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The Effects of a Low Carb High Fat or Ketogenic Diet on Athletic Performance

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Abstract

This paper reviews the literature in ketogenic diets and athletic performance. The review aims to compare, and contrast differing scientific opinions and gain a clearer understanding of the diet's validity in athletic performance. The role of a low carbohydrate and high fat (LCHF) diet or ketogenic diet on athletic performance has created much debate in recent years. Evidence identifying that the diet fails to improve and rather diminishes performance has been discussed in literature, however advocates of the diet have found methodological flaws in research previously conducted. The purpose of this paper is to review literature surrounding the use of LCHF diets in sports performance and compare these reviews with previous literature on the efficacy of carbohydrates as a main fuel source. A total of 63 papers and scientific presentations were utilized for review. A large portion of research for the LCHF diets suggests an adaptation period lasting between 4 weeks to as high as 3 months is required before improvements start to be noticed. Studies follow a trend with improvements being more common over longer-term dietary interventions rather than short term investigations. Evidence continually shows improved fat oxidation on a LCHF; however, this phenomenon does not necessarily correlate with performance output with some investigations identifying reduced VO2max results. Alternatively, longer investigations have identified no difference between groups (i.e., no loss in performance) or in some cases an improved VO2max output. Results on power output have again showed interesting features with the diet being clearly advantageous for weight loss that is not associated with performance deterioration. Overall, the jury remains out over the effects of a diet of this nature, however there is room for collaboration between the low carbohydrate and high carbohydrate groups to create methodological sound studies that may shed more light on the actual benefits and detriments of such a diet.

Keywords: Performance, Ketogenic diet, Keto-adaptation, Low carbohydrate, High fat

Introduction

In recent years, the debate over dietary effects of reducing carbohydrate intake on health and athletic performance has increased [1,2]. Sports medicine practitioners, sports scientists and nutritionists are fervently contesting alternative theories for performance-based diets and for general health and well-being [1].

Some medical experts point to the rise of refined and processed carbohydrate intake as the main cause of obesity [1,2]. Traditional theories of poor nutrition are based on caloric surplus and the inclusion of high amounts of saturated fats in the diet [3-5]. With continued research in the field of diet and weight loss, the trend is starting to swing in the direction of low carbohydrate diets providing more prominent weight loss than traditional low-fat diets in both athletic and non-athletic populations [6,7] and therefore play an active role in a healthy lifestyle. Low carbohydrate and high fat diets have been shown to decrease basal glucose and insulin levels whilst increasing fat oxidation [8,9].

A low carbohydrate diet tends to be any diet where less than 25% of the caloric intake comes from a carbohydrate source. Whilst a very low carbohydrate diet commonly contains less than 10% of the total caloric intake [10,11]. Alternatively, the fat intake is much higher and well above what is commonly suggested [16]. The macronutrient breakdown for a low carbohydrate and high fat (LCHF) diet, commonly referred to as a ketogenic diet, is approximately 10% carbohydrates, 20% protein and 70% fats [10,11].

Further to this, a LCHF diet has also identified an alternative fuel source to glucose. Ketone bodies are the result of metabolic changes in the diet which result in the body utilizing fat stores as the predominant fuel source. Due to the abundance of fat and the rate at which fat is burnt in comparison to glucose, some researchers argue that using this dietary approach prior to sporting performance may be beneficial [9,10,12,13]. With the advent of sports science and professionalism in sport many teams have their own nutritionist involved whose primary aim is to create individualized or team dietary plans to ensure athletes body composition meet the demands of their sport and that athletes attain peak performance through nutritional fuel pre performance and for recovery post performance [14,15]. Whilst a large body of research conducted in weight loss has shown the benefits of the LCD compared with an LFD [7], there is still much debate over the efficacy of such a diet on sports performance. There is still a large body of work suggesting that carbohydrates are vital for energy output and improved performance [8,16,17]. These same studies also debunk the theory of a low carbohydrate and high fat diet being effective or equivalent to a high carbohydrate diet in performance.

The aim of this paper is to review literature surrounding the use of low carbohydrate and high fat diets (Ketogenic Diets) to fuel sports performance and compare results with previous literature on the efficacy of carbohydrates as a main fuel source.

