

Impact Of Ketogenic Diet On Athletes: Current Insights

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Abstract: The impact of a ketogenic diet (KD) (<50 g/d carbohydrate, >75% fat) on athletic performance has sparked much interest and self-experimentation in the past 3–4 years. Evidence shows 3–4-week adaptations to a KD in endurance-trained athletes were associated with maintenance of moderate (46–63% VO_{2max}) and vigorous intensity (64–90% VO_{2max}) endurance exercise, while at intensities >70% VO_{2max} , increases in fat oxidation were associated with decreased economy (increased oxygen consumption), and in some cases, increased ratings of perceived exertion and heart rate. Two investigations in recreationally active endurance athletes noted no vigorous intensity exercise decrement following 3- and 12-week adaptations. Moderate (70–85% one repetition maximum) and near-maximal to maximal intensity (>85% 1RM) strength performance experienced no decrement following a 3-12-week KD adaptation. Beneficial effects were noted for 2000 m sprint and critical power test completed for short duration at vigorous intensity, while two additional tests noted no decrement. For sprint, near-maximal exercise (>91% VO_{2max}), benefit of the KD was observed for six-second sprint, while no decrement in performance was noted for two additional maximal tests. When protein is equated (grams per kilogram), one investigation noted no decrement in muscle hypertrophy, while one noted a decrement. One investigation with matched protein noted the KD group lost more body fat. In conclusion, moderate-to-vigorous intensity exercise experiences no decrement following adaptation to a KD. Decreases in exercise economy are observed >70% VO_{2max} in trained endurance athletes which may negate performance within field settings. Beneficial effects of the KD during short duration vigorous, and sprint bouts of exercises are often confounded by greater weight loss in the KD group. With more athletes pursuing carbohydrate-restricted diets (moderate and strict (KD)) for their proposed health benefits, more work is needed in the area to address both performance and health outcomes.

Keywords: keto-adaptation, performance, endurance, strength, high intensity, low carbohydrate

Introduction

Exercise lasting more than a couple of minutes in duration is fueled by a combination of intra-muscular and extra-muscular carbohydrates, and lipids, with minor contribution from amino acids.¹ Since the introduction of muscle biopsy technique for determination of human muscle metabolism in the 1960s, it has been widely accepted that possessing high-levels of pre-exercise muscle glycogen is a precursor for optimal athletic performance.² Sports nutrition guidelines have reflected this, recommending carbohydrate-based diets,³ and more recently, periodized carbohydrate-based diets,⁴ to optimize athletic performance for an array of sports and physical endeavors.

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Interest in low-carbohydrate alternatives grew following publications by Phinney and colleagues in the 1980s, demonstrating, overweight patients⁵ and well-trained cyclists⁶ could sustain exercise capacity at submaximal intensities following 21–28 days of a low-carbohydrate ketogenic diet (KD), respectively. A KD is characterized by low-carbohydrate (<20–50 g/d), moderate protein and high-fat (>75–80% energy) intakes,^{7,8} with prioritization of monounsaturated and saturated fatty acids recommended⁷ and observed within the literature.⁹ Following preliminary KD work,^{5,6} through the years 1995–2005, extensive work examined acute (<5 days) low-carbohydrate, high-fat (LCHF) diets (~25% carbohydrate energy, >60% fat energy). This work attempted to increase fat oxidation during submaximal exercise, i.e., slow the oxidation of finite carbohydrate stores, and sustain near-maximal performance through increased carbohydrate availability, stemming from less oxidation at submaximal intensities. Despite increased fat oxidation, and maintenance of glycogen stores, no clear performance benefits were noted.¹⁰

More recently, a KD has (re)grown¹¹ in popularity, following popular publication in lay press,⁷ and within peer-reviewed literature.^{10,12} Similar to an LCHF diet, a KD is associated with an elevation in circulating free fatty acids. Due to relative glucose deprivation attributing from greater carbohydrate restriction, a KD is associated with an elevation in ketone bodies, namely, acetone, acetoacetate (AcAc) and beta-hydroxybutyrate (βHB).⁸ βHB is the primary ketone body found in peripheral tissues, and in circulation, therefore, it is a common measure of ketogenesis and dietary adherence.⁸ Its elevation represents the balance between hepatic production and peripheral breakdown, with values of 0.5–3.0 mM βHB demonstrating “nutritional ketosis”.^{7,8} During nutritional ketosis, ketones bodies replace glucose as the primary fuel source for peripheral tissues, such as the brain and heart.⁸

Whether nutritional ketosis yields any tangible performance benefits to athletes is a contentious subject within nutrition science.^{10,12} This academic debate has brought about several investigations in an array of athletes, including endurance athletes, resistance-trained athletes, and CrossFit trainees. The aim of this review is to examine the KD performance literature to determine if performance benefits exist for athletes and recreationally trained athletes, and to provide some clinical insights as to the place of LCHF and KDs in athletes.

