# Effects of Ketogenic Diet on Both Anaerobic and Endurance Athletic Performance

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**Abstract:** Glycogen storage and breakdown in the muscles are well recognized as critical metabolic processes for maintaining adequate intramuscular energy levels during extended, high-intensity activity. However, increasing evidence suggests that other substrates, such as ketone bodies, could be just as effective in producing energy during exercise. Ketosis, in which ketones are used as the primary oxidative fuel, can be achieved through a low-carbohydrate, high-fat ketogenic diet. The ketogenic diet is undoubtedly effective at facilitating weight loss with minimal loss of lean mass, and current research suggests that the ketogenic diet plays a complex role in both anaerobic and aerobic exercise performance. This review mainly focuses on the general introduction about ketogenic diet, its physiological basis, and ketogenic diet on both performances of anaerobic and endurance athletes. The underlying factors that contribute to the controversial debates will also be discussed.

## 1. Introduction

The ketogenic diet is a nutritional approach that consists of high fat and appropriate protein content but with insufficient carbohydrates to meet metabolic demands. The energy provided by the ketogenic diet was consisted of 80% of energy from daily fat intake, 15% from protein and 5% from carbohydrate, with a 4:1 lipid: nonlipid ratio. Nevertheless, some modifications have been made based on the original ketogenic diet, including lowering the lipid: nonlipid ratio or no restriction in daily energy intake with ab libitum protein and fat [1].

The ketogenic diet has gain popularity and become mainstream globally in recent years. Despite its well-established treatment effect on epilepsy, the research investigating the influence on the performances of athletes is relatively scarce, especially that for anaerobic athletes. However, the ketogenic diet plays an important role in the energy production system, which is highly associated with athletic performances. Therefore, this review aims to examine the ketogenic diet on performances of both anaerobic and endurance athletes, including Olympic weight lifting, artistic gymnasts, recreationally trained subjects and cross-country cycling. The review will undergo the format: Firstly, the general introduction about the ketogenic diet and its physiological basis. Secondly, ketogenic diet on performance of anaerobic athletes. Thirdly, the underlying factors that contribute to the controversial results. Finally, the ketogenic diet on performance of endurance athletes.

## 2. History of ketogenic diet

Physicians of ancient Greece believed that fasting and dietary regulation had been treating epilepsy at least 400 BC ago. However, the earliest published records of fasting in treatment of seizures can only be traced back in 1921, which was recorded and published by a physician called H. R. Geyelin. The published results show that unclassified patients with convulsive episodes considerably decreased

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after fasting for 3 weeks [2]. Similar results can be found in the patients of M. G. Peterman in 1925, who identified minimum daily protein needs in conjunction with the ketosis induced by high fat intake and carbohydrate restriction, and his patients turned out that more than half became no seizures, and the other half had reduced their incidence of seizures to fewer than 50 percent [3]. For the next two decades, KD remained the main effective treatment for epilepsy until the discovery and use of diphenylhydantoin in the 1940s that it was relegated to the backstage [4]. Despite trying a variety of medicines, 25–30% of people are still unable to obtain such control [5]. Therefore, diet has returned to play a role in epilepsy management for this group, particularly children.

Since the mid-1990s, when the ketogenic diet has already flourished in the United States, some medical centers, including Asian countries, have begun to use the ketogenic diet. Today, the ketogenic diet has been popularized in more than 70 countries and regions worldwide, and there are more than 200 medical centers that can provide ketogenic diet therapy [6]. Recently, the ketogenic diet has also achieved good results in treating other diseases, such as Alzheimer's disease, Parkinson's disease, nonalcoholic fatty liver disease, obesity, and range of cancers. Looking to the future, the ketogenic diet will be more widely used in disease treatment to help more people in need.