Method

This research utilized the key search terms of 'low carbohydrate diet', 'high fat diet', 'ketogenic diet', 'fat', high carbohydrate, 'ketone adapted', 'body composition', 'sports performance', 'athletic performance', 'fat loss', 'weight loss', 'endurance athlete', 'resistance training', 'strength training' 'aerobic performance', 'anaerobic performance' and 'effective nutritional requirements for sports performance', on electronic databases including Google Scholar, PubMed and SPORT Discus as well as within The University of Sydney's Library database. Search terms were entered in a variety of combinations. Searches were also performed manually using reference lists of literature pertaining to the above topics. Throughout the search, scientific presentations were also discovered in video format and information discussed in these presentations was utilized within the discussion and conclusion. In total, a combination of 63 research articles, reviews and scientific presentations were utilized in this paper. Studies that were included had to have either compared a traditional LFD with a LCD or alternatively looked specifically at one form of diet and its effect on weight loss or athletic performance. Throughout the search, more information was discovered on the positive effects of the LCD on certain lifestyle diseases such as obesity and Type 2 diabetes. Papers fitting these criteria were also included to highlight potential health benefits of a LCD, however they were not a focus of the review. Papers studying the effect of ketogenic diets on certain conditions such as epilepsy were not utilized as they did not fit the above criteria and were excluded as they did not add relevance to the review on athletic performance. Papers published before the 1st September 2020, that fit the criteria of the research were utilized for critical evaluation and analysis.

Discussion

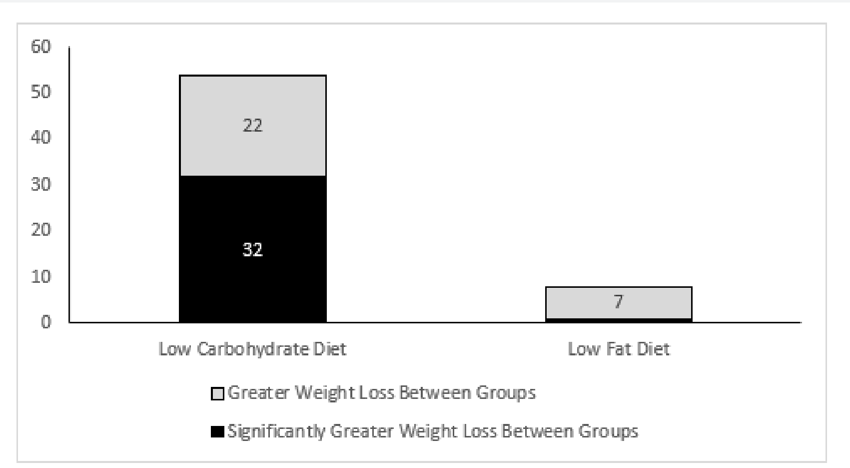

Figure 1: Weight Loss Results from 63 Published Randomized Controlled Trials Between Low Carbohydrate and Low-Fat Diets.

Despite the argument for LCHF diets in athletic performance, a large quantity of literature is now identifying the benefits for weight loss. The Public Health Collaboration tallied the results of 63 studies comparing the clinical results of low carbohydrate diets (LCD) versus low fat diets (LFD). Figure 1 summarizes the findings where, of the 63 research projects, 32 showed a significant amount of weight loss using an LCD. Another 22 of the studies identified a practical or minor improvement in the LCD. In comparison none of the LFD group showed a significant increase in the amount of weight loss and only 7 of the LFD studies revealed a practical or minor improvement in weight loss than the LCD group [7]. These results provide interesting data that may

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benefit general health and well-being and be a suitable response to the obesity epidemic associated with the standard western diet. However, these results provide little insight into the role that the macronutrients may provide in athletic performance. There is, however, some relationships to performance that will be discussed later in the paper.