Materials And Methods

Literature Search

Keyword searches took place on electronic databases including PubMed and SPORTDiscus. Search terms included “performance”, AND “ketogenic”, AND “keto”, AND “keto-adapted”, AND “carbohydrate”, AND “fat”, AND “low-carbohydrate”, AND “high-fat”, AND “low-fat”, AND “high-carbohydrate”, AND “body composition”, AND, “hypertrophy”, AND “fat loss”, AND “weight loss”, AND “endurance athlete”, AND “resistance training”, AND “powerlifting”, AND “Olympic weightlifting”, AND “athlete”. Search terms were entered in several combinations. Manual searches were conducted using reference lists of existing narrative, and meta-analytic reviews on LCHF/KD performance literature.

Study Selection

Study selection criteria were as follows: 1) a controlled KD trial, defined by a) dietary analysis indicating <50 g/d carbohydrate and/or b) ketone bodies (>0.5 ± 0.1 mM βHB);^{7,8} 2) within a trained or recreationally trained athlete population, 3) measured cardiorespiratory or musculoskeletal physical fitness,¹³ a) cardiorespiratory fitness at moderate intensity (46–63% maximal oxygen consumption (VO_{2max})), b) cardiorespiratory fitness at vigorous intensity (64–90% VO_{2max}), c) short duration (>30 s, <60 mins) vigorous exercise (64–90% VO_{2max}), d) sprint-near maximal exercise (<30 s) (~91% VO_{2max}), e) strength at moderate (50–69% one repetition maximum (1RM)) to vigorous intensity (70–84% 1RM), f) strength at maximal intensity (>85% 1RM), or g) body composition with matched protein intakes (% energy, or g·kg).

Participant Classification

To improve the translational quality of this work, and because differences in ketone metabolism are reported between trained and untrained persons,⁸ groups will be classified according to training status.¹⁴

Cardiorespiratory Fitness

Participants were categorized as, a) trained athletes and b) recreationally trained athletes, according to how original manuscripts defined training status. Classification according to traditional standards (VO_{2max}, peak power output, etc.)¹⁴ is not possible, as many investigations either failed to appropriately assess VO_{2max} or peak power output, or, contained males and females, and gender-specific values were not described.

Strength And Body Composition

Investigations containing participants for strength and body composition assessment were categorized as (a) trained and (b) recreationally trained, due to varying dose responses observed by both populations.¹⁵

Exclusion Criteria

Study exclusion criteria were as follows: 1) implementation of a KD, but report a carbohydrate intake >50 g/d, 2) case study, or 3) cross-sectional study, 4) recreationally active endurance athletes with $VO_{2max} < 50.0 \text{ mL}\cdot\text{kg}\cdot\text{min}^{-1}$, and 5) participants >50 years of age.

Results

Thirteen investigations met the inclusion criteria and are presented in Tables 1–4 as follows: Table 1: Endurance; Table 2: Strength; Table 3: Short duration and Table 4: Body composition.

Endurance Performance

Moderate Intensity (46–63% VO_{2max})

Endurance-trained athletes experienced no decrement in endurance capacity following 28-day adaptation to a KD (Table 1A).⁶

Vigorous Intensity (64–90% VO_{2max})

Endurance-trained athletes adhered to a KD for 21–31 days, and maintained time to exhaustion (TTE) at 70% VO_{2max} , and 10 km TT performance (Table 1B).^{16,17} Recreationally trained endurance athletes experienced no decrement to endurance performance following 21–84 day KD adherence (Table 1C).^{18,19}

Strength Performance

Moderate (50–69% 1RM) To Vigorous Intensity (70–84% 1RM)

No decrement in strength endurance and power, and isometric strength were observed following 3–4 weeks of a KD in trained gymnasts and taekwondo athletes (Table 2A).^{20,21}

Near-Maximal To Maximal Intensity (>85% 1RM)

Resistance training coupled with a KD for 10–12 weeks maintained 1RM back squat, bench press, clean, jerk, and deadlift performance within trained athletes (Table 2B).^{22,23} Recreational athletes experienced no decrement in 1RM back squat, bench press and max press-ups (Table 2C).²⁴

Short-Duration Performance

Vigorous Intensity (64–90% VO_{2max} , >30 s)

Beneficial effects for 2000 m run performance were noted following 21-day adaptation within trained taekwondo athletes (Table 3A).²⁰ No decrement to 400 m outdoor run, graded exercise test TTE and 5 x 3 min interval sprints were observed within recreationally trained athletes (Table 3B).^{19,24–26} Beneficial effects for completion of CPT were observed following 12-week adherence within recreational endurance athletes (Table 3B).¹⁹

Sprint-Near Maximal Exercise (>91% VO_{2max} , <30 s)

Wingate and 100 m sprint performance experienced no decrement following 21-day adaptation within trained athletes (Table 3C).²¹ Six second (SS) sprint performance improved,¹⁹ and 30–15 sprint performance experienced no decrement following 12-week KD adherence within recreationally trained athletes (Table 3D).²⁶

Body Composition

Knowledge relating to the KD and muscle hypertrophy is mixed; an investigation within trained athletes noted no decrement (Table 4A),²² while an investigation within recreationally trained athletes noted a decrement (Table 4B).²⁷ Body fatness remained unchanged within trained athletes (Table 4A), while recreationally trained athletes consuming a KD experienced decreases in body fat (Table 4B).

