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Endurance Capacity and High-Intensity Exercise Performance Responses to a High-Fat Diet

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The effects of adaptation to a high-fat diet on endurance performance are equivocal, and there is little data regarding the effects on high-intensity exercise performance. This study examined the effects of a high-fat/moderate protein diet on submaximal, maximal, and supramaximal performance. Twenty non-highly trained men were assigned to either a high-fat/moderate-protein (HFMP; 61% fat) diet ($n = 12$) or a control (C; 25% fat) group ($n = 8$). A maximal oxygen consumption test, two 30-s Wingate anaerobic tests, and a 45-min timed ride were performed before and after 6 weeks of diet and training. Body mass decreased significantly (–2.2 kg; $p \leq .05$) in HFMP subjects. Maximal oxygen consumption significantly decreased in the HFMP group (3.5 ± 0.14 to 3.27 ± 0.09 $L \cdot min^{-1}$) but was unaffected when corrected for body mass. Perceived exertion was significantly higher during this test in the HFMP group. Main time effects indicated that peak and mean power decreased significantly during bout 1 of the Wingate sprints in the HFMP (–10 and –20%, respectively) group but not the C (–8 and –16%, respectively) group. Only peak power was lower during bout 1 in the HFMP group when corrected for body mass. Despite significantly reduced RER values in the HFMP group during the 45-min cycling bout, work output was significantly decreased (–18%). Adaptation to a 6-week HFMP diet in non-highly trained men resulted in increased fat oxidation during exercise and small decrements in peak power output and endurance performance. These deleterious effects on exercise performance may be accounted for in part by a reduction in body mass and/or increased ratings of perceived exertion.

Key Words: ketogenic, fat adaptation, cycling, power output

Introduction

Historically high-carbohydrate diets have been considered superior to high-fat diets for enhancing exercise endurance performance (3). Recently, there has

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been an interest in high-fat diets because they result in reduced rates of glycogen depletion during exercise due to metabolic adaptations that enhance the utilization of fat as an energy source at rest and during exercise. These adaptations include decreased muscle and liver glycogen storage and rate of breakdown (4, 17, 22, 23), increased gluconeogenesis (4), increased muscle triacylglycerol storage and utilization (8, 16, 18, 24), increased mitochondrial oxidative capacity (1, 7, 18, 21, 25), increased ketone production (23), and decreased use of glycolysis-derived acetyl CoA. The effects of high-fat diets on performance are, however, equivocal with some studies showing that endurance capacity is impaired (12), not affected (10, 23), or enhanced (17). These variable responses could be due to differences in training status, exercise protocols, diet composition, or duration of the diet interventions.

The majority of high-fat diet studies have examined the effects on prolonged endurance capacity in highly trained athletes. Since metabolic demands vary widely depending on the intensity and duration of exercise, the effects of a high-fat diet on performance may differ depending on the specific exercise configuration. There is a paucity of data examining the effects of high-fat diets on high-intensity and supramaximal exercise performance. Lambert et al. (17) demonstrated that adaptation to a high-fat diet (70% of energy) for 2 weeks in trained cyclists resulted in no impairment in high-intensity exercise performance despite