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Low-Carbohydrate-High-Fat Diet:
Can it Help Exercise Performance?

by
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Low-carbohydrate-high-fat (LCHF) diets have been used as a means of weight loss and control of symptoms in several clinical conditions. There is emerging evidence that the metabolic changes induced by LCHF diets enhance endurance performance. The aims of this review are to examine the evidence of LCHF diets in improving various aspects of athletic performance. Long-term LCHF dietary intake may help control body weight and fat mass while maintaining lean body mass in athletes in weight-sensitive sports. LCHF-adapted endurance athletes can reach the maximal fat oxidation rate of approximately 1.5 g/min, with a lower carbohydrate oxidation rate and similar muscle glycogen content and a resynthesis rate compared to their counterparts consuming high-carbohydrate-low-fat (HCLF) diets. The elevated fat oxidation rate and glycogen sparing effect may improve performance in ultra-endurance events. These metabolic changes may also prevent the decline in performance in later stages of repeated high-intensity movements, in which the aerobic metabolism becomes more important. However, elevated blood concentrations of non-esterified fatty acids and ammonia during exercise after LCHF diets may lead to early development of central fatigue. It appears that at least several months of adaptation to a LCHF diet are required for the metabolic changes and restoration of muscle glycogen to occur. Further investigations on LCHF diets are needed regarding (1) performance after weight loss in weight-categorized sports; (2) repeated high-intensity exercise performance; (3) development of central fatigue during endurance events; (4) perceptual-motor performance during prolonged intermittent sports; and (5) ideal dietary fatty acid compositions.

Key words: ketogenic diet, substrate metabolism, endurance exercise, repeated high-intensity exercise, central fatigue, perceptual-motor performance.

Introduction

For the past several decades, the mainstream scientific opinion on healthy diets and the recommendations for dietary intake have favored high-carbohydrate and low-fat (HCLF) diets. This position has led most countries in the world to issue dietary guidelines in favor of lowering dietary fat and increasing starch and fiber intake (Myers et al., 2013). These guidelines have largely been followed as dietary carbohydrate content has gradually increased at the expense of fat (Johnston et al., 2014). Despite the scientific and dietary progress in the recent decades, overweight and obesity have been rising among adults world-wide in parallel with type 2 diabetes (Shaw et al., 2010) and cardiovascular disease (Naghavi et al., 2015).

While the mainstream science has advocated HCLF diets, in recent decades a group of scientists, practitioners, and the general public have explored the efficacy of low-carbohydrate-high-fat (LCHF) diets such as the Atkins diet as a means of weight loss (Gudzune et al., 2015). In addition, a number of clinical studies revealed the beneficial effects of LCHF diets on a wide range of

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metabolic risk factors exceeding, or at least matching, those of HCLF diets.

A less well explored question is whether LCHF diets may exert beneficial effects on exercise and athletic performance. Despite the concept that eating a LCHF diet goes counter the traditional view that athletes require high-carbohydrate intake to maintain sufficient muscle glycogen for high-intensity and endurance performance, the efficacy of LCHF diets has been explored in various sports. There is emerging scientific evidence that LCHF diets at least maintain, if not enhance, endurance performance while at the same time improving body composition compared to HCLF diets. These results have raised the awareness that a re-examination of LCHF diets for sport performance is necessary (Burke, 2015). The aims of this review were to examine the evidence for the efficacy of LCHF diets in body composition, performance in endurance and high-intensity exercise, central fatigue, and perceptual-motor ability in athletes.

Overview of LCHF diet

LCHF diets, or ketogenic diets, usually contain less than 20% of energy from carbohydrate, more than 50% of energy from fat, and variable amounts of protein (Hession et al., 2009; Hu et al., 2012; Zajac et al., 2014). Several studies used extreme LCHF diets that contained less than 5% of carbohydrate (Langfort et al., 2004; Martin et al., 2011; Paoli et al., 2012). LCHF diets usually lead to ketosis when the liver oxidizes high concentrations of non-esterified fatty acids (NEFA) into ketone bodies, including 3-hydroxybutyrate, acetoacetate, and acetone (Owen et al., 1967; Paoli et al., 2015). The physiological ketosis from LCHF diets results in blood ketone body concentration of around 7-8 mM and blood pH of 7.4 (Paoli et al., 2015). Although the brain prefers glucose as the main energy source, it can metabolize ketone bodies as fuel for long periods of time during starvation and hypoglycemia (Owen et al., 1967). Muscles and other organs also are able to oxidize ketone bodies as an alternative source of energy when carbohydrate supply is limited. Oxaloacetate becomes a limiting factor for fat oxidation after several days of LCHF diets because of inadequate glucose availability. In order to maintain citric acid cycle function, oxaloacetate has to be