Discussion

Endurance – Moderate Intensity (46–63% VO_{2max})

Trained Athletes

Phinney demonstrated that 28 days of a KD was a sufficient duration to retool the muscle mitochondria to sustain endurance capacity at moderate intensity (Table 1A).⁶ One of the arguments put forward for endurance athletes to consume a KD is humans' limited stores of carbohydrate (~2200 kcal) versus fat (~30,000 kcal in someone with 7–14% body fat).¹² It was hypothesized that athletes would have a greater capacity to complete moderate-intensity exercise, relying on a combination of free fatty acids, ketone bodies, muscle and hepatic glycogen, and increased glucose from fat- and protein-derived precursors (gluconeogenesis), when keto-adapted.^{7,12} Despite achieving nutritional ketosis and increased lipid oxidation, endurance capacity remained limited by glucose availability (Table 1A).⁶ Prior to the commencement of exercise, glycogen stores were reduced by

Table 1 Endurance Capacity In Athletes Consuming A Ketogenic Diet At A Variety Of Intensities

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
IA. Endurance capacity in trained endurance athletes consuming a ketogenic diet (KD) at moderate intensity (46-63% VO_{2max})				
Phinney et al, ⁶ Well-trained male cyclists >65 mL·kg·min ⁻¹ Crossover design with order effect (control first)	4 weeks (28 days) HC (n=5: 57% CHO, 29% fat, 14% protein); KD (n=5: <20 g CHO, 85% fat, 15% protein)	Yes βHB 1.16-2.44 mM	TTE at 63% VO _{2peak} Fasted	No decrement TTE 151 mins KD vs 147 mins HC (p>0.05)
IB. Endurance capacity in trained endurance athletes consuming a ketogenic diet (KD) at vigorous intensity (64-90 VO_{2max})				
Burke et al, ¹⁶ Elite race walkers 64 mL·kg·min ⁻¹ Non-random parallel group design	3 weeks (21 days) HC (n=9: 65% CHO, 20% fat, 15% protein); PC (n=8: 65% CHO, 20% fat, 15% protein); KD (n=10: <50 g CHO, 78% fat, 15% protein)	Yes βHB >1.0 mM	10 km race HC & PC – 2 g·kg CHO prior, 60 g/h CHO during, KD energy equivalent LCHF snack Graded economy test (4 stages, treadmill)	No HC groups 10 km time improved 124–190 sec (p<0.01), KD performance decreased 23 sec (p>0.05), NS between groups (p>0.05) No RER lower (p<0.001), and VO ₂ (p<0.01), HR (p<0.01), and RPE (p<0.01), increased stages 1–4 following KD
Shaw et al, ¹⁷ Trained endurance athletes 59.4 mL·kg·min ⁻¹ Crossover	4 weeks (31 days) HD (n= 8: 43% CHO, 38% fat, 19% protein), KD (n=8: 4% CHO, 78% fat, 18% protein)	Yes βHB 0.94 ± 0.45 mM	Run to exhaustion at 70% VO _{2max} Fasted Graded economy test (6 stages, treadmill) HC or HF meal prior; 55 g. h of CHO or coconut oil	No decrement TTE –6 mins HD (p=0.44), & –20 mins KD (p=0.36) No Efficiency maintained <60% VO _{2max} . Energy expenditure (p<0.05), & oxygen consumption increased >70% VO _{2max} (p<0.05)
IC. Endurance performance and capacity in recreationally active endurance athletes consuming a ketogenic diet at vigorous intensity (64-90 VO_{2max})				
Heatherly et al, ¹⁸ Recreationally active runners Crossover design with order effect (control first)	21 days KD (7% CHO, 64% fat, 29% protein) Fasted	Yes βHB ~0.7 mM (handheld meter)	50 min run, followed by outdoor 5 km TT	No decrement 5 km TT maintained (HC 23.92 ± 2.57 mins; KD 23.45 ± 2.25 mins, p=0.025) 2.5 kg weight loss (p<0.001)

(Continued)

Table 1 (Continued).

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
McSwiney et al, ¹⁹ Endurance athletes 53.6 mL·kg ⁻¹ ·min ⁻¹ Non-randomized control trial	12 weeks (84 days) HC (n=11: 65% CHO, 20% fat, 14% protein); KD (n=9: <50 g/d CHO, 77% fat, 17% protein)	Yes βHB 0.5 mM	100 km TT HC or LC meal prior: HC consumed 30–60 g/h CHO; KD water + electrolytes during	No decrement 100 km TT maintained (HC – 1.13 mins; KD –4.07 mins) (p=0.057)

Abbreviations: VO_{2max}, maximal oxygen uptake; mL·kg⁻¹·min⁻¹, milliliters per kilogram bodyweight per minute; HC, high carbohydrate; CHO, carbohydrate; g, gram; KD, ketogenic diet; βHB, beta-hydroxybutyrate; mM, millimoles per liter; TTE, time to exhaustion; VO_{2peak}, peak oxygen consumption; min, minute; PC, periodized carbohydrate; km, kilometer; LCHF, low-carbohydrate high fat; NS, non-significant; RER, respiratory exchange ratio; HR, heart rate; HD, habitual diet; HF, high fat; g·h, grams per hour; TT, time trial.