Carbohydrates as the predominant fuel source for performance

It has been identified previously that carbohydrates act as a fuel source for skeletal muscle [17-19]. These findings are supported by findings from over a century of research with other studies identifying benefits in performance with carbohydrates over other macronutrients [20-23]. Results identified increased energy yields per liter of oxygen consumed, as well as the subjects believing that a set exercise regime was easier following carbohydrate ingestion than completing the same task following carbohydrate restriction. As technologies increased, later research conducted muscular biopsies which further enhanced the understanding that carbohydrate ingestion was beneficial to athletic performance [21]. Consequently, athletes have been encouraged to carbohydrate load prior to competition and for recovery purposes to take full advantage of muscle glycogen stores [20,24]. Whilst this theory has been refined to adopt to the energy requirements of a given sport or task [8,25-27], the theoretical underpinnings of exogenous carbohydrate ingestion for performance fuel has remained. This belief has become a staple in nutritional sports performance. For example, the current recommendations of carbohydrate intake are shown below in the Table 1. These amounts have been recommended by the Academy of Nutrition & Dietetics, Dietitians of Canada, and the American College of Sports [28]. According to this information, an example of a 100kg elite rugby league athlete who trains 1-3 hours per day may require up to 1kg of carbohydrates per day. The impact of such a large quantity of one macronutrient in this case is questionable [29]. With more and more data pointing to high refined carbohydrate diets adding to the obesity and type 2 diabetes epidemic [2,30,31]is there another way for athletes to fuel their performances without such high proportions of carbohydrate intake without impacting performance? In recent times some alternate theories have been proposed by some members of the scientific community including sports practitioners [1,10,11,32]. These ideas suggest that using fat as a predominant fuel source with limited carbohydrate ingestion may assist performance and recovery protocols. Because of the questions these theories pose, the debate over nutrition for sports performance has been rebooted [1].

Table 1: Prescribed carbohydrate intake in grams (g) per kilogram of body weight (kg) per day (d) as suggested by the Academy of Nutrition & Dietetics, Dietitians of Canada, and the American College of Sports.

Low intensity or skill-based activities	3-5g/kg/d
Moderate exercise program (eg ~1hr/d)	5-7g/kg/d
Endurance program (eg 1-3hr/d moderate-high intensity exercise)	6-10g/kg/d
Extreme commitment (eg >4-5 hr/d moderate-high intensity exercise)	8-12g/kg/d

Research has been conducted on the efficacy of a low carbohydrate and high fat diet (LCHF) otherwise known as a ketogenic diet as opposed to high carbohydrate diet (HCD) [8] and a periodized carbohydrate diet (PCD). This study was recognized as a 'logistical feat' [33] due to the level of athletes recruited and the controlled nature of having all athletes remain in the same venue throughout the testing procedure. In total, twenty-one [19] world class race walkers were divided into the three dietary groups. Each group was put on their specific diet for a period of three [24] weeks. During the three-week period the athletes undertook a controlled series of intense training sessions. Race performances of the athletes were tested before the training camp and at the completion of the training camp.

Findings from the study identified that the three weeks of intense training provided an increase in peak aerobic capacity in all three groups. It could be surmised that this was consistent with the training effect on the athletes. Interestingly, the LCHF or ketogenic diet group significantly increased their rate of whole-body fat oxidation achieving peak rates of 1.57±0.32g/min during 2h of walking at ~80% $\dot{V}O2$ peak compared with 1.03-1.23 g/min in the carbohydrate group, however this resulted in a reduced energy economy (-1.6%) required for race walking performance. This reduction in energy economy was not noted in either the HCD or PCD groups which led Burke et al. [8], to conclude that using a LCHF diet lessens race performance in elite endurance athletes. This result closely resembled previous outcomes [22,23], which identified that carbohydrate ingestion was associated with increased energy returns compared with a higher fat and lower carbohydrate diet. Following the publication of this research, there was noted criticism from the ketogenic advocates suggesting that the period of three weeks was not long enough for the LCHF diet group to adapt metabolically to the diet and furthermore that there were multiple micronutrients (e.g., Sodium) typically associated with a successful ketogenic diet that were not controlled or supplemented which may have confounded the results of the LCHF group.

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As a result of this criticism, Burke et al. performed another study [18], using the same methodology however increased the period of the diet to five and a half weeks to allow for greater metabolic adaptation to the ketogenic diet. The 2020 study again produced similar results to the 2017 edition with the LCHF group failing to show improvements in athletic performance whilst the HCD once again produced significant improvements [18]. According to Burke et al., this was a defining result that complemented previous results and other studies performed over the last decade [18]. Results [8,18] were like another study performed on a single world-class long-distance triathlete who suffered from gastrointestinal distress [34]. The athlete, who also happened to be vegetarian, attempted a switch from his usual HCD to a LCHF diet. Whilst performing in three professional races, his performances were significantly lower whilst on the LCHF diet and his gastrointestinal issues did not improve. Despite these findings, potential methodological flaws continue to be discussed within the LCHF community. This paper will aim to review the literature surrounding the theories of using a low carbohydrate and high fat diet in athletic performance and compare it with the contrasting literature.

