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Low-carbohydrate, ketogenic diet impairs anaerobic exercise performance in exercise-trained women and men: a randomized-sequence crossover trial

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Abstract

BACKGROUND: Low-carbohydrate, ketogenic diets cause mild, sub-clinical systemic acidosis. Anaerobic exercise performance is limited by acidosis. Therefore, we evaluated the hypothesis that a low-carbohydrate, ketogenic diet impairs anaerobic exercise performance, as compared to a high-carbohydrate diet.

METHODS: Sixteen men and women (BMI, 23±1 kg/m2, age 23±1 yr) participated in a randomized-sequence, counterbalanced crossover study in which they underwent exercise testing after four days of either a low-carbohydrate, ketogenic diet (LC; <50 g/day and <10% of energy from carbohydrates) or a high-carbohydrate diet (HC; 6-10 g/kg/day carbohydrate). Dietary compliance was assessed with nutrient analysis of diet records, and with measures of urine pH and ketones. Anaerobic exercise performance was evaluated with the Wingate anaerobic cycling test and the yo-yo intermittent recovery test.

RESULTS: The diets were matched for total energy (LC: 2333±158 kcal/d; HC: 2280±160 kcal/d; p=0.65) but differed in carbohydrate content (9±1 vs. 63±2% of energy intake; p<0.001). LC resulted in lower urine pH (5.9±0.1 vs. 6.3±0.2, p=0.004) and the appearance of urine ketones in every participant. LC resulted in 7% lower peak power (801±58 vs. 857±61 watts, p=0.008) and 6% lower mean power (564±50 vs. 598±51 watts, p=0.01) during the Wingate test. Total distance ran in the yo-yo intermittent recovery test was 15% less after LC diet (887±139 vs. 1045±145 meters, p=0.02).

CONCLUSION: Short-term low-carbohydrate, ketogenic diets reduce exercise performance in activities that are heavily dependent on anaerobic energy systems. These findings have clear performance implications for athletes, especially for high-intensity, short duration activities and sports.

Key Words: performance-enhancing effects - exercise nutrition physiology - diet, carbohydrate-restricted - sports performance - anaerobic metabolism

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Introduction

Athletes and other exercise enthusiasts often experiment with energy- and/or macronutrient-restricted dietary practices. The nature of dietary practices and reasons for using restrictive practices vary widely, depending on the athletes' goals. A common goal is to reduce total body mass and fat mass without compromising lean mass or exercise capacity.[1] Accomplishing such goals can provide competitive advantages by increasing power-to-body mass ratio, by allowing an athlete to compete in a lower weight class, by providing more favorable judging in "aesthetic" sports, or through other effects.[1] Some examples of dietary strategies that have been evaluated in athletes include modest (vs. severe) dietary energy restriction,[2] high protein intakes,[3, 4] and intermittent fasting strategies, such a time-restricted feeding during which food intake is limited to a few hours each day.[5, 6]

Another form of dietary restriction that has become popular among athletes is a very low carbohydrate, ketogenic diet. To prevent endogenous carbohydrate production (gluconeogenesis) from amino acid metabolism, these diets are also limited in protein. These diets do not comply with joint recommendations from the Academy of Nutrition and Dietetics, the American College of Sports Medicine, and Dietitians of Canada, which indicate that athletes with high training loads should consume a high-carbohydrate diet.[1] The basis for the high-carbohydrate recommendations is that inadequate dietary carbohydrate reduces glycogen stores, increases the risk of glycogen depletion, and impairs performance during long-duration, vigorous-intensity endurance exercise.[7] However, far less is known about the effects of low carbohydrate intake on the performance of high-intensity, short-duration exercise, which depends heavily on anaerobic energy metabolism.