~45% (76 vs 140 mM/kg wet weight muscle) following a KD. Webster et al²⁸ noted endurance-trained athletes consuming a KD for >8 months oxidized $1.21 \pm 0.15 \text{ g}\cdot\text{min}^{-1}$ of carbohydrate, versus $2.89 \pm 0.41 \text{ g}\cdot\text{min}^{-1}$ in a homogenous group consuming a mixed diet (49% carbohydrate, 33% fat), and produced similar glucose through gluconeogenesis at 72% VO_{2peak}. Therefore, similar to a carbohydrate-based athlete, carbohydrate feeding appears necessary when keto-adapted to sustain moderate-intensity exercise >3 hrs, at a rate of $>1\text{--}2 \text{ g}\cdot\text{min}^{-1}$,²⁸ if findings were to be replicated within experimental settings.

Endurance – Vigorous Intensity (64–90% VO_{2max}) Trained Athletes

Decreased economy observed at vigorous intensity is noteworthy as it better represents the intensity of competitive endurance athletes (Table 1B).^{16,17} For example, “fast runners” complete a treadmill-based marathon in 2 hrs 43 mins at 75% VO_{2max}, while “slower runners” complete 3 hrs 20 min marathon at 65% VO_{2max}.²⁹ Increased oxygen cost of ATP production from fatty acids versus carbohydrate has been understood since the early 1900s.³⁰ Unfortunately, due to the nature of field tests, extensive blood and gas analysis did not take place during the 10 km TT; therefore, it is difficult to precisely determine the KD's limiting factor.¹⁶ However, considering increased oxygen consumption, and that HR and RPE were evident at 20 km race pace within laboratory settings, decreased efficiency was likely a contributing factor at 10 km race pace,¹⁶ or perhaps, it could be argued the adaptation period was too brief. The length of an adaptation period is often identified as important when discussing a KD and an athlete's ability to regain performance, with advocates suggesting months necessary to become keto-adapted.^{7,12,31,32} Questionably, however, race walkers achieved higher rates of fat oxidation ($1.54 \pm 0.18 \text{ g}\cdot\text{min}^{-1}$ at 70% VO_{2max}³² vs $1.57 \pm 0.32 \text{ g}\cdot\text{min}^{-1}$ at 80% VO_{2peak}¹⁶) during a 25 km walk, and similar concentrations of βHB (both, >0.5–1.0 mM) to a group habituated to a KD for >9 months,³² in as little as 21 days.¹⁶ Therefore, it remains unclear, what other measurable adaptations, if any, must take place prior to an athlete being considered keto-adapted.

Recreationally Trained Athletes

Endurance performance ranging from 70 to 168 mins in duration was sustained in recreationally trained individuals (Table 1C).^{18,19} Heatherly and colleagues suggested a KD

Table 2 Strength Performance In Athletes Consuming a Ketogenic Diet At A Variety Of Intensities

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet			
2A. Strength performance in trained athletes consuming a ketogenic diet at moderate (50–69% IRM) to vigorous intensity (70–84% IRM)							
Paoli et al, ²⁰ Elite male artistic gymnasts Crossover design	4 weeks (30 days) WD (n=8: 47% CHO, 39% fat, 15% protein); KD (n=8: <25 g CHO, 55% fat, 41% protein)	Not measured	Squat jumps	No decrement			
			All fasted	WD 0.0 r; KD 0.0 r (p>0.05)			
			Countermovement jumps	No decrement			
				WD -0.0 r; KD 0.0 r (p>0.05)			
			Reverse grip chin-ups	No decrement			
				WD 0.0 r; KD +0.4 r (p>0.05)			
			Push ups	No decrement			
				WD +6.5 r; KD + 2.8 r (p>0.05)			
			Legs closed barrier test	No decrement			
				WD +1.2 r; KD +2.5 r (p>0.05)			
Rhyu and Cho ²¹ Taekwondo athletes Randomized control trial	3 weeks (21 days) HC (n=10: 40% CHO, 30% fat, 30% protein); KD (n=10: 4% CHO, 55% fat, 41% protein)	Not measured	Parallel bar dips	No decrement			
				WD +4.0 r; KD +2.4 r (p>0.05)			
			Grip test	No decrement			
			All fasted	Left: NKD +0.6 N; KD 0.0 N (p>0.05) Right: NKD -1.6 N; KD -0.5 N (p>0.05)			
			Back muscle strength	No decrement			
				NKD +5.1 N; KD +3.3 N (p>0.05)			
			Sit-up test (60 s)	No decrement			
				NKD +1.5 r; KD +5.3 r (p>0.05)			
			2B. Strength performance in trained athletes consuming a ketogenic diet at near-maximal to maximal intensity (>85% IRM)				
			Wilson et al, ²² Resistance trained males Randomized control trial	10 weeks WD (n=12: 50% CHO, 30% fat, 20% protein), KD (n=13: 5% CHO, 75% fat, 20% protein)	Yes βHB 0.5–1.0 mM (handheld meter)	IRM bench press	No decrement
Both fasted	WD +5.5%; +3.3% KD IRM bench						
IRM back squat	No decrement						
	WD +10%; +5.4% KD IRM squat						
IRM bench press	Yes						
Both fasted	KD +4.5% (p<0.05); WD unchanged (p>0.05)						
Weeks 10–11 WD remained unchanged; KD (20% CHO, 40% fat, 20% protein)		No	IRM back squat	Yes			
				KD +4% (p<0.05), WD unchanged (p>0.05)			

(Continued)

Table 2 (Continued).