Ketogenic diet

Humans have survived through a variety of environments, some as harsh as the Arctic, where carbohydrates are scarcely found in the available foods. The food available in an artic ecosystem is dense in animal fats and protein [10,11]. This sort of diet looks very similar to a ketogenic diet, high in fat and low in carbohydrates with a moderate amount of protein required for growth and development [35,36]. A general macronutrient breakdown on a ketogenic diet tends to follow the rule that 10% of the diet comes from carbohydrates, 20% from protein and 70% from fats. This breakdown varies depending on the source and can be manipulated from very low (<10% carbohydrate source) to low (<25% carbohydrate source) [10,11]. For the purposes of this review, all low carbohydrate approaches will be investigated. The basis of the ketogenic diet is that the body will adapt to using fat as its predominant fuel source rather than carbohydrates. A study conducted to investigate energy expenditure on an LCD compared to a HCD, identified this phenomenon [2]. It was established that there was an increased energy availability in LCD in comparison to the HCD which showed a reduction in energy availability. The difference noted between LCD and HCD was significant at approximately 278kcal/d which equates to roughly an hour of moderate exercise.

In terms of comparing fat and glycogen derived from carbohydrates as sources of energy, it has been established that one gram of fat is much more energy dense than a gram of carbohydrate. For example, it is presumed, that depending on the body composition of an athlete, that 600g of glycogen stored in muscle and liver amount to less than 10,000kj of energy [33,38,39]. Whilst the muscles and liver have the capacity to store glycogen, the storage level is finite, and any excess glucose exogenously consumed in the diet may be turned to fat as was discovered with carbohydrate over feeding studies [40-42]. On high carbohydrate diets energy from fats is inaccessible as fat adaptation for energy requires limiting carbohydrate intake for an extended period [43]. Alternatively, fat stores on a small and lean athlete with approximately 4 kilograms of fat can provide up to 150,000kj of energy in an appropriately fat or keto adapted athlete [33]. Because the energy provided by a molecule of fat is much larger than the energy provided by a molecule of glycogen, there is a growing belief that using fat as a predominant fuel source could be advantageous in some aspects of performance [10]. Opponents to this view argue that the glycogen molecule is more efficient at being broken down into energy and therefore is more effective even though it may provide less energy per gram in weight [39]. Whilst the argument for utilizing fat as energy develops, it is also important to highlight that fat adaptation is not instantaneous. Whilst the body is starved of glucose, the adaptation of the body to begin burning fat as a predominant source takes place over an extended period [43]. This adaptation period is known as keto adaptation. The production of ketones requires the production and use of ketones in the liver. Free fatty acids entering the liver need to be converted into ketones or beta hydroxy butyrate (βHB). βHB enters the circulation where it is transferred to the muscle and is transferred inside. Once in the muscle it is transferred to ACAT acetyl co a so that it can enter the Krebs cycle and produce ATP for energy [44]. This complex action does not mean fat is automatically turned into energy. This adaptation process takes time to occur. There tends to be a consensus that the keto adaptation period for someone who has been on a predominantly carbohydrate-based diet can take between four to six weeks [10,43]. Some studies on uric acid in the urine suggest the length is closer to twelve weeks [34]. Utilizing urine tests to measure ketones has been one form of measuring the level of ketogenic state of the body. Initial ketone level in early stages of adaptation is quite high as our body is inefficient at utilizing these for energy and uric acid content becomes much higher. Unused ketones are expelled from the body through the urine [16,35].

Whilst uric acid rises are common with the beginning a ketogenic diet [27], the level of uric acid begins to drop as the body adapts. It was identified that it takes approximately 4-6 weeks on the ketogenic diet before uric acid returns to normal levels. In some cases, however, the period before normal uric acid levels were noticed was 12 weeks [45]. This further suggests that the 3-week intervention [8]and possibly even the 5-and-a-half-week intervention [10] [18] did not allow sufficient time for the studies to provide substantial evidence. Some practitioners suggest it could be even longer before full adaptation benefits are realized [33,46]. Therefore, there is still some debate over the amount of time to become keto adapted. It could be surmised that for everyone, the keto adaptation period may differ due to genetics and the abundant variation in the human biome. This may play

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a role in the variety of outcomes presented in the scientific literature. The methodology of the dietary intervention period used by Burke et al. [8] is therefore questioned and whilst the researchers addressed this with their subsequent study [18], the five-and-a-half-week period is still only allowing for the minimal adaptation period and therefore some athletes may not have been completely adapted. Burke et al. [18] do however draw attention to previous research [43] that identifies ketone adaptation as a period of four weeks and highlights that the methodology in the 2020 edition surpasses this period.