While the implementation of ketogenic diet in elite athletes is highly linked with the understanding of human metabolism and energy production, which took almost a century to research, this field has started to be explored since the early 1920s, focusing on investigating carbohydrates and glucose. A correlation between energy production & performance and carbohydrate deprivation & blood glucose was found [7]. Then the adenosine triphosphate (ATP) was identified to act as the fundamental energy currency for major biochemical functions as well as the oxidative energy utilization route (Krebs/TCA/citric acid cycle) was comprehensively studied around 1937 [8, 9]. Until 1967, the idea of intramuscular glycogen served as a primary source of energy during exercise has been demonstrated, and researchers started to recognize that the energy requirements of exercise were restricted by the glycogen store in liver and muscle [10]. Therefore, the importance of fat utilization has been emphasized as a significantly higher amount of energy is stored in adipose tissue than intramuscular glycogen stores [11]. Furthermore, Phinney et al. were the first to propose that an athlete may adjust to a low carbohydrate ketogenic diet without sacrificing performance which acts as a pioneering study about the effect of ketogenic diet on athletic performances [12]. Researches later have established that athletes can increase the power-to-weight ratio; participate in competitions at a more favourable weight level; cooperate with fitness to achieve the ultimate slim state in bodybuilding championships; improve the metabolism of endurance athletes to increase their endurance [13].

## 3. Physiological basis

Ketogenic diet induces a 'fasting-like' state and leads to firstly undergo gluconeogenesis and then producing ketone bodies (ketogenesis). Initially, to provide glucose, which is the fuel that can cross the blood-brain barrier for the central nervous system, our body starts to break down glycogen in liver and muscle or even break down muscle tissue to provide the amino acid precursors for gluconeogenesis [14]. However, gluconeogenesis is a wasting condition and is not sustainable. Then ketogenesis will be stimulated to produce ketone body primarily in liver hepatocytes which acts as an alternate fat-based fuel that does not deplete muscle protein. (Figure 1.) The ketone body is water-soluble, mainly referred to three metabolites: β-hydroxybutyrate, acetoacetate and acetone, and meet around 70% of the brain's energy demands [15].

The process of ketogenesis starts when the free fatty acids are broken down from the adipose tissue and enter the hepatic mitochondria, where the β-oxidation occurs. During β-oxidation, the ketone bodies are produced, in which the β-hydroxybutyrate is produced the highest. Then ketone bodies are released into the blood circulation and finally reach muscle through the transporter protein (monocarboxylate transporter 1) on muscle. Once inside the muscle there is a series of steps to convert the ketone bodies into acetyl-CoA, which are facilitated by ketolytic enzymes (indicated by the green cross), to enter the Krebs cycle and produce ATP for energy [16]. (Figure 2.) After the adaptation period, the body will shift to take fat as the major energy source instead of relying on carbohydrates.

It is worth mentioning that there is a certain relationship between the increase in fat oxidation by ketogenesis and the lack of muscle mass increase. This is mainly due to the extremely low levels of insulin (7 mU/L) during ketogenic period. Insulin/glucagon (I/G) ratio has been considered the key factor in liposynthesis and lipolysis. Therefore, low insulin/glucagon (I/G) ratio will in turn cause increase in lipolysis as well as fat oxidation [17]. On the other hand, insulin is fundamental for the muscle growth pathway via Insulin-like growth factor (IGF-1), Mechanistic Target of Rapamycin Kinase (mTOR), Protein kinase B (PKB) Etc., so low levels of insulin would contribute to the lack of muscle mass increase [14]. Despite the lack of muscle mass increase, maintenance of muscle mass or no decrease in lean muscle mass during ketogenic period has been indicated by a study [14]. The preservation of lean muscle mass is mainly due to a protein synthesis effect via the mTOR signaling pathway due to the relative increase of amino acid uptake in the ketogenic diet, such as leucine.

