Studies on the Ketogenic diet revealed an association of ketogenic with reduced production of reactive oxygen species (ROS) by the mitochondria and lessened potential tissue damage while ensuring rapid recovery from injury (Volek et al., 2015). In addition, during prolonged exercise, when fatty acids are used as fuel, the brain receives a balanced supply of energy in the form of ketone bodies, which helps sustain cognitive and physical performance while bypassing the need for a high carbohydrate intake. Besides studies on human beings, a mouse study showed that muscle recovery following exhaustive exercise was improved after following a Ketogenic diet for eight weeks (Huang et al., 2018). Blood biomarkers were used to indicate injury and lactate levels of fatigue. The results suggest the potential use of the Ketogenic diet to prevent fatigue and faster recovery from injury for endurance athletes.

The positive and negative effects of the ketogenic diet on sports are shown in the figure 2 above for endurance, weight loss, and strength/power (Paoli et al., 2015). The work of the researcher, Paoli, has done much to enable sports trainers, physicians, and dieticians to achieve a better understanding of the impact of adopting this particular nutritional regime on these critical parameters. Additionally, the Ketogenic diet can improve anaerobic performance by increasing the availability of ketones for energy production. It is important to note that the Ketogenic diet may not be suitable for all athletes. This diet can be difficult to follow and may decrease energy levels and performance in some individuals. Additionally, athletes who engage in high-intensity exercise may require more carbohydrates for optimal performance.

The are few limitations in this review article as follows this review may rely on a narrow range of studies, potentially overlooking relevant research from different populations or athletic levels. The demographics of study participants (age, sex, fitness level) may limit generalizability to broader athletic populations. There may be a lack of robust evidence supporting the ketogenic diet's effects specifically on anaerobic performance. Many studies may focus on short-term effects, lacking insights into long-term impacts on performance and health. Variability in performance measurement methods across studies can make it difficult to draw definitive conclusions.

Conclusion

In conclusion, the Ketogenic diet has been shown to have numerous health benefits and can also improve both aerobic and anaerobic athletic performance. Ketogenic diet likely emphasizes that while the ketogenic diet may offer benefits for certain aspects of aerobic performance, its effects on anaerobic performance remain inconclusive. The article may suggest that individual responses to the diet can vary significantly, and further research is needed to clarify its long-term impacts and optimize dietary strategies for athletes across different sports. Overall, a balanced approach considering both the ketogenic diet, and traditional nutritional strategies may be most beneficial for enhancing athletic performance.

Acknowledgement

The authors would like to thank the Deanship of Scientific Research at Shaqra University for supporting this work.

Declaration of Interest

There is no conflict of interest among authors.

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