Effects of ketogenic diets on athletic performance.

There have been several studies that have tested the hypothesis that a ketogenic diet can be beneficial on athletic performance. The following section will attempt to unpack these studies and compare previous literature that have negated any positive effects of this diet on performance. Several studies have suggested that the positive effects from a ketogenic include enhanced fat oxidation [8,18], reduced oxidative stress, better cognition, fat loss and improved power to weight ratio, immune function, cell membrane protection, stress resistance, improved recovery and reduced inflammation [9,13,47]. Presently there is little evidence to refute these claims. In fact, the argument for utilizing a ketogenic diet as a natural remedy to reverse lifestyle diseases such as obesity, type 2 diabetes and cardiovascular disease is gaining traction [2]. There is also some research around the diets assisting cognitive impairments such as Alzheimer's disease and dementia [48]. The most common form of performance-based research is founded on the assumption that LCHF diets are best suited for sports where the aerobic system is the predominant energy source utilized. This includes sports such as race walking, marathon running, triathlon. The immediate studies presented are those of Burke et al. [8,18], where the effects of the ketogenic diet provided a significant reduced energy output than the high carbohydrate alternative. As previously mentioned there has been some criticism of these studies firstly to do with the length of the study [8,18]and secondly with micronutrient content of the ketogenic diet administered [8,18,34].

In alternate studies identifying the role of ketogenic diets on athletic performance, three variations were examined. Firstly, short term effects of LCHF over a period of 1-7 days [49]. The effects identified included better fat oxidation but poorer athletic performance, especially when athletes were using higher intensities (anaerobic energy systems). These outcomes are in line with the work of Burke et al. [8]. Then over a medium term of 10 days to 4 weeks which again identified higher levels of fat oxidation by the body but this time mixed effects on performance [50,51]. These results tend to reflect again closely those found by Burke et al. [8]. however, the findings suggesting some aspects of performance improved further suggests that adaptation periods differ from person to person. Longer term effects over 4 weeks produced again improved fat oxidation, power output of athletes was improved and there was an equal or positive effect shown relative to HC approaches. These results do not tend to match those found in Burke et al. [8,18], however, there is a possible trend forming. The trend suggests that the longer an athlete is keto adapted the more beneficial the impact is on both aerobic performance and higher intensity performance. Furthermore, studies identifying the role of LCHF on strength and high intensity efforts have again provided favorable strength and intensity outcomes, with results improving over longer trials that have ranged from 4-, 9- and 12-week interventions [46,52-54].

The trend of time associated fat adaptation is further enhanced by the study of Volek et al. [13], whose study utilized 20 elite ultra-endurance athletes who had been keto adapted between a period of 9 and 36 months with a mean adaptation period of 20 months. This study involved a maximal graded exercise test and a 3-hour submaximal run at 64% VO2max. Muscle biopsies were taken at baseline before exercise, immediately after the 3-hour run and then again 2 hours later. The results again provided more evidence that a LCHF diet doubles fat oxidation (LC=1.54 + 0.18 vs HC=0.67 + 0.14g/min). It was also noted that an elite marathon runner will run at a race pace of approximately 82% VO2max. At 82% the HC athlete has low fat oxidation compared with the LC athlete (HC=0.2g/min compared with LC=>1g/min at 82% VO2max).

Interestingly, following muscle biopsies, muscle glycogen levels showed no significant differences during a rested state and both the LCHF and HC groups showed similar depletion immediately post exercise (-64%). Post exercise, the LCHF group was provided a high fat shake with a macronutrient content of C=5%; F=81%; P=14% and the HC group was provided a high carbohydrate shake with a macronutrient content of C=50%; F=36%; P=14%. Following the recovery shake and a 2-hour recovery period muscle glycogen levels were again tested showing again no significant differences between groups (-36%). These results are illustrated in Figure 2 taken from [13]. These results led the researchers to conclude that whilst a LCHF diet is preferable to fat oxidation, there are no differences associated with muscle glycogen utilization and recovery during sub maximal aerobic exercise between a LCHF diet or a HC diet. One other aspect identified during the study [13] was that longer-term keto adapted athletes were able to convert pyruvate dehydrogenase (PDH) to higher levels of lactate than HC athletes. In comparison, shorter term adapted athletes would have a much lower conversion to lactate. Lactate plays a role in gluconeogenesis to fuel performance; therefore, this process also supports the identified trend of longer ketone adaptation relating to higher performances in athletes using a LCHF diet. Due to the increases in dietary adaptation, the physiological processes of the body adapt to reduce potential performance decrements that have been identified on shorter-term studies [13].