I. Dietary fat: triglyceride → fatty acid + glycerol
  A. Fatty acids
    i. Ketone bodies ("ketogenesis")
  B. Glucose ("gluconeogenesis")
II. Dietary protein
  A. Glucose ("gluconeogenesis")

Figure 1. Major fuel sources on a low-carbohydrate ketogenic diet [17]

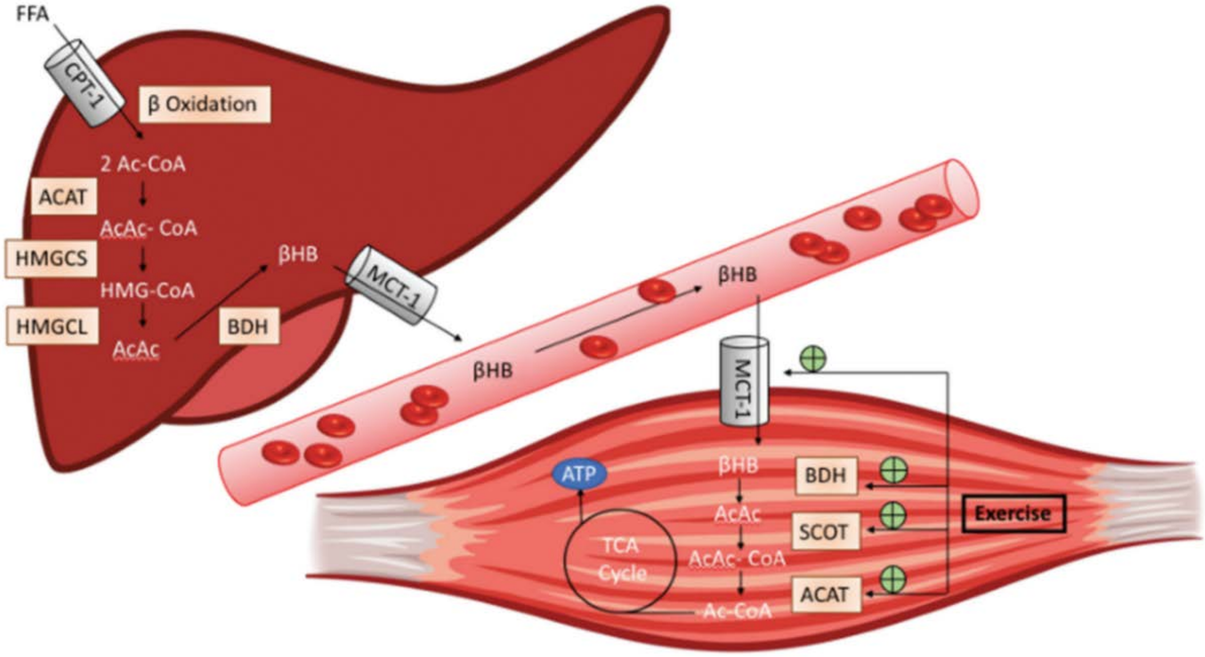


Figure 2. Overview of the metabolism of ketone bodies (KBs) in liver and skeletal muscle. AcAc, acetoacetate; ACAT, acetoacetyl-CoA thiolase; BDH, 3-hydroxybutyrate dehydrogenase; CPT-1, carnitine palmitoyl trans ferase-1; FFA, free fatty acid; HMGCL, 3-hydroxy-3-methylglutaryl-CoA lyase; HMG-Co A, 3-hydroxy-3-methylglutaryl-CoA; HMGCS, 3-hydroxy-3-methylglut arylsynthetase; MCT-1, monocarboxylate transporter 1; SCOT, succinyl-CoA/3-ketoacid-CoA transferase; TCA, tricarboxylic acid cycle; βHB, β-hydroxybutyrate [16].