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
Greene et al, ²³ Intermediate to elite competitive lifting athletes Crossover design	12 weeks UD (n=12: 49% CHO, 33% fat, 22% protein); KD (8n = 12: 8% CHO, 69% fat, 23% protein)	Yes βHB 0.4 ± 0.2 mM (handheld meter)	IRM: snatch + clean + jerk + squat + bench + deadlift = "lifting performance" All fasted	No decrement Lifting performance minus ~0.5% KD (p>0.05)
2C. Strength performance in recreationally trained athletes consuming a ketogenic diet at near-maximal to maximal intensity (>85% IRM)				
Kephart et al, ²⁴ CrossFit Trainees Non-randomized control trial	90 days (12 weeks) HC (n=5: n/a); KD (n=7: 6% CHO, 77% fat, 17% protein) Pre-exercise meal(s) not controlled (g/kcal)	Yes βHB ~1.0 mM (handheld meter)	IRM back squat	No decrement HC + 5 kg; KD 0 kg (p=0.422)
			All Fasted	No decrement HC + 1 kg; KD -2 kg (p=0.347)
			IRM power clean	No decrement HC + 8 r; KD +8 r (p=0.716)
			Max push up test	

Abbreviations: WD, western diet; CHO, carbohydrate; KD, ketogenic diet; HC, high carbohydrate; r, repetitions; NKD, non-ketogenic diet; N, newtons; βHB, beta-hydroxybutyrate; mM, millimoles per liter; IRM, one-repetition maximum; kg, kilogram; UD, usual diet; MD, mixed diet.

affords an opportunity “to eat to satiety while maintaining a more competitive racing weight and body composition versus high carbohydrate (HC)” (pg. 578).¹⁸ It is noteworthy that participants lost weight (-2.5 kg, p<0.001) whilst being instructed to eat fat ad libitum, but it is important to note that body composition improvements can be achieved with low- or high-carbohydrate intakes, granted protein and caloric needs are appropriate.³³ From work in trained individuals,^{16,17} adopting a KD to improve running economy could be counter-productive, or at least negligible, if metabolic efficiency is negated >70% VO_{2max},^{16,17} versus ensuring carbohydrate availability and implementing an energy deficit. Improved economy attributing from weight loss was not a confounding variable within McSwiney et al due to 100 km TT being completed on a stationary bike (WattBike) with self-selected resistance.¹⁹ Notably, 100 km TT performance was sustained, despite the KD group consuming only water and electrolytes during post-intervention testing, versus the HC group who consumed 30–60 g/h of carbohydrate.¹⁹ Whether performance can be sustained >100 km without carbohydrate feeding within recreationally trained athletes remains to be seen within experimental settings. However, experimental and non-experimental work in trained endurance athletes would suggest carbohydrate feeding is necessary to sustain moderate to vigorous activity >3 hrs.^{6,28}

Strength Performance Moderate (50–69% IRM) To Vigorous Intensity (70–84% IRM)

Despite <50 g/d of carbohydrates, trained gymnasts and taekwondo athletes experienced no decrement in strength endurance and power following 3–4-week adherence (Table 2A).^{20,21} Maintenance of performance in both KD diet groups achieved significant weight loss is noteworthy, as a lean physique and making weight while limiting negative impacts on performance are important to each respective sport.^{20,21} Notably however, there were considerable discrepancies in protein intakes within Paoli et al (HC 1.1 g·kg protein, KD 3.1 g·kg protein)²⁰ and Rhyu and Cho (HC 30% protein, KD 40.5% protein)²¹ investigations, which likely contributed to ad libitum weight loss,²⁰ with the KD group outperforming the control group in terms of weight loss,²¹ through improved satiety and other mechanisms.³³

Near-Maximal To Maximal Intensity (>85% IRM)

Until recently, maximal strength performance through 1RM in response to a KD remained unexplored. Current evidence suggests no decrement in maximal strength

Table 3 Short-Duration Exercise In Athletes Consuming a Ketogenic Diet At A Variety Of Intensities