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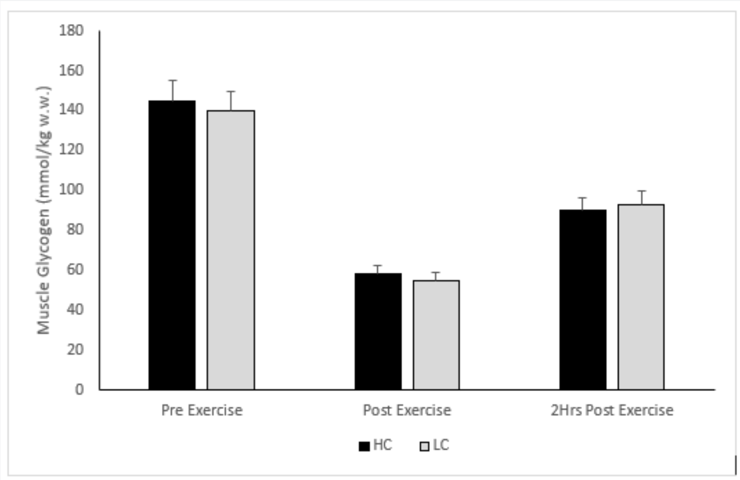

Figure 2: Mean muscle glycogen concentrations pre-exercise, immediately post-exercise, and 2 hours post-exercise. No significant differences identified between LC = low-carbohydrate diet group and HC = high-carbohydrate diet group.

Initially the positive effects of a LCHF diet were said to be on the aerobic system due to the rate of fat oxidation and the requirement of glucose to fuel ATP production. However, the effects of a LCHF diet on high intensity interval training (HIIT) was conducted with 17 moderately trained males where 9 of the group utilized a LCHF approach and the remaining 8 maintained a standard western diet. Results identified that fat oxidation increased in the LCHF group and no adverse effects on physical performance was noted [50].

In a similar study [6], it was surmised that LC (<50g CH) dietary changes in weightlifting athletes provided significantly greater weight loss (body mass -3.2kg and lean mass -2.26 kg) than usual diets (>250g CH) with no adverse reaction to lifting performances. Therefore, the researchers advocated the diets use for athletes dropping weight classes for sports that require athletes to meet certain weight targets such as weightlifting and boxing. However, in contrast to this result, it was identified that whilst it was possible to lose weight without compromising muscular strength (Table 2), it was difficult to increase muscular strength or increase lean muscle mass whilst on a LC diet in comparison to a usual Western Diet (WD) [9,51]. This outcome suggests that the diet may be successful for short term weight loss but not useful during the strength training phase.

Table 2: Performance, anthropometric and body composition results Start and End diet intervention [40].

	LC Start	LC End	WD Start	WD End
Anthropometric and Body Composition Results				
Muscle Kg	37.6 ± 3.9	37.9 ± 4.5	38.4 ± 4.1	38.6 ± 4.5
Fat Kg	5.3 ± 1.3	3.4 ± 0.8 **	5.1 ± 1.3	4.9 ± 1.1
Fat %	7.6 ± 1.4	5.0 ± 0.9 **	8.0 ± 1.3	7.7 ± 1.2
Lean body mass Kg	64.2 ± 6.5	63.1 ± 7.1	61.5 ± 4.3	61.8 ± 4.6
Lean body mass %	92.4 ± 1.4	95.0 ± 1.0 **	92.0 ± 1.3	92.3 ± 1.2
Weight	69.6 ± 7.3	68.0 ± 7.5 **	70.1 ± 6.2	70.0 ± 6.3
Performance Results				
Squat Jump	0.42 ± 0.04	0.42 ± 0.05	0.41 ± 0.04	0.40 ± 0.04
Counter Move't Jump	0.45 ± 0.04	0.43 ± 0.05	0.43 ± 0.06	0.43 ± 0.05
Reverse grip chin ups	17 ± 4.2	16.6 ± 4.6	15.2 ± 3.4	15.2 ± 5.8
Push-ups	36 ± 6.3	38.8 ± 4.7	37 ± 11.8	43.5 ± 18.1
Legs closed barrier	19.2 ± 4.96	21.7 ± 6.35	17.2 ± 5.0	16 ± 4.77
Parallel bar dips	25.8 ± 8.35	28.2 ± 9.31	23 ± 12.19	27 ± 10.61