## 4. Ketogenic diet on performance of anaerobic and endurance athletes

### 4.1. Ketogenic diet on anaerobic athletic performances

Anaerobic exercise is classified as high intensity and short duration exercise, such as strength and power training, depending on energy fuel mainly generated by the phosphagen system (ATP-CP system) and lactic acid system [6]. The ATP-CP system is the most rapid anaerobic energy system that can power intense muscle contraction for 5 to 6s, depending on the muscle ATP and phosphocreatine (PC) as the energy fuel [18]. However, both ATP and PC are limited, and then muscle glycogen starts to converted into lactate and produce more ATP during this process at a lower rate when compared with ATP-CP system. As a result of diet-induced muscle glycogen depletion, carbohydrate-restricted dietary methods have been thought to degrade strength and power performances as well as long-term muscle adaptation responses to training. Therefore, a high carbohydrate intake diet has been traditionally advised to the short duration and resistance exercise based on the importance of glycogen [19].

The research on the effect of ketogenic diet on anaerobic sports performance is scarce. Only a few studies evaluated that and with contradictory results. David et al. demonstrated that ketogenic diet is an effective and safe weight-reducing method when compared with other rapid weight loss strategies, such as dehydration, dramatic energy reduction and medications. It helps powerlifting and Olympic weightlifting athletes to achieve optimum power-to-weight ratio in a specific weight class and without compromising in both training quality and lifting performances [19]. Paoli et al. also proved that there is no significant difference in performance of artistic gymnasts before and after the 30 days of low carbohydrate ketogenic diet and 30 days of a typical western diet. While a significant reduction in body weight, fat mass, and fat percentage after the ketogenic diet has been observed, there is no significant difference in those indexes when gymnasts used the western diet [14].

However, there are also several studies demonstrated the adverse impact of ketogenic diet on anaerobic performance. It is worthy to mention that those essays' publish time demonstrated the negative effect of ketogenic diet on anaerobic performance are around 2000. Therefore, a scientific update about this will be needed. The recreationally trained subjects in one study showed a reduction in isotonic squat strength performance at 80% 1RM, but not isokinetic leg extension performance after taking the ketogenic diet [20]. Another study reported that low carbohydrate ketogenic diet caused a reduction in the mean power output during 30s bout of all-out exercise but without changing the maximal power output in healthy non-highly trained subjects [21]. While, another study, which also studied the healthy non-highly trained subjects, reported a slightly different result. It shows that both the mean and maximal output was reduced [22]. In general, scientists agree that the ketogenic diet is an effective weight-reducing method achieved by appetite reduction function of ketone bodies, reduction in lipid synthesis, increased lipolysis, increase in fat metabolism, and increased metabolic expenditure [14]. Unlike other traditional weight-loss strategies, such as saunas, diuretics and other medications, ketogenic diet-induced weight loss would not cause weakness, disturbance in electrolytes and water balance, and so on [1].

### 4.2 Ketogenic diet on athletic endurance performances

The ketogenic diet aims to increase fat metabolism during physical exercise by reducing the utilization of carbohydrates, which means endurance athletes will gradually adapt to a long-term low-carbohydrate diet, making free fatty acids the main metabolic fuel to slow down the rate of carbohydrate usage during activity [11]. Therefore, the depletion of muscle and liver glycogen is delayed and available late in exercise, which referred to as the sparing of glycogen effect. Furthermore, reducing dependence on glycolysis may also reduce lactic acid production, giving it a higher lactic acid threshold while reducing the accumulation of hydrogen ions and other metabolic byproducts during metabolism [23]. The reduction in glycolytic metabolism may also help save muscle glycogen reserves. This allows these athletes to produce less lactic acid under the same load. Those effects help endurance athletes to perform for longer periods of time before experiencing glycogen depletion and fatigue [24].