provided by deamination of glucogenic amino acids such as aspartate and asparagine. Therefore, daily consumption of between 1.3 to 2.5 g/kg of protein is necessary to ensure the maintenance of muscle mass, gluconeogenesis and fat oxidation when consuming LCHF diets (Paoli et al., 2012; Phinney, 2004).

Many studies have shown that consuming a LCHF diet over months or years does not lead to metabolic imbalances or serious adverse effects provided that it supplies sufficient energy and adequate amounts of protein (Bueno et al., 2013; Hession et al., 2009; Hu et al., 2012; Paoli et al., 2015). Contrary to the popular concept that diets high in fat would increase the risk for obesity, cardiovascular disease, and diabetes, several meta-analysis and systematic reviews document that long-term LCHF diets actually reduce these metabolic risk factors (Bueno et al., 2013; Frape et al., 1997; Hession et al., 2009; Hu et al., 2012; Sharman et al., 2004; Volek et al., 2004).

LCHF diet and body composition

One of the most popular applications of LCHF diets is weight reduction. Several systematic reviews and meta-analyses have shown that long-term LCHF diets combined with reduced energy consumption are more effective than, or at least as effective as, HCLF diets in reducing body weight and fat mass in overweight and obese populations. The weighted mean difference was -0.91 kg (Hession et al., 2009) and -1.05 kg (Bueno et al., 2013) compared to HCLF diets after 12 months or longer.

Although the advantage of LCHF diets over HCLF diets in reducing body weight may seem small, it is crucial in weight-sensitive sports. Deliberate pre-match weight loss is practiced to a great extent by athletes in such sports (Brito et al., 2012; Franchini et al., 2012). However, extreme energy restriction and dehydration practices implemented by these athletes to achieve weight loss produce acute negative energy balance, carry serious health risks, and thus may be detrimental to athletic performance (Khodaee et al., 2015). Even though some athletes may maintain physiological performance after rapid weight loss, the detrimental effects on psychological functions and mood states are still present (Marttinen et al., 2011).

The potential of LCHF diets in reducing

body weight and fat mass has drawn little attention from the scientific and athletic community. A cross-over study revealed that after 4 weeks of a LCHF diet, body weight and fat mass were significantly decreased in well-trained off-road cyclists (Zajac et al., 2014). Consuming a hypocaloric LCHF or HCLF diet for 3 weeks resulted in similar decreases in body weight and fat mass in high school taekwondo athletes (Rhyu and Cho, 2014).

In addition to fat mass, the effect of LCHF diets on fat-free mass is important to athletic success. In studies that used hypocaloric diets with the aim to induce weight loss in overweight or obese subjects, LCHF and HCLF diets resulted in similar degrees of loss in fat-free mass (Brinkworth et al., 2009b; Ruth et al., 2013). In a study that encouraged normal-weight subjects to consume adequate energy to maintain body weight, a LCHF diet led to a significant increase in fat-free mass, while a western diet did not change body composition (Volek et al., 2002).

Few studies investigated the effects of the combination of resistance training and LCHF diets on body composition. A study in overweight women suggested that a LCHF diet in combination with resistance training reduced body weight and fat mass while maintaining lean body mass, whereas resistance training in combination with a regular higher-carbohydrate diet increased fat-free mass but maintained fat mass (Jabekk et al., 2010). These changes are at least partially due to reduced anti-lipolytic insulin action and protein-protective action of increased total and free thyroxine index after a LCHF diet (Volek et al., 2002). Furthermore, a LCHF diet led to a similar magnitude increase in the muscle protein synthesis rate, activation of AMP-activated protein kinase and 4E-binding protein-1 compared to a HCLF diet after resistance exercise in rats (Roberts et al., 2016). Therefore, it is possible that LCHF diets, in combination with resistance training, can maintain fat-free mass while receiving the benefit of loss in fat mass and body weight.