When carbohydrate availability is sufficiently low, the liver produces ketones, which are used by the nervous system for energy.[8, 9] Ketones rapidly dissociate a proton at physiologic pH[10] and consequently promote systemic acidity.[11] Fatigue during high-intensity, short-duration "anaerobic" exercise is partly attributable to exercise-induced, metabolic acidosis.[12] In this context, the mild systemic acidity caused by low-carbohydrate ketogenic diets might predispose muscle to more rapidly develop more severe acidosis during high-intensity anaerobic exercise, thereby inhibiting muscle contractile function and impairing performance. If this scenario is true, it would be expected that high-intensity, short-duration "anaerobic" exercise performance would

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be lower when athletes consume low-carbohydrate ketogenic diets as compared to high-carbohydrate diets. Some existing evidence supports this possibility; [11, 13, 14] however, these studies were limited in that the exercise performance tests were heavily dependent on both aerobic and anaerobic energy metabolism (i.e. lasting 3-6 minutes in duration), thereby precluding definitive conclusions about anaerobic exercise performance.

We evaluated the hypothesis that 4-days of a low-carbohydrate, ketogenic diet impairs anaerobic exercise performance, when compared to a high-carbohydrate diet that meets recommendations.[1] More specifically, we hypothesized that a low-carbohydrate diet results in lower peak and 30-second mean power output during the Wingate anaerobic cycling test in the laboratory and lower run distance during a field test (yo-yo intermittent recovery test) designed to simulate the sporadic anaerobic demands of many team and ball sports. Given the popularity of low-carbohydrate diets in the general population, and the likelihood that athletes are also using such diets, the findings from this study may have important implications.

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Participants and Methods

Participants and Screening

The study was performed from January through August, 2016. Young (18-30 yr) men and women were recruited from the St. Louis, Missouri metropolitan area, primarily by convenience sampling. The recruitment strategies included informal verbal recruitment, distribution of electronic and hardcopy advertisement flyers, and verbal announcements to local collegiate athletic teams. Promotional materials/advertisements encouraged interested volunteers to contact the research team. Volunteers were prescreened by telephone or in-person with brief eligibility questions and then attended an on-site consent and screening appointment, during which the nature and requirements of study were discussed as well as their willingness and ability to participate. After obtaining informed written consent, the participants completed a personal information and demographics questionnaire and the American Heart Association/American College of Sports Medicine Preparticipation Screening Questionnaire.[15] All racial and ethnic groups were eligible for inclusion. Participants were required to be exercise-trained ≥3 moderate- to vigorous-intensity exercise sessions/week for ≥30 minutes/session over the past ≥6 months). Self-reported medical history was used to classify volunteers as low-, moderate- or high-risk for medical complications during exercise based on criteria from the American College of Sports Medicine;[15] only low-risk individuals were eligible to participate. All participants provided informed written consent to participate in the study, which was reviewed and approved by the Saint Louis University Institutional Review Board.

Study Design

The study was a crossover trial in which participants underwent two study trials separated by a 7-day washout period. In one trial, the participants consumed a low-carbohydrate ketogenic diet for 4 days before undergoing exercise testing; in the other trial, they consumed a high-carbohydrate diet before testing. The sequence of the two trials was randomized with blocking (www.randomization.com) and counterbalanced, such that half of the participants underwent the low-carbohydrate ketogenic diet first, and half underwent the high-carbohydrate diet first. The randomization scheme was generated by the study statistician (PVK); researchers involved in the intervention and outcomes assessments were blinded to the allocation sequence until subjects

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were deemed eligible and needed to be allocated. Both dietary interventions were 4 days in duration and outcomes were measured on day 4. Both study trials for each participant were completed within 3 weeks to minimize potentially confounding effects of seasonal changes in dietary habits, training status, and other factors. Testing was performed during mid-day or afternoon. For each participant, testing was performed at the same time of day for both study trials. Fasting was not required. The participants were instructed to use the same timing and quantities of food, water, and caffeine intake during the 24 hours prior to testing in both study trials, with the exception of adjusting the types of food to remain compliant with the macronutrient requirements for the low- and high-carbohydrate diets. The interventions and data collection were performed by KAW and MNT, both of whom are registered dietitians and certified personal trainers (American College of Sports Medicine) and worked under the supervision of EPW.