The increase in fat oxidation capacity is shown in the research on endurance cross-country cycling in which training sessions usually last from 1 to 4 hours, and it can be concluded that athletes have a higher mitochondrial and capillary density in their muscle which enables them to oxidize more fat [25]. Phinney et al. also observed that the usage of fatty acids increased, as shown by respiratory quotient dropped to 0.72, among well-trained athletes performing sub-maximal power exercises at 65% of $VO_{2max}$ [26]. Furthermore, there was a substantial 155 percent increase in treadmill time and a mean weight loss of 7.1kg compared to baseline. A study published by Durkalec-Michalski et al. in 2019 also showed enhancement in fat oxidation among CrossFit-trained athletes [27]. According to Figure 3, the higher number of athletes had an increase in fat metabolism than a decrease. This phenomenon is caused by promoting an adaptive response which is called mitohormesis. During mitohormesis, oxidative stress induced by mitochondrial reactive oxygen species enhances mitochondrial function, allowing them to oxidize more fat [27]. Nevertheless, the fat oxidation is only predominant at submaximal intensities at 65% or below $VO_{2max}$, while the energy system will shift to carbohydrate based fuel when the exercise intensities reach above 65% of $VO_{2max}$ [27].

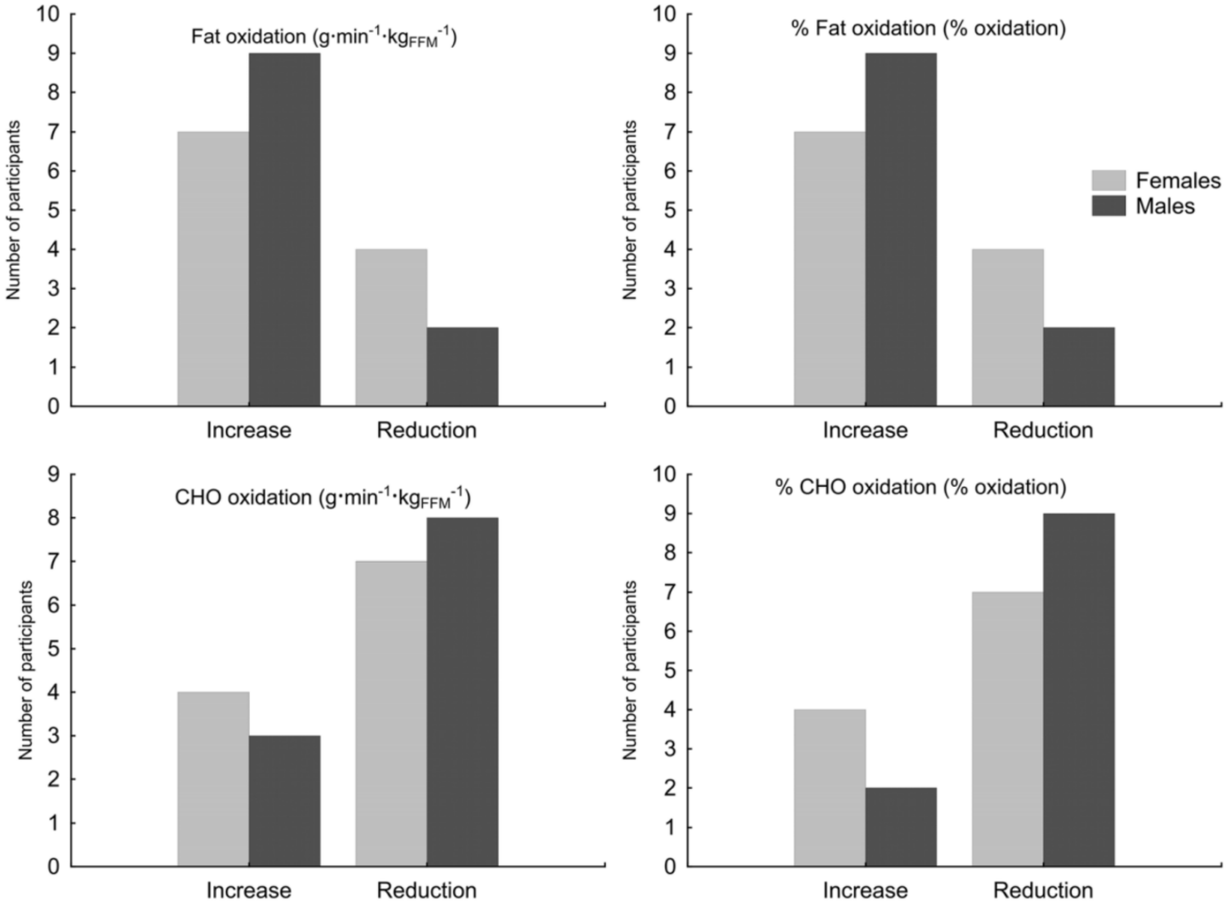


Figure 3. Numbers of female and male participants who experienced an increase or reduction in fat and carbohydrate utilization after the KD diet [27].

## 4.3 The pros and cons of ketogenic diet

Before an endurance competition, the most traditional preparation is to consume carbohydrates to increase glycogen storage. However, ketogenic diet can prevent hyperinsulinemia as well as alleviate the gastrointestinal discomfort and logistical problems caused by high carbohydrate intake [11]. In addition, ketogenic diet stands for a fat-rich diet, mainly provided by a large amount of marine fish (i.e., salmon, salmon, tuna) rich in Omega-3 fats, which can reduce inflammation, insulin resistance and muscle damage after exercise [27]. A research project observed that the activity of plasma creatine kinase (CK) and lactate dehydrogenase (LDH) activity decreased during rest and low-intensity exercise. This is through omega-3 polyunsaturated fatty acids to enhance the integrity of red blood cell membranes, improve red blood cell deformability and blood viscosity, and promote circulation and oxygen delivery to working muscles [28].