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Another study recruited athletes form a range of sports such as triathlon, cycling and marathon [32]. The athletes were again separated into LC or HC groups for a period of 12 weeks. In this study the athletes underwent a training regime that included a combination of endurance, strength, and high intensity interval training (HIIT). As in previous studies both groups performed better following the training stimulus which would be assumed to be associated with a training effect. However, the LC group lost significantly more body fat (HC − 0.7%, LC − 5.2%; P = 0.008) associated with a reduction in body mass (HC − 0.8 kg, LCKD −5.9 kg; P = 0.006). Unlike previous studies where there was either no difference identified between groups in performance [13] or the HC group had outperformed the LC group [8,18], in this study the LC group outperformed the HC group. There was a non-significant but practical improvement in the 100km time trial with the LC group reducing their overall time by 4.07mins on average compared with the HC group improving their times by an average of 1.13mins. Peak power output on a six second sprint showed a significant improvement in the LC group with a 0.8watt per kilogram of bodyweight compared to no improvement in the HC group. A critical power test where power was measured for 3 minutes also showed a significant improvement for the LC group. This paper infers that power output is improved on a LC diet.

Another argument against the studies [8,18,34] purporting to show decremental performance in LCHF diets, was that the changes in diet may also be associated with a reduction of micronutrients. This suggests that the diets were not just low carb diet but also micronutrient reduced diets [33]. Low carbohydrate diets (and possibly vegetarian diets) [34] lead to sodium, potassium, and electrolyte losses [11]. For this reason, sodium needs to be supplemented into the diet, as a reduction in sodium can lead to poorer athletic performances. This was not taken into consideration [33]. Potassium has also been associated with poor bone mineral density and poorer athletic performance [11,13]. Again, this was not taken into consideration and could have been administered as part of the dietary intervention to increase the validity of the outcome [33]. Many practitioners identify that a low carbohydrate diet can quite easily provide high micronutrient densities as micronutrients are often more abundant in organ meats such as liver regular animal meats and low carbohydrate vegetables than refined carbohydrate sources [10,13].

Phinney has performed multiple examinations [11] on the effects of a LCHF diet on athletic performance and has gained quite favorable results suggesting that improved performance can be associated with a LCHF diet. However, one strategy that Phinney utilized, was the inclusion of the macronutrient's sodium and potassium because of the role they played in the body. The 6-week LCHF dietary intervention included no athletic training throughout the duration of the experiment, except for the testing procedures. It involved supplementation with electrolytes, sodium, and potassium. Performance testing included a VO2max treadmill test which was performed after a 2-week weight maintenance baseline diet, again after one week of the LCF diet and finally after 6 weeks of the LCHF diet [11,12]. Subjects lost a significant amount of weight (mean >10kg), so the final performance test was done using a weighted backpack to compensate for any weight lost.

The results were quite surprising, as the subjects' peak aerobic power did not decline despite being on a LC diet, as a matter of fact, there was a practical improvement in performance noted despite the additional weight being carried with a backpack. The endurance time to exhaustion was consistent with other studies, showing a reduction after one week of the LCHF diet. However, this result was reversed with a significant increase above the baseline levels at the completion of the 6-weeks. This again correlates with the idea of an adaptation period necessary for athletic performance to show improvements. These findings also suggest that both the macronutrient and micronutrient content of the diet were sufficient to preserve functional tissue and provide some strength to the argument that the studies [8,18] did not sufficiently prescribe a correct micronutrient rich diet that would support athletic function.

Conclusion and Practical Applications

Evidence is growing to suggest that there are some advantages in lowering carbohydrates to improve body composition and reduce body fat (PHC). There is also a large body of work promoting this form of eating as a natural remedy to lifestyle diseases such as obesity [2,30,40] and type 2 diabetes [2,30]. However, there is still much debate around the idea of lowering carbohydrates to improve sports performance. Without any definitive answers it could be considered clumsy or irresponsible to prescribe a LCHF diet to an athlete without considering some of the potential flaws with this approach. If a LCHF approach was to be taken the following considerations should be adhered to.