Diet Interventions

The energy content of the 4-day study diets were matched to the participants' usual diets (evaluated as described below). Participants were instructed to abstain from antacid supplements and medications, as they might affect systemic pH. The low-carbohydrate ketogenic diet limited carbohydrate intake to ≤50 g/day or 10% of total energy intake. The diet was rich in unsaturated fats and limited saturated fat to <10% of energy intake.[16] Protein intake was 1.3-1.8 g/kg/day, which matched that in the high-carbohydrate diet. Written and verbal strategies for avoiding carbohydrate-rich foods were provided, as were examples of meal plans that would that meet the goals for the low carbohydrate diet.

The high-carbohydrate diet was based on joint recommendations from the Academy of Nutrition and Dietetics, the American College of Sports Medicine, and Dietitians of Canada for athletes with high training loads.[1] Accordingly, carbohydrate intake was 6-10 g/kg/day, protein intake was 1.3-1.8 g/kg/day, and the remainder of energy intake was from fat (primarily unsaturated with saturated limited to <10% of energy intake. Participants were encouraged to get most of their dietary carbohydrate from fruits, starchy vegetables, grains, legumes and low-fat dairy products. Although not encouraged, desserts, sweets, and sugar-sweetened beverages were allowed.

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For the baseline dietary assessment and during the two dietary intervention periods, the participants recorded all foods and beverages consumed by using MyFitnessPal smartphone application (Under Armour, Inc., Baltimore MD); the participants “shared” their user accounts with the research team. For day-by-day feedback on dietary compliance, the study dietitian monitored energy and macronutrient intakes, as analyzed by the MyFitnessPal application. Participants were contacted every day during the dietary interventions (in person or by email or telephone) to provide feedback on dietary compliance, to answer questions, and to devise strategies for altering the diet if participants were having difficulty with compliance. For nutrient intakes in the present report, foods recorded in MyFitnessPal were analyzed by using IProfile nutritional analysis software (John Wiley and Sons Inc. 2016, Version 3.0).

Urinary Assessment

The participants self-monitored fasted morning urine pH to the nearest 0.5 pH unit with color-based pH strips (Colorphast pH strips, catalog #109533, EMD Millipore, Inc., Billerica, MA) every morning during both dietary interventions. The subjects were given instructions and supplies for performing these measures at home. In brief, the participants were instructed to perform the measures during their first urination after waking in the morning. They were instructed to initiate urination into the toilet and then during urination, briefly insert the end of the pH strip into the urine stream to saturate the end of the strip. Approximately 30-60 seconds after saturating the strip, the color that developed on the strip was compared to a color chart on the container to determine pH. On the last day of each intervention, fasted morning urine pH and ketones (Ketostix, catalog #2880, Bayer, Inc., Elkhart, IN) were measured by study personnel. The methods for this were the same as described above except that the subject provided a mid-stream urine sample in a cup to be tested by the investigators. A shift toward more acidic urine and the presence of detectable urine ketones (≥5 mg/dL) was used as an indication of compliance with the low-carbohydrate ketogenic diet.[17-19]

Wingate Anaerobic Cycling Test

The Wingate test is reliable[20] and commonly used to measure anaerobic exercise performance.[21] The test was performed on a computerized, electronically-braked cycle ergometer (Velotron with Wingate test software, version 1.0, RacerMate, Inc., Seattle, WA). Participants