Nevertheless, despite the benefits of the ketogenic diet, several side effects of the ketogenic diet on exercise performance include dehydration, hypoglycemia, and increased risk of kidney stones. In addition, a high-fat, low-carbohydrate ketogenic diet may cause metabolic disorders, leading to acidosis, weight loss, insufficient growth, hyperlipidemia, vitamin, trace element deficiencies (zinc, selenium, and copper), hypoglycemia, hyperglycemia, Uric acidemia, anemia, and leukopenia [23].

### 4.4 The potential reasons for controversial results

The impact on both anaerobic or endurance performance is still controversial, which is mainly due to three reasons. Firstly, the study does not give the subject enough adaptation time. Based on the existing evidence, around 7 to 14 days are required to fully adapt to physiological ketosis [1]. Otherwise, a significant decrease in athletic performance would be observed. This can be explained by the concept of "keto-adaptation". The adaptation process takes time to show upregulation of key enzymes involved in oxidative phosphorylation, the citric acid cycle, fatty acid oxidation, ketosis, as well as downregulation of carbohydrate-oxidation-supporting enzymes, including pyruvate dehydrogenase [16]. The transporters for ketone bodies to enter the muscle also are upregulated. It is important to note that being in ketosis does not always simply imply that the body is burning ketone bodies efficiently. Therefore, in the early stages of a ketogenic diet, the ketones are insufficiently used and accumulated in blood circulation. If the athletes measure ketones in urine after starting a ketogenic diet, a high level of ketones is usually detected initially due to the clearance of ketones by kidney. After a period of time using ketogenic diet, the level of ketones will gradually decrease, indicating the keto-adaptation and efficient usage of ketone bodies as the alternative energy fuel. Secondly, study does not provide electrolyte supplements, as sodium and potassium are needed to maintain tissue function and nitrogen balance during a ketogenic diet [1]. This can be explained by Figure 4. Which shown that the transporters in kidneys mainly control the sodium re-absorption, and those transporters are insulin stimulated [29]. Therefore, the low insulin level during ketogenic diet causes a higher amount of sodium lost in urine and sodium supplementation is needed. Thirdly, no sufficient amount of protein is provided during the ketogenic diet, requiring higher protein intake due to gluconeogenesis, leading to the loss of muscle mass [1].