Firstly, the reasoning for administering a LCHF approach should be clearly established. As a great deal of sports promote body composition as a key performance indicator with a higher amount of lean mass being the preferred somatotype, a short term LCHF diet may be worthwhile for athletes who are required to lose weight to meet specific criteria for their sports. The use of a LCHF diet can be utilized of short-term weight loss in sports that require athletes to meet weight targets. Events such as Olympic weightlifting, boxing, and wrestling compete in weight categories and a LCHF diet has been shown to be effective for reducing fat mass without compromising power and strength in the short term [6,59]. Alternatively, a gymnast looking to reduce weight for performance reasons may also utilize this form of diet to decrease body fat and increase their power to weight ratio [51].

Another example of an athlete that may benefit from LCHF diets may be a footballer who has had a serious knee injury (such as an ACL rupture) and has had extended time out of playing and training. If this athlete's body fat percentage has increased during the rehabilitation period a LCHF diet may be a suitable option for returning to a more appropriate body composition

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required for performance. Considerations in doing this are that rapid weight loss should, in principle, be avoided. With the data we have associated with this form of diet, LCHF tends to be safer than other forms of crash dieting, such as caloric restriction and starvation diets and other forms of weight loss such as extreme sauna usage and diuretics which cause dehydration and impair performance contrary to what the athlete is trying to achieve. If planning to utilize a LCHF diet for weight loss, long-term planning and gradual body weight reduction is recommended with at least a 2-week dietary intervention necessary to avoid any negative effects on performance [51,53,57,58].

Periodic carbohydrate cycling has also been merited with performance, and provides the benefits associated with LCHF as well as the benefits of HC. An example of this being utilized in a performance model was the Major League Soccer team Columba's Crew, who utilized a low carbohydrate approach throughout the preseason and cycled moderate amounts of carbohydrates back into their squad around match performance schedules [32]. The results of this dietary intervention by their Head of Athletic Performance saw an increase in average player running meters per match over a three-year period, reduction in injuries, and an increase in time that athletes spent in high-speed running. Associated with these performance improvements was also the players mentality around performance with many players claiming they felt better eating a low carbohydrate diet [32]. The exceptional results recorded with the Columba's Crew Football team were not mirrored in a similar short-term study on basketball players where carbohydrate loading was utilized 7 days prior to performance (33). In this case no improvements were noted.

Another argument for periodic cycling of carbohydrates is the idea that athletes train low glycogen levels and compete with high glycogen levels. This idea is much like the idea of altitude training where athletes train and adapt to performing with a lower oxygen content. In this case athletes train under a stress (low glycolytic state) and once that stress is removed, due to adaptation, the performance is improved. For athletes willing to adopt a LCHF diet on a continual basis, whether this be for performance or lifestyle reasons one of the biggest considerations to factor in is the adaptation period that has been identified in the literature. Therefore, Long term versus short term goals need to be assessed, if an athlete has a major competition coming up in the short term, we note that multiple investigations identify a drop in VO2max over the short term with potential improvements being identified only after a full adaptation period has taken place. With no clear adaptation period identified within the literature this time may be anywhere between 4 weeks and 9 months [13,43]. Therefore, it would be impractical to make this dietary change for an elite athlete in the lead up to a major event. If the athlete has time to trial the diet and allow full adaptation over an extended period, this dietary intervention may be more practical.

Another consideration to factor in is the micronutrient densities required for successful adaptation and performance. Sodium (5g/d minimum as bouillon or salt in cooking) and potassium (1g/d as bicarbonate) content have been identified as vital for a LCHF diet [55]. In addition to this calcium (600mg) and magnesium (300mg) were deemed necessary along with a minimum of 2litres of non- caloric beverages (e.g., water) daily [55]. Dietary protein is also something that should be considered (15-18% of daily caloric intake or 1.75g per kg body weight) with a fat intake of approximately 83-85% of daily caloric intake and limiting carbohydrates to no more than 20g/d [12,55,56], as this was considered a potential flaw in past investigations [8,18,34].

Considering all the research that has taken place in recent years over the beneficial or detrimental effects of a LCHF diet on athletic performance, there is still further evidence required to provide certainty for both aerobic and anaerobic conditions [57-63]. The studies reviewed above demonstrate, that the use of LCHF diets in sports warrants more research. Finally, there needs to be some collaboration between advocates of the LC and HC diets so that investigations can be completed with methodological consensus within the groups. Until that is done it may be assumed that the two groups continue to perform research under methodological flaws that allow the debate to continue.

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