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
3A. Short-duration (>30 s) vigorous exercise in athletes consuming a ketogenic diet				
Rhyu and Cho ²¹ Taekwondo athletes Randomized control trial	21 days Diet – see Table 2A	Not measured	2000 m run	Yes NKD unchanged +1.4 s; KD -32 s (TxG, p<0.05)
3B. Short-duration (>30 s) vigorous exercise in recreationally trained athletes consuming a ketogenic diet				
Kephart et al. ²⁴ CrossFit trainees Non-randomized control trial	90 days (12 weeks) Diet – see Table 2C	Yes βHB ~1.0 mM (handheld meter)	400 m outdoor run Pre-exercise meal(s); not controlled (g/kcal)	No decrement WD +0.6 sec; KD +0.1 sec (p=0.326)
McSwiney et al. ¹⁹ Endurance athletes Non-randomized control trial	12 weeks Diet – see Table 1C	Yes βHB 0.5 mM	CPT (3 min sprint)	Yes CPT relative peak power increased in KD (p=0.047). CPT average power (p=0.336) *Note: KD had greater body fat (kg) at baseline (p<0.05)
Cipryan et al. ²⁵ Moderately trained males Randomized control trial	4 weeks (28 days) HD (n=9; 48% CHO, 35% fat, 17% protein); KD (n=9; 8% CHO, 63% fat, 29% protein)	Yes βHB 0.4–0.7 mM (handheld meter)	Graded exercise test TTE	No decrement HD +1.8 min; KD +2.5 mins (ES ± 90% CI = -0.1 ± 0.3) HD -0.8 kg; KD -4.7 kg, 75–95% CI
			5 x 3 min interval sprints at 100% VO _{2max} ; 1.5 mins recovery	No decrement RER decreased (HD -0.01 RER; KD -0.1 RER; ES ± 90% CI = -1.5 ± 0.1), but mean % VO _{2max} unchanged (HD = +0.6%; KD = -0.1%; ES ± 90% CI = 0.05 ± 0.0)
Dostal et al. ²⁶ Non-randomized parallel group Recreationally trained men and women	12 weeks (n=12, 46% CHO, 35% fat, 19% protein); KD (n=12, 8% CHO, 69% fat, 23% protein)	Yes βHB >0.5 mM (handheld meter)	Graded exercise test TTE	No decrement +82 sec (p=0.005) increase in TTE within KD and +69 sec (p=0.018) in HC groups HC -0.9 kg; KD -3.6 kg
3C. Sprint-near maximal exercise (<30 s) in athletes consuming a ketogenic diet				
Rhyu and Cho ²¹ Taekwondo athletes Randomized control trial	21 days Diet – see Table 2A	Not measured	Wingate	No decrement NKD -0.61 w/kg, KD -1.05 w/kg (p>0.05)
			100 m sprint	No decrement NKD +0.22 sec, KD +0.18 sec (p>0.05) *Note: KD lost greater body mass (NKD -2.5 kg; KD -3.7 kg); may have confounded weight bearing tests (2000/100 m sprints)

(Continued)

Table 3 (Continued).

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
3D. Sprint-near maximal exercise (<30 s) in recreationally trained athletes consuming a ketogenic diet				
McSwiney et al. ¹⁹ Endurance athletes Non-randomized control trial	12 weeks Diet – see Table 1C	Yes βHB 0.5 mM	SS Sprint Test nutrition – see Table 1C	Yes SS peak power: increased KD (+0.8 w/kg), & unchanged HC (-0.1 w/kg) (p=0.025)
Dostal et al. ²⁶ Non-randomized parallel group	12 weeks Diet – see Table 3B	Yes βHB >0.5 mM (handheld meter)	30-15 Intermittent Fitness Test	No decrement TTE increased in KD (158.1 sec, BF ₁₀ ≥100; p=0.001) and HC (116.5 sec, BF ₁₀ ≥100; p=0.001)

Note: Evidence categories were: 1 no evidence, 1–3 anecdotal evidence, 3–10 moderate evidence, 10–30 strong evidence, 30–100 very strong evidence, and >100 decisive evidence.
Abbreviations: VO_{2max}, maximal oxygen uptake; m, meter; NKD, non-ketogenic diet; KD, ketogenic diet; sec, second; w/kg, watts per kilogram; kg, kilogram; βHB, beta-hydroxybutyrate; mM, millimoles per liter; CPT, critical power test; SS, six-second sprint; HC, high carbohydrate; WD, western diet; HD, habitual diet; TTE, time to exhaustion; ES, effect size; CI, confidence interval; VO_{2peak}, peak oxygen consumption; RER, respiratory exchange ratio; AP, absolute power; BF₁₀, Bayes Factor (statistical index that quantifies evidence of hypothesis, compared to alternative hypothesis).

(Table 2B). A 1RM represents an extreme of the exercise continuum, requiring maximal-force production. Short-duration, maximal-force production is fuelled primarily by ATP within the muscle, and the ATP phosphagen system.¹ Rest, or recovery periods allow replenishment of oxygen stores, and resynthesis of ATP and phosphocreatine within muscle.¹ Therefore, granted a 1RM is performed in a rested state, which is currently the case within the literature, strength performance will likely experience no decrement through KD consumption.

Short-Duration Vigorous Intensity (64–90% VO_{2max}, >30 s)

Evidence suggests no decrement to short-duration vigorous-intensity exercise following 3–12 weeks of a KD within trained (Table 3A)²¹ and recreationally trained athletes (Table 3B).^{19,24–26} Findings are contrary to sports nutrition guidelines, which recommend carbohydrate availability to enable vigorous performance.^{3,4} However, improved 2000 m performance (duration: >8 mins),²¹ and maintenance of CPT (duration: 3 mins)¹⁹ can be explained mechanistically. For example, world-class, female cyclists completing a 3000 m pursuit (duration: 3:30 mins), and males completing 4000 m pursuit (duration: 4:11 mins) rely on ~75%, and ~85% aerobic metabolism, respectively.³⁴ Therefore, although not a measured component, aerobic metabolism likely fuelled a large proportion of the 3–8 min tests. As previously noted (Table 1A–C), a KD is proficient at sustaining aerobic performance. Maintenance of 400 m sprint performance is noteworthy, however,²⁴ considering 400 m sprints are glycolytic.³⁵ Findings were confounded by weight loss (KD -3 kg p=0.022; CTL -0.3 kg p>0.05),²⁴ which would improve running economy (power-to-weight ratio),³⁶ and potentially mask metabolic inefficiency observed >70% VO_{2max}.^{16,17}