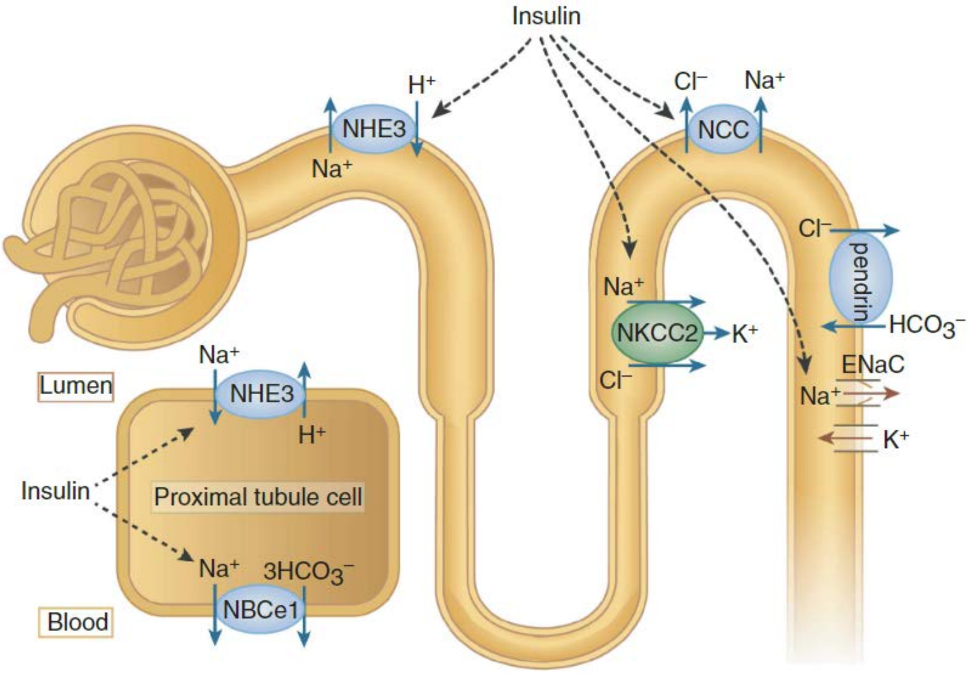


Figure 4. Effect of insulin on salt transporters in the proximal tubule, thick ascending limb of Henle, distal convoluted tubule, and collecting duct [29].

### 5. Conclusion

A ketogenic diet refers to a diet in which carbohydrate content is reduced, usually less than 20 g/d or less than 5% of total daily energy intake from carbohydrate, but a high protein and fat intake to meet daily energy consumption. Ketogenic diet in anaerobic and strength sports or sports with a strict weight-class category is usually used as a weight-loss strategy. Metabolic ketosis induced by a ketogenic diet can inhibit hunger and increase fat oxidation, thereby reducing weight. Unlike another traditional weight-loss strategy, adverse effects on health are less likely to be imposed. Endurance athletes can delay the period of time before muscle fatigue occurs by imposing the glycogen sparing effect caused by ketogenic diet.

However, the effects of low carbohydrate ketogenic diet on athletes' performance in various endurance and strength events are still controversial, so it needs further research. In most studies, the objective performance of athletes is evaluated in a laboratory environment, which is unable to reflect the true situation in the dynamic and complex environment of competitive sports. Furthermore, acknowledging the importance of statistically significant differences in performance, it should be considered that elite athletes may win due to small differences in performance. Therefore, the 95% confidence interval may not be able to capture these differences. Future studies should also take cautions with their experimental design, ensuring a sufficient period of time to allow full adaptation, sufficient electrolyte supplements and protein are provided during the ketogenic diet. This would effectively reduce the invalid experimental data and reduce the controversy in results. The ketogenic diet does not cause major health problems, but trainers, sports doctors, and dietitians must fully understand the correct steps to adopt this diet method and its advantages and disadvantages.

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