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performed 5-minutes of warm-up cycling on the ergometer. Then, during a 10-second ramp-up phase with no resistance, the participants gradually increased pedal rate with the goal of reaching maximum pedal rate during the last 2 seconds. A resistance equivalent to 7.5% body weight was then applied and the participant pedaled as fast as possible for 30 seconds, with verbal encouragement throughout the test. Data were electronically recorded (10 samples/second) by the same computer that controlled the ergometer. Stored data were analyzed with the Wingate software and summarized as peak power (highest single power value recorded during the 30-second test, mean power (average power recorded during the 30-second test), minimum power (lowest power recorded during the test), and total work performed during the test. Peak and mean power were generated in absolute terms and relative to then subject's body weight. Heart rate during the last seconds of the test was measured with a wrist-watch/chest strap-type monitor (Polar Electro, Inc., Kempele, Finland). Ratings of perceived exertion (RPE, 6-20 point Borg scale) were measured immediately after the test.

Yo-Yo Intermittent Recovery Test

The yo-yo intermittent recovery test is a reliable[22] field test designed to simulate the repeated bouts of high-intensity, anaerobic exercise that occurs during many team and ball sports (e.g. soccer, tennis).[23] The test was performed on an indoor running track. A 5-min warm-up of light jogging preceded the test. The test consisted of repeated running bouts in which the participants ran 20 meters out to a marker and back, interspersed with a 10-second periods of active recovery (walk/jog). The pace of the running bouts and recovery were governed by using recorded audio cues (freely available from[24]), which differ for men and women. Test level 2 (for more fit athletes) was used for all participants. The pace of each running bout increases progressively and the test ends when the subject twice fails to reach the turnaround or finishing lines in the allotted time-frame. Total distance run (40 meters multiplied by the number of complete out/back runs before fatige) was recorded as the measure of performance. Heart rate and RPE were measured at the end of the test using the same methods as described above for the Wingate test.

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Statistical Analysis and Power

Data are summarized as means ± SE. Paired t-tests were used to test for statistically significant differences between mean values from the high carbohydrate trial and the low-carbohydrate ketogenic trial. The t-tests were two-tailed and p-values of ≤ 0.05 were considered significant. Data distributions were evaluated for normality by using Shapiro-Wilk tests. Except as noted in the results, the data distributions were not significantly different from normality. For data distributions that were significantly different from normality (based on $p<0.05$), Kolmogorov-Smirnov non-parametric analyses were performed in addition to the paired t-tests. Analyses were performed with IBM SPSS (version 23, Armonk New York) and Microsoft Excel (Microsoft Office 2010, Redmond, WA). Based on other highly controlled cross-over studies that have evaluated short-term or acute interventions on exercise performance, sample sizes of seven to fifteen were deemed to be common.[25-27] Therefore, an initial sample size of 15 was selected. Furthermore, to confirm that this would be sufficient for detecting an intervention effect, an *a priori* statistical power analysis was performed (G*Power software, version 3.1.5, University of Kiel, University of Dusseldorf, and University of Mannheim, Germany). The power analysis was based on the following inputs: two-tailed paired t-test, alpha=0.05, desired power=0.80, sample size=15 subjects. The results indicated that a standardized effect size of 0.78 (i.e. large effect) would be detectable.

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Results

Study Participants

Seventeen volunteers were eligible, enrolled, and randomized. One participant withdrew from the study due to inability to adhere to the dietary interventions. Wingate test data from 1 participant and yo-yo intermittent test data from 5 participants were unavailable due to technical problems during testing. Therefore, the analyses for the present report included 16 participants total, 15 participants for the Wingate test, and 11 subjects for the yo-yo intermittent recovery test.

Six (38%) of the 16 participants were men and 10 (62%) were women. One participant was Asian/Pacific Islander; all others were White/Caucasian. All met the criteria to be considered exercise trained. Average BMI was 23.4 ± 0.7 kg/m^2. Average age of the participants was 23 ± 1 years.