Collectively, available literature suggest graded exercise test performance ranging from 19.8 to 27.2 mins in duration is sustained following 4–12-week adaption.^{25,26} Using muscle biopsies, a 4-fold reduction in muscle glycogen was observed following a 28-day KD,⁶ while cross-sectional studies have observed a 1.8-fold reduction,²⁸ and no decrement,³² following >8,²⁸ and >9 months³² adherence. If this is a stepwise occurrence, it is suggestive that greater resting muscle glycogen stores are achieved following elongated adaptation, despite reported, continued <50 g/d carbohydrate intake.^{28,32} If true, and whether longer adaptations, for example, 9 months,³² enables improved performance of vigorous-intensity exercise

Table 4 Body Composition In Athletes Consuming a Ketogenic And Non-Ketogenic Diet With Matched Protein Intakes

Population & Study Design	Study Duration & Diet	Nutritional Ketosis	Performance Test & Nutrition	Advantage Of Ketogenic Diet
4A. Body composition in trained athletes consuming a ketogenic diet				
Wilson et al, ²² Resistance trained males Randomized control trial	10 weeks Diet – see Table 2B Protein matched: yes WD 1.7 g·kg protein; KD 1.6 g·kg protein (p>0.05)	Yes βHB 0.5–1.0 mM (handheld meter)	(Measure: DXA) Fat mass	No decrement WD –1.8 kg; KD –4 kg (both, p<0.0001)
	Weeks 10–11 Protein matched: yes WD 1.6 g·kg protein; KD 1.6 g·kg protein (p>0.05)	No	(Measure: DXA) Lean body mass	No decrement WD +2.7 kg, and KD +1.5 kg (both, p<0.01) Advantage of CHO refeed
			(Measure: DXA) Fat mass	No KD increased fat mass p<0.0001; WD unchanged
			(Measure: DXA) Lean body mass	Yes KD +3 kg (p<0.0001); WD unchanged
4B. Body composition in recreationally trained athletes consuming a ketogenic diet				
Vargas et al, ²⁷ Healthy individuals Randomized control trial	8-week NKD (55% CHO, 25% fat, 20% protein); KD (10% CHO, 70% fat, 20% protein) Protein matched: g and g·kg protein not displayed	Yes (urinary ketones; not outlined)	(Measure: DXA) Fat mass	Yes NKD (–0.4 kg, p>0.05); KD (–1.1 kg p<0.05)
			(Measure: DXA) Lean body mass	No NKD +1.4 kg, KD +0.3 kg (TxG p=0.025)

Abbreviations: WD, western diet; KD, ketogenic diet; g·kg, gram per kilogram; mM, millimoles per liter; DXA, dual-energy X-ray absorptiometry; kg, kilogram; NKD, non-ketogenic diet; CHO, carbohydrate; TxG, time x group.

through the greater reestablishment of resting glycogen stores remains to be seen within experimental settings.

Sprint-Near Maximal Intensity (>90% $\text{VO}_{2\text{max}}$, <30 s)

No decrement to Wingate,²¹ 100 m sprint²¹ and 30–15 repeated sprint performance²³ were observed following 3–12-week adaptation, while benefit to SS sprint performance¹⁶ was observed following 12-week adherence within trained (Table 3C)²¹ and recreationally trained athletes (Table 3D).^{16,23} The phosphocreatine energy system would likely fuel SS sprint,¹ while during a Wingate, healthy subjects utilize 16% aerobic, 56% glycolytic, and 28% phosphocreatine energy systems.³⁷ Although maintenance of sprint-near maximal intensity exercise with reduced carbohydrate intake is noteworthy, it is important to consider findings in context. For example, tests were performed in taekwondo athletes attempting to make weight, where fatigue and reduced glycogen stores were likely a contributing factor,²¹ and within recreationally trained endurance athletes.^{16,23} Therefore, findings are not representational of well trained, or elite athletes who compete in events <30 s in duration, such as 100 and 200 m sprinters, with high anaerobic thresholds and carbohydrate availability.