LCHF diet effect on endurance exercise performance

It is well-known that the maximal fat oxidation rate is reached at moderate-intensity exercise corresponding to 59-64% VO_{2max} in endurance-trained individuals, and 47-52% VO_{2max} in the general population. The fat oxidation rate drops significantly above this exercise intensity and is almost zero above 90% VO_{2max} (Achten and Jeukendrup, 2004).

NEFA availability is one of the limiting factors for fat oxidation during exercise. At 80% of maximal effort, NEFA utilization is 30% lower than at 65% of relative effort, while muscle glycogen utilization is increased (Romijn et al., 1993). Elevating plasma NEFA by infusion of medium-chain or long-chain fatty acids significantly increases the fat oxidation rate during exercise at 40 to 80% VO_{2max}. Rates of carbohydrate oxidation and glycogenolysis are concomitantly decreased. However, endurance exercise capacity is similar despite these metabolic changes (Hawley, 2002). Excess availability of plasma NEFA by infusion of intralipid and heparin during exercise at 85% VO_{2max} restores only about a quarter of the decline in the fat oxidation rate from the maximal 43 μmol/kg/min at 65% VO_{2max}, indicating that other factors are involved in regulating fat oxidation during high-intensity exercise (Romijn et al., 1995). These other factors may include enzymes responsible for fatty acid transport across mitochondrial membrane and the free carnitine pool (Jeukendrup, 2002; Stephens et al., 2007).

Sport nutritionists have long advocated high-carbohydrate diets for athletes to ensure sufficient muscle glycogen during exercise. The inference that HCLF diets are better than LCHF diets for endurance performance was generated in studies contrasting the short-term (less than 2 weeks) effects of exposure to HCLF and LCHF diets. Indeed, in the absence of long-term adaptation, reduced muscle glycogen content after LCHF diets leads to hypoglycemia, impaired endurance performance (Karlsson and Saltin, 1971; Walker et al., 2000), and an increased feeling of fatigue (White et al., 2007). These results led to the current guidelines for high-carbohydrate intake for athletes.

However, endurance performance, measured by time trials after fixed-intensity prolonged exercise, was maintained in elite cyclists when muscle glycogen was restored with a 1-day high-carbohydrate diet after 5-6 days of a LCHF diet (Burke and Hawley, 2002). Even such short-term consumption of a LCHF diet resulted

in a significantly higher fat oxidation rate of 0.7 to 0.8 g/min and a lower carbohydrate oxidation rate of 2 to 2.3 g/min during exercise at 70% of $VO_{2\,max}$ in these highly-trained endurance athletes, compared to those who consumed a HCLF diet during the study period (Burke and Hawley, 2002). The glycogenolysis rate and pyruvate dehydrogenase activity were also lower compared to a HCLF diet, during prolonged and sprint cycling after such dietary intervention (Stellingwerff et al., 2006).

Long-term adaptation to LCHF diets produces even greater metabolic benefits, including a higher rate of fat oxidation and lower rates of carbohydrate oxidation and glycogenolysis. Endurance athletes who adapted to LCHF diets for 9-36 months could reach the maximal fat oxidation rate of approximately 1.5 g/min at about 70% VO_{2max} (Volek et al., 2016). This value is higher than what carbohydrate-adapted endurance athletes ever reported (~1.0 g/min) (Venables et al., 2005). Several researchers have suggested that long-term LCHF diets may be as effective, or even beneficial in many aspects of endurance performance as HCLF diets while providing several metabolic advantages in athletes (Brukner, 2013; Burke, 2015; Noakes et al., 2014; Paoli et al., 2015; Volek et al., 2015). Large decreases in the carbohydrate oxidation rate (from 15.1 to 5.1 mg/kg/min) and muscle glycogen utilization rate (from 0.61 to 0.13 mmol/kg/min) without compromising the time to exhaustion at moderate intensity were found after consuming a LCHF diet for 4 weeks in well-trained cyclists (Phinney et al., 1983). Even though these athletes had lower resting muscle glycogen levels after consuming a LCHF diet, the post-exercise level of muscle glycogen was similar to that before the dietary intervention.

Surprisingly, a recent study (Volek et al., 2016) revealed that ultra-endurance athletes who had consumed LCHF diets (<20% energy from CHO, >60% from fat) for at least 6 months achieved higher peak exercise intensity supported by fat oxidation than athletes on HCLF diet (LCHF: 70.3 ± 6.3; HCLF: 54.9 ± 7.8% VO_{2max}). These fat-adapted athletes also showed a higher fat oxidation rate (LCHF: 1.54 ± 0.18; HCLF: 0.67 ± 0.14 g/min) and a lower carbohydrate oxidation rate during prolonged exercise at 64% VO_{2max}. They also had similar muscle glycogen contents at

rest (approximately 140 mol/g wet tissue) and immediately after a 3-hr run at 65% VO_{2max} (approximately 50 mol/g wet tissue) compared to their counterparts consuming normal or HCLF diet. It is noteworthy that the glycogen resynthesis during the 2-hr post-exercise recovery remained the same in both groups (LCHF: 44.8 ± 7.5; HCLF: 34.6 ± 23.9 mol/g wet tissue) despite the fact that the LCHF group consumed only 5% carbohydrate, while the HCLF group consumed 50% carbohydrate during that period. This study indicated that endurance athletes could maintain normal muscle glycogen content, utilization and recovery after long-term adaptation to LCHF diets. These metabolic adaptations to LCHF diets may benefit endurance performance. Thus, it has been hypothesized that long-term LCHF diet may enhance performance in ultra-endurance events such as the ultra-marathon and ironman triathlon by supporting a higher fat oxidation rate at higher relative exercise intensity and by having a glycogen sparing effect (Langfort et al., 1996). In these events, the LCHF-adapted athletes may be able to maintain higher relative exercise intensity during most of the distance, while preserving muscle glycogen for sprints at the later stage of competitions. Future studies may evaluate endurance performance in LCHF-adapted athletes using a race-like design, rather than constant workload protocols.

Subcellular changes that support skeletal muscle adaptation to LCHF diets include upregulation of enzymes involved in fatty acid oxidation such as β-hydroxyacyl CoA dehydrogenase (Cameron-Smith et al., 2003), fatty acid translocase/CD36 (Cameron-Smith et al., 2003), and carnitine palmitoyl transferase-1 (Goedecke et al., 1999), and downregulation of enzymes supporting carbohydrate oxidation such as pyruvate dehydrogenase (Chokkalingam et al., 2007). These enzymatic changes after LCHF diets may account for the increase in the fat oxidation rate. The potential effects of long-term adaptation to LCHF diets on endurance performance are presented in Figure 1.

LCHF diet effect on high-intensity exercise

Exercise above 70% VO_{2max} requires significant energy from the anaerobic metabolism (Brooks and Mercier, 1994). A single bout of short-

term high-intensity exercise mostly utilizes energy from creatine phosphate and glycolysis (Gaitanos et al., 1993b). Therefore, an elevated fat oxidation rate after adaptation to a LCHF diet is unlikely to increase performance in this mode of exercise.

In many field-based sports such as soccer, rugby, basketball, and hockey, the ability to perform multiple sprints at the highest speed after short rest is crucial for game performance (Rampinini et al., 2007; Ross et al., 2015; Spencer et al., 2005). Although a single sprint relies mostly on the anaerobic metabolism, repeated sprints significantly increase the demand for the aerobic metabolism during the later stages of exercise. In 10 x 6-s sprints separated by 30 s rest periods, the anaerobic metabolism provided most energy in the first sprint, but it fell to approximately 60% in the last sprint (Gaitanos et al., 1993a; Girard et al., 2011). On the other hand, the proportion of energy from the aerobic metabolism increased from almost zero in the first sprint to 40% in the last one (Girard et al., 2011). A 4-fold increase in plasma glycerol in combination with a much smaller increase in plasma NEFA during intermittent sprints also indicated a significant contribution of fat utilization and the aerobic metabolism (Chang et al., 2015; McCartney et al., 1986). In addition, subjects with greater aerobic capacity are more able to maintain power output during later stages of repeated sprints (Bishop and Edge, 2006; Brown et al., 2007). Thus, the increased fat oxidation rate and muscle-glycogen sparing effect after long-term adaptation to LCHF diets may be helpful to maintain and/or improve performance in latter stages in these sports.
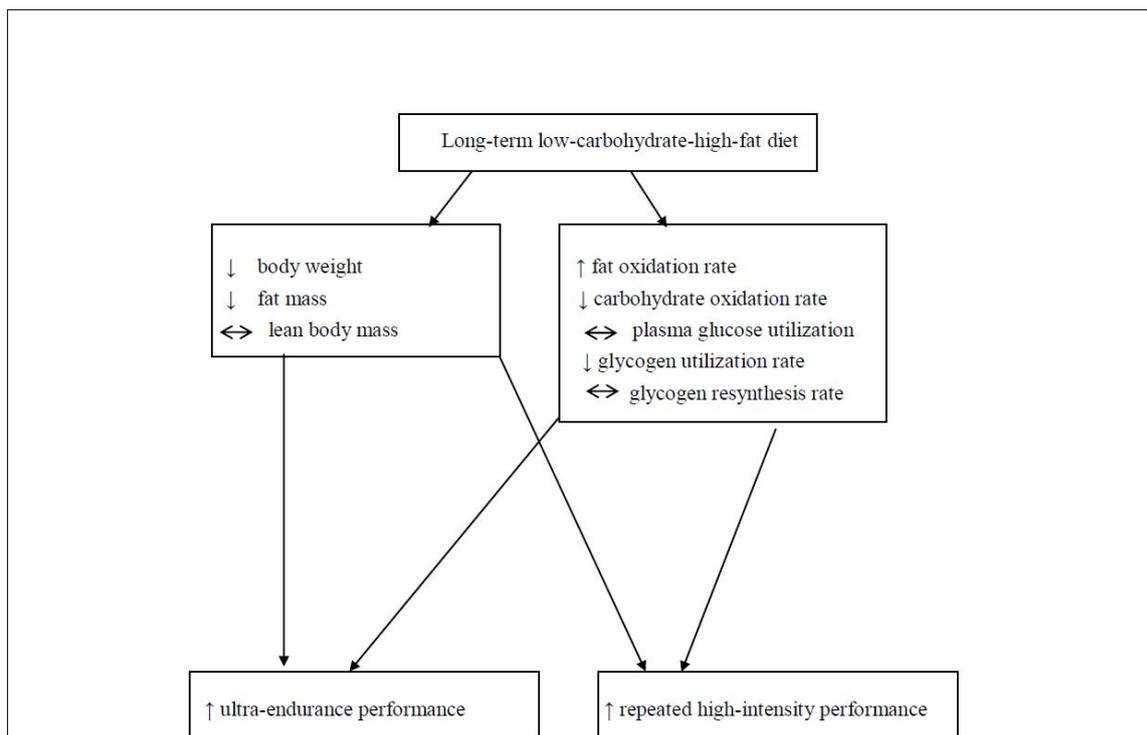

Figure 1

Potential mechanisms to improve endurance and repeated high-intensity exercise after long-term adaptation to low-carbohydrate-high-fat diets
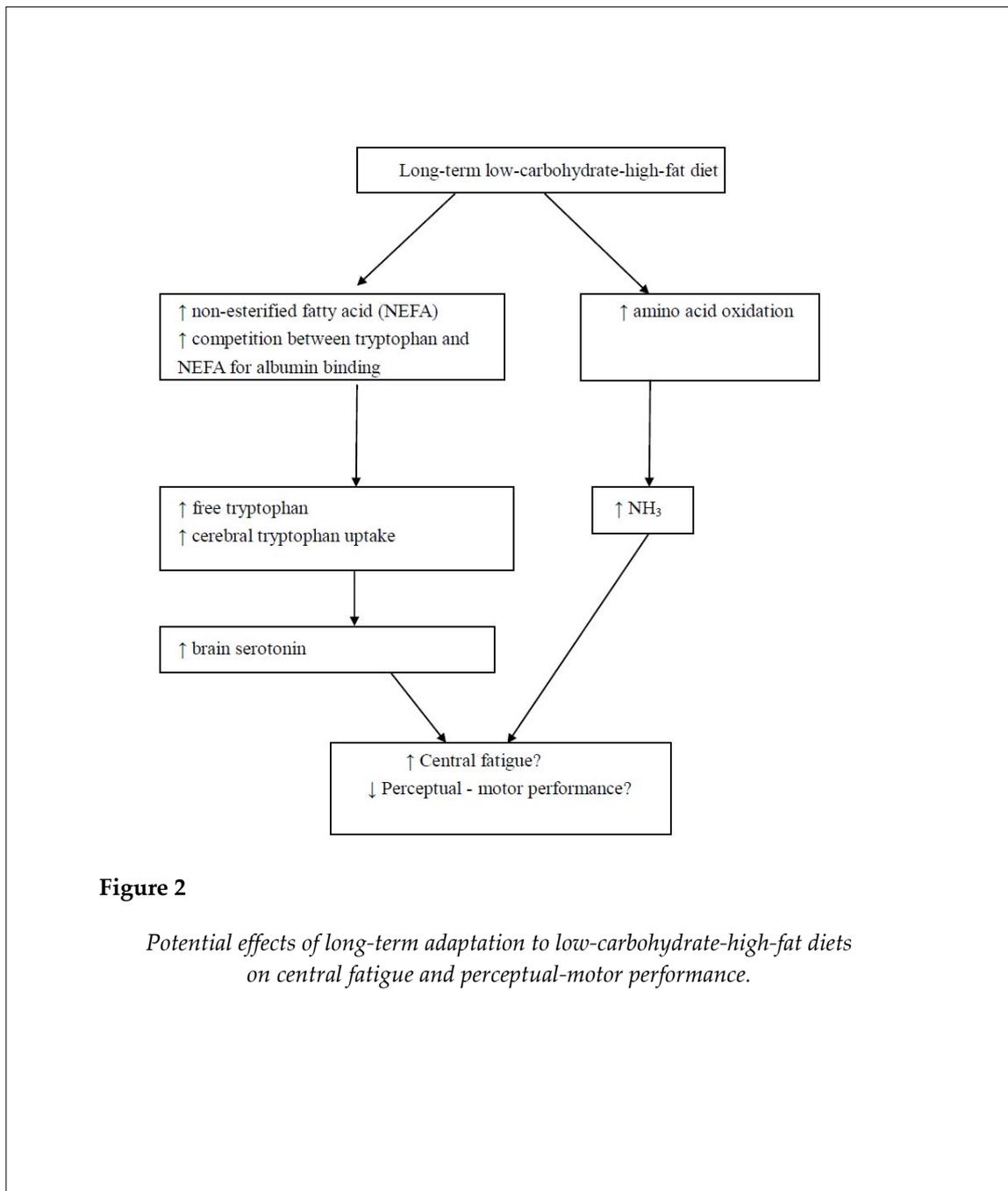
Figure 2

Potential effects of long-term adaptation to low-carbohydrate-high-fat diets on central fatigue and perceptual-motor performance.

Only a few studies have examined the impact of LCHF diets on high-intensity exercise. Several of them failed to account for the changes in body weight and/or body composition associated with LCHF diets when evaluating exercise performance. Maximal repetitions of exercises that support body weight, such as push-ups and chin-ups, are widely used for regular monitoring of strength performance. However, performance of these exercises depends on strength as well as endurance factors and can be affected by body weight and composition. The maximal height in squat jumps can also be affected by body weight and composition. Thus, caution should be taken in interpreting the results that are not normalized to body weight.

It has been shown that elite male gymnasts maintained maximal repetitions of push-ups, reverse grip chins, and parallel bar dips after 30 days of a LCHF diet while experiencing significantly reduced body weight and fat (Paoli et al., 2012). In another study, combining a LCHF

diet for 3 weeks with a 25% energy restriction resulted in the loss in lean body mass and impairment in anaerobic performance measured by the Wingate test in high school taekwondo athletes (Rhyu and Cho, 2014). It is noteworthy that performance requiring greater endurance capacity such as a 2000 m sprint, and a fatigue index in the Wingate test were actually increased in the LCHF group. Zajac et al. (2014) reported that maximal power output was significantly decreased after consuming a LCHF diet for 4 weeks in well-trained off-road cyclists. However, the LCHF diet also resulted in lower body mass and body fat, and increases in VO2max and VO2 at lactate thresholds. The decrease in maximal power output, expressed as W, was not normalized to body weight to account for its change after the diet manipulation (Zajac et al., 2014). Future studies should normalize the results to body weight or fat-free mass in power and strength performance, as in high-intensity repetitive exercise, such as W/kg in squat jumps, in order to clarify the changes.

The potential effects of long-term adaptation to LCHF diets on repeated high-intensity exercise performance are shown in Figure 1. More research is needed to elucidate whether long-term adaptation to a LCHF diet would affect repeated sprint performance in field-based sports, especially in later stages of the competition.

LCHF diet effect on central fatigue

In addition to the aforementioned physiological changes in the muscle, the metabolic changes induced by long-term LCHF diets may also affect the central nervous system during exercise (Figure 2). The role of the central nervous system in the development of physical fatigue has long been recognized (Asmussen, 1993; Gandevia, 2001). Alterations in the metabolic fuel use during exercise after adaptation to a LCHF diet can affect cerebral amino-acid uptake, the energy metabolism, and neurotransmission. The increased rate of fat oxidation during exercise after adaptation to a LCHF diet is likely to increase brain uptake of free tryptophan. This is the consequence of increased competition for binding to albumin by rising concentrations of NEFA. Free tryptophan is the precursor of serotonin (5-hydroxytryptamine), a brain

neurotransmitter associated with the feeling of lethargy and tiredness that may contribute to the loss of central drive and motivation (Davis and Bailey, 1997). Increased brain uptake of free tryptophan has been reported to favor cerebral serotonin synthesis and contribute to central fatigue (Pardridge, 1998).

High protein content of LCHF diets also leads to elevated ammonia production during exercise (MacLean et al., 1996; Meeusen et al., 2006; Struder et al., 1998). Ammonia is another factor that could induce central fatigue by altering the cerebral energy metabolism and neurotransmission, and affect signaling pathways within the neural circuits (Mutch and Banister, 1983; Wilkinson et al., 2010). Subjects adapted to LCHF diets experienced higher plasma concentrations of NEFA and ammonia, two agents contributing to central fatigue, during exercise at various intensities (Langfort et al., 1996, 2004). A pilot study with untrained adults consuming a hypocaloric LCHF diet for 2 weeks suggested that increased blood concentration of ketone bodies was associated with the feeling of fatigue and disturbance of the mood during submaximal exercise, indicators of central fatigue (White et al., 2007). There is currently a knowledge gap regarding the possible effect of long-term adaptation to LCHF diets on central fatigue in various types of exercise that is in need of additional research.

LCHF diet effect on perceptual, cognitive and motor functions

Perceptual-motor performance, i.e., the ability to better anticipate opponent's movements, plan appropriate strategies and activate the musculoskeletal system to execute necessary actions, is a major factor that separates experts from non-experts in many sports (North et al., 2009). These skills require high levels of perceptual, cognitive and motor abilities. Consuming LCHF diets for 1-2 years was reported to slightly improve certain cognitive functions and mood states in middle-aged overweight subjects, compared to HCLF diets (Brinkworth et al., 2009a; Halyburton et al., 2007). A recent animal study also suggested that ketone bodies may protect against obesity-induced cognitive impairment (Davidson et al., 2013). However, these studies used simple cognitive tests that are

not related to athletic competitions. There is evidence that central fatigue may contribute to the decline in perceptual-motor performance during exhausting exercise (Chen et al., 2016; Yang et al., 2016). Whether a long-term LCHF diet would increase central fatigue and subsequently impair perceptual-motor performance in athletes is still unclear.

Conclusions and future directions

Long-term LCHF diets appear to be safe and may even improve several metabolic risk factors for chronic diseases in the general population. LCHF diets provide a promising way to help control body weight and fat mass while maintaining lean body mass in athletes engaged in weight-sensitive sports. There is emerging evidence that LCHF diets could be beneficial, particularly for performance in ultra-endurance sports. Their effect on field-based sports that require repeated high-intensity activities is also promising. It appears that at least several months of adaptation to a LCHF diet are required for the metabolic changes and restoration of muscle glycogen to occur. However, some aspects regarding the effects of long-term LCHF diets in athletes are still unexplored and in need of investigation, including:

1. Strength, power, psychological status, and perceptual-motor performance after weight loss, especially in weight-categorized sports such as wrestling, judo and taekwondo.

2. Performance in repeated high-intensity exercise in field-based sports such as soccer and basketball.

3. The development of central fatigue during endurance events.

4. Perceptual-motor performance during prolonged intermittent sports such as tennis and soccer.

5. The ideal composition of saturated, monounsaturated and polyunsaturated fatty acids in LCHF diets.

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