Adherence to Dietary Interventions: Nutrient Intakes, Urine pH, and Urine Ketones

Energy intake did not differ between diets (p=0.65, **Table 1**), as was intended by study design. Also by design, carbohydrate intake was higher (~7-fold) during the high-carbohydrate diet, regardless of whether it was reported relative to body mass (g/kg/d) or relative to energy intake (both p<0.001, **Table 1**). Protein intake was 1.4±0.1 g/kg/d during the high-carbohydrate diet, which was within the prescribed range of 1.3-1.8 g/kg/d; this was 0.4±0.1 g/kg/day lower (p=0.005) than during the low-carbohydrate diet (**Table 1**). Fat intake was 3-fold higher in the low-carbohydrate diet, regardless of whether it was expressed relative to body mass (g/kg/day) or relative to energy intake (both p<0.001). Body weight was lower (p=0.03) after the low-carbohydrate diet (**Table 1**), likely due to water losses associated with glycogen depletion. Because the body weight data distribution was significantly different from normal (p=0.048), a non-parametric analysis was also performed and the body weight differences remained significant (p=0.04).

Urine pH was slightly but significantly higher (more alkaline) on day 1 before the initiation of the low-carbohydrate diet, as compared to the high-carbohydrate trial (p=0.04; **Figure 1**). As expected, urine pH decreased during the low-carbohydrate diet, such that on day 4,

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urine pH was 0.4±0.1 units lower than during the low-carbohydrate diet (p=0.004, **Figure 1**). The urine pH data for days 3 and 4 were not normally distributed (p=0.004 and p=0.001 for days 3 and 4, respectively). Therefore the differences between treatment conditions were also evaluated with non-parametric analysis; the treatment effects remained significant for both days (p=0.001 and p=0.004, respectively).

On the morning of exercise testing during the low-carbohydrate trial, urine ketones were detectable (≥5 mg/dL) in all participants, indicating compliance with the ketogenic diet.

Wingate Anaerobic Cycling Test

Peak power was 7% lower (p=0.008) after the low-carbohydrate ketogenic diet, as compared to that after the high-carbohydrate diet (**Table 2**). Thirty-second mean power was 4% lower during the low-carbohydrate trial. When expressed relative to body weight, the differences between trials was partly offset by lower body weight during the low-carbohydrate trial, such that the between-trial differences in peak and mean power were attenuated (p=0.06 and p=0.12, respectively; **Table 2**). Total work was 6% lower in the low-carbohydrate trial (p=0.005). Heart rate and RPE at the end of the Wingate test did not differ between trials (p=0.32 and p=0.78, respectively; **Table 1**).

Yo-Yo Intermittent Recovery Test

Total distance ran during the yo-yo intermittent recovery test was approximately 1000 meters but varied widely (range: 320–800 meters). All but one of the participants ran further during the high carbohydrate trial. On average, the distance ran was 15% lower after the low-carbohydrate ketogenic diet than after the high-carbohydrate diet (p= 0.02, **Table 3**). Peak heart rate and peak RPE did not differ between the two trials (p=0.76 and p=0.61, respectively).

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Discussion

During periods of very low carbohydrate intake, mild sub-clinical acidosis develops as a consequence of ketogenesis.[8, 28, 29] Because anaerobic energy production during high-intensity exercise is limited by acidosis, we proposed that a low-carbohydrate, ketogenic diet accelerates the onset of fatigue and impairs performance during high-intensity, anaerobic exercise. Results from the present study support this hypothesis. As expected, the low-carbohydrate diet decreased the pH of fasted morning urine, suggesting systemic acidification. When compared to the high-carbohydrate diet, the low-carbohydrate diet impaired exercise performance, as evidenced by 7% lower peak power, 4% lower mean power, and 6% lower work performed during a 30-second Wingate cycling test. Furthermore, performance during a field test designed to mimic the intermittent anaerobic exercise demands of team and ball sports, such as soccer, was reduced by 15% after the low-carbohydrate diet. Findings from the present study are novel and advance those from the few other studies that have evaluated ketogenic diet effects on anaerobic exercise performance. As described in more detail below, our study is the only one to evaluate ketogenic diet effects on very short term exercise tasks (<30 sec) and on a field test designed to simulate the anaerobic demands of many team and ball sports. Our study is also novel in that we included both women and men (other studies only evaluated men), which makes the results more generalizable.