Body Composition

For the first 10 weeks of Wilson et al's investigation,²² groups experienced similar muscle hypertrophy (Table 4A). Thereafter, following 1 week of increased carbohydrate consumption (263.5 ± 42.0 g), the KD group increased body mass and estimations of lean body mass by ~3 kg,²² bringing lean body mass across the 11-week intervention to 2.7 kg in the non-KD group, and 4.5 kg in the KD group ($p > 0.05$).²² This acute gain in lean body mass in week 11 is not entirely uncommon, considering 3 days of HC feeding and rest is associated with increased body mass (0.6 kg, $p = 0.001$) and estimations of lean body mass (0.9 kg, $p < 0.0001$) within non-obese men using a DXA scanner.³⁸

In contrast, Vargas et al demonstrated recreationally trained men consuming a non-KD increased lean body mass to a greater extent when compared to a KD group following an 8-week training intervention.²⁷ Baseline dietary assessment was absent, therefore, it is unknown if the non-KD group increased or sustained carbohydrate intake, thereby potentially impacting DXA reliability, for reasons previously outlined.³⁸ In addition, groups were instructed to consume a hyper-caloric diet to promote greater gains in lean body mass, however, mean body weight decreased

within the KD group (-1.4 kg, TxG, $p = 0.016$). Therefore, an appropriate synopsis is, a hypocaloric KD decreased fat mass, and maintained lean body mass (Table 4B). Had carbohydrate restoration/loading taken place, to standardize habitual carbohydrate-availability (g/kg unknown from manuscript), increases in lean body mass parallel to the non-KD group, may have taken place, as previously observed.²²

Conclusions, Clinical Insights And Future Directions

Available knowledge demonstrates no clear performance benefit to athletes following a KD, with some benefit shown mainly in short duration, vigorous-intensity tests, when weight loss was likely a confounding variable. While many of the trials provided no performance benefit, it is important to note that a KD often did not cause a performance decrement, particularly in recreationally trained athletes. Decreases in metabolic efficiency were common among trained athletes competing at >70% $\text{VO}_{2\text{max}}$ following acute adaptation.^{16,17}

Despite inconsistent outcomes, we continue to see in practice (i.e., anecdotally), endurance athletes pursuing a carbohydrate-restricted dietary approach. Long-term anecdotal and subjective evidence is mixed, however. For example, “elite ultra-marathoners and ironman distance triathletes”,³² and ‘well-trained cyclists’,²⁸ habituated towards a KD style of eating for 20³² and 8 months,²⁸ respectively, report remaining highly competitive. Whilst a “world-class vegetarian long-distance triathlete”, reported their worst-ever half-Ironman performance (21 weeks), second-worst Ironman performance (24 weeks), and failed to complete Ironman in week 32, discontinuing the diet thereafter.³⁹

Maunder et al proposed that endurance athletes should adopt an exercise training session and nutritional practices to minimize the endogenous carbohydrate cost of exercise at competitive intensities, through adaptation to an LCHF or KD, whilst maximising pre-competition glycogen stores (carbohydrate feeding/restoration) and providing exogenous carbohydrate during competition.⁴⁰ As previously outlined, considerable research has identified that an acute LCHF diet (5–10 days) approach with carbohydrate restoration (6.8–11 g/kg CHO for 1–3 days) does not decrement endurance performance.¹⁰ Conversely, there is strong evidence demonstrating that such an approach is associated with a reduction in glycogenolysis during

exercise, and a reduction in the active form of pyruvate dehydrogenase at rest, and during submaximal and maximal exercise.⁴¹ Whether these undesirable adaptations persist with longer adaptation periods remains to be seen mechanistically within experimental settings.

Furthermore, it was proposed that ketone bodies would provide fuel for the brain, in combination with greater contribution from gluconeogenic substrates.^{7,12} As previously outlined, Webster et al, provided evidence that the energy contribution from gluconeogenesis is not enhanced subsequent to 8 months of consuming a KD.²⁸ Therefore, non-experimental²⁸ and experimental evidence⁶ suggest endurance performance remains limited through glucose availability in trained endurance athletes consuming a KD. Thus, the case for advocating a KD versus a less extreme LCHF diet must be questioned. Although this has not been specifically explored, if glycogen restoration and/or exogenous carbohydrate feeding were to take place during exercise, as is recommended,^{39,40} ketogenesis, hypothetically, would no longer take place due to increased glucose availability.⁸ Therefore, it must be questioned why a KD is recommended, versus a less extreme LCHF diet, to achieve increases in fat oxidation, as ketone bodies' contribution to energy expenditure would be negligible, if not obsolete, with current recommendations.^{39,40}

A further reason why we propose the popularity of carbohydrate-restricted approaches is due to other reported benefits of this dietary approach. These include, reports of improved energy for both training and competition,¹² reductions in exogenous caloric requirements during training and competition,¹² improved symptoms derived from inflammatory conditions,^{12,42} and the reduced incidence of delayed onset of muscle soreness and gastrointestinal complaints.¹² Furthermore, nutritional ketosis has emerged as a potent modulator of inflammation over the past decade.^{43,44} Such a collection of outcomes may impact athletes' overall health which could have potential downstream effect on performance; however, this is yet to be examined comprehensively in athletes within experimental settings. Therefore, heed must be taken, as many potential confounding variables may have been overlooked within anecdotal reports.

Future research on carbohydrate-restriction in athletes could also address aspects of health alongside performance – both quantitatively and qualitatively. This will help connect the evidence with the growing interest and practice and provide further understanding of the potential, holistic benefits of carbohydrate-restriction in the athlete context.

Disclosure

The corresponding author, Dr Caryn Zinn has co-authored a book titled “What The Fat – Sports performance” which assume an LCHF nutrition approach; co-author, Dr Dan Plews, delivers an online course which focuses on LCHF nutrition for endurance athletes. The authors report no other conflicts of interest in this work.

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