Only one other laboratory has studied the effect of low-carbohydrate diets on short-term high-intensity exercise performance and they also observed reductions in performance. [11, 13, 14] A key difference between our study and these earlier studies is that the earlier studies used considerably longer duration exercise performance tests (~3-6 minutes). Maximal effort tests of this duration depend heavily on both aerobic and anaerobic energy metabolism. In the present study, peak power during the Wingate test occurs within 5 seconds of starting the test and average power reflects maximum 30-second energy production; therefore, these metrics dependent more exclusively on anaerobic metabolism, including the ATP-PC (phosphagen) energy system and anaerobic glycolysis, respectively.[20] These differences in performance tests have major implications in that they correspond with very different types of athletic performance. For example, our peak power measures and 30-second mean power assessments would be relevant for track and field event such as the triple jump, and 100-200 meter sprints. In

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contrast, the 3- to 6-minute tests in earlier studies would be more reflective of longer duration events such as 1500 meter (1 mile) running competitions.

While we did not study mechanisms, findings from the present study are consistent with the notion that ketogenic diet-induced acidosis may have contributed to earlier onset and/or more severe muscle fatigue, and consequently impaired performance. Indeed, high myocellular H^+ concentrations reduce peak power in isolated muscle fibers,[30] although elevations in inorganic phosphate may also contribute.[31] One possible mechanism for such effects could be an inability of ATP production to keep up with ATP demand by the working muscle. Peak power during the Wingate test occurs within the first 5 seconds of the test and is heavily dependent the creatine kinase reaction for ATP synthesis.[32, 33] This reaction is slowed by acidic pH within the physiologic range,[34] which is consistent with our finding that the more acidic state after the low-carbohydrate diet resulted in lower peak power. Average power and total work performed during the Wingate test are reflective of the capacity of anaerobic glycolysis to provide ATP for exercise.[35, 36] Because anaerobic glycolysis is limited by acidosis (via inhibition of the rate limiting enzyme, phosphofructokinase[37]), the finding of reduced average power and total work performed during the Wingate test are consistent with the notion that the low-carbohydrate diet reduced the rate of ATP production through anaerobic glycolysis.

In addition to reducing ATP production, acidosis during the low-carbohydrate diet may have also caused muscle fatigue and reduced exercise performance by altering myofibrillar cross bridge cycling and/or excitation-contraction coupling. At the level of the myofilaments, acidic pH in skeletal muscle reduces troponin sensitivity to Ca^{2+}, thereby preventing actin-myosin binding, cross-bridge cycling, and myofibrillar force generation.[38] Myosin ATPase activity is reduced by acidic pH, which also inhibits cross-bridge cycling and force generation. However, this may be a consequence of the reduced calcium sensitivity of troponin rather than an independent effect.[38] The negative effect of low pH on excitation-contraction coupling appears to be attributable to reduced activities of other ATPases that result from an acidic milieu. Impairments in sarco(endo)plasmic reticulum ATPase (SERCA) that result from an acidic environment blunt the recovery of Ca^{2+} by the sarcoplasmic reticulum,[39] which results in a smaller Ca^{2+} release upon subsequent depolarization and consequently a smaller myofibrillar response. Likewise, acidic pH, among other factors, may reduce the activity of the sarcolemmal

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Na^{2+}-K^{+} pump (ATPase), which is important for repolarizing the sarcolemma.[40] Inadequate repolarization results in a smaller membrane potential and reduced cell excitability, and consequently fatigue.

Alterations in systemic pH through other interventions also affects anaerobic exercise performance (for comprehensive review, see reference[41]). Increases in systemic pH caused by bicarbonate loading improve anaerobic exercise performance[42-46] while decreases in pH induced by ammonium chloride (NH_4Cl) loading impair performance.[44, 47] Although we did not measure systemic or muscle pH in the present study, renal acid excretion is highly correlated with both arterial blood and muscle pH.[48] Therefore, the decrease in urine pH observed in the present study likely corresponded with decreases in systemic and muscle pH and, as was seen in the aforementioned studies on ammonium chloride loading, this reduced anaerobic exercise performance.[44, 47]

A practical implication of the present study is that athletes who follow low-carbohydrate diets may unintentionally impair their anaerobic exercise performance. The prevalence of low-carbohydrate dieting in athlete populations is not clear. However, it is conceivable that such diets are popular among athletes, as they are in the general population. Activities that are affected by these diets would likely include events demanding maximal exertion for time periods ranging from seconds to a few minutes. Examples would include pole vaulting, a single “play” in American football, and 100- to 800-meter track running. The degree of carbohydrate restriction that impairs anaerobic performance is not clear; however, until this is known, it would be prudent for athletes to follow the recommended 6 – 10 g/kg/day carbohydrate intake.[1]

Our study has limitations. First, we used a short-term dietary intervention; therefore, the results may not reflect responses to longer-term, low-carbohydrate diets, especially if ketogenesis and acidosis are not sustained. However, the short-term intervention might also be viewed as strength because it is especially relevant to athletes in “weight class” sports (e.g. wrestling, boxing), who often use short-term carbohydrate restrictions to qualify for a lower weight class. Another limitation is that carbohydrate intake was based on self-reported food intake. However, the shift toward more acidic urine pH and the presence of urine ketones provides objective evidence of compliance with the low-carbohydrate diet. Lastly, the dietary intervention used in the present study involved alterations in whole dietary patterns and foods,

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not solely macronutrients. In one respect this is a strength of the study, as real-world carbohydrate restriction would require similarly broad changes in dietary patterns. However, it is also possible that changes in other dietary components may have differed between trials and contributed to the observed effects.

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Conclusions

Results from the present study show that a low-carbohydrate, ketogenic diet impairs anaerobic exercise performance, when compared a high-carbohydrate diet that complies with recommendations for athletes. This effect was observed in both a laboratory test and a field test designed to simulate the demands of team and ball sports. In this context, unless there are compelling reasons for following a low-carbohydrate diet, athletes should be advised to avoid these diets and follow the recommendations to consume a high-carbohydrate diet.

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Authors Contributions -

KAW, MNT, and EPW conceived the study idea and developed the research plan; KAW and MNT performed the data collection; KAW, MNT, and EPW performed the data analyses and initial data interpretations; KAW, MNT, and EPW drafted the manuscript; all authors reviewed and provided intellectual feedback on subsequent drafts of the manuscript.

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Table 2. - Anaerobic exercise performance measures from the low- and high-carbohydrate diet intervention trials.

TITLES OF FIGURES

Figure. - Urine pH during the low- and high-carbohydrate diets. Urine tests were performed with fasting morning urine collected each day during the diet interventions. Values are means ± SE. P-values reflect results from paired t-tests comparing means between trials.

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Table 1. Body weight and nutrient intakes during the low- and high-carbohydrate carbohydrate dietary interventions (n=16).

	Low-Carbohydrate Diet	High-Carbohydrate Diet	P-value
Body weight, kg	67.7 ± 3.2	69.3± 3.5	0.03
Total energy intake, kcal/day	2280 ± 160	2333 ± 158	0.65
Carbohydrate intake, % energy intake	9.3 ± 0.7	63.1 ± 2.2	<0.001
Carbohydrate intake, g/kg/day	0.8 ± 0.1	5.2 ± 0.2	<0.001
Protein intake, g/kg/day	1.9 ± 0.2	1.4 ± 0.1	0.005
Protein intake, % energy intake	22.2 ± 1.3	17.1 ± 0.6	<0.001
Fat intake, % energy intake	69.7 ± 1.4	22.1 ± 1.9	<0.001
Fat intake, g/kg/day	2.6 ± 0.2	0.8 ± 0.1	<0.001

Values are means ± SE. P-values are from paired t-tests. Nutrient intakes are based on nutrient analysis of 4-day food diaries that were recorded during the dietary interventions.

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Table 2. Anaerobic exercise performance measures from the low- and high-carbohydrate diet intervention trials.

	Low Carbohydrate Trial	High Carbohydrate Trial	P-value
Wingate anaerobic cycle test			
Peak Power, watts	801 ± 58	857± 61	0.008
Peak Power, watt/kg	11.9 ± 0.4	12.4 ± 0.3	0.06
Mean Power, watts	564 ± 50	598 ± 51	0.01
Mean Power, watt/kg	8.5 ± 0.4	8.7 ± 0.3	0.12
Min Power, watts	394 ± 42	415 ± 43	0.06
Total Work, kilojoules	17.2 ± 1.5	18.3± 1.5	0.005
Peak Heart Rate, bpm	180 ± 2	179 ± 3	0.78
Peak RPE, 6-20 Borg scale	18.0 ± 0.2	17.6 ± 0.4	0.32
Yo-Yo intermittent recovery test			
Distance Run, meters	887 ± 139	1045 ± 145	0.02
Peak Heart Rate, bpm	189 ± 3	189 ± 3	0.76
RPE, 6-20 Borg scale	18.0 ± 0.4	18.3 ± 0.5	0.61

Values are means ± SE. P-values are from paired t-tests. Wingate test data were missing for one subject due to technical problems. Yo-Yo Intermittent Recovery test data were missing for five subjects due to technical problems. RPE, rating of perceived exertion.

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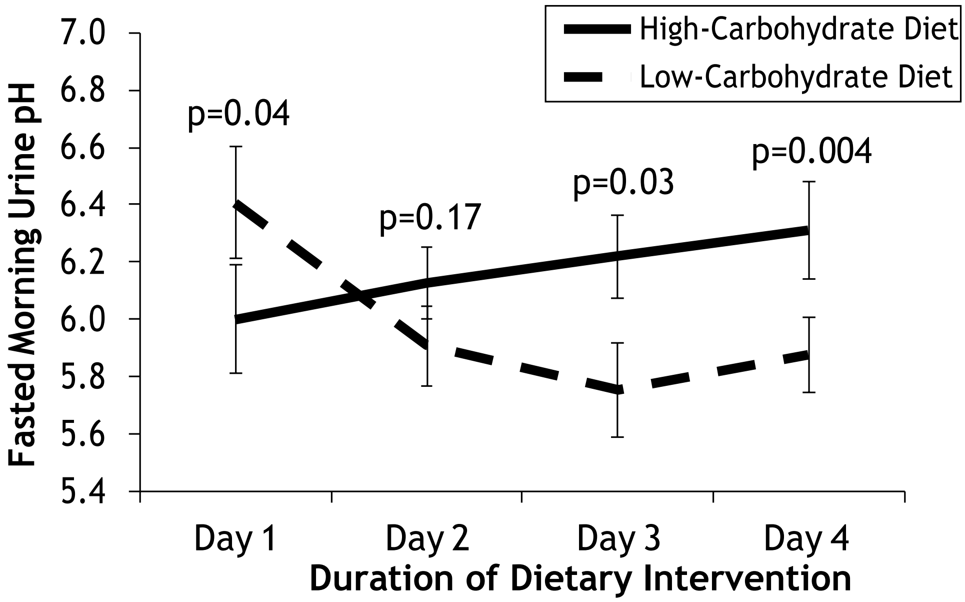
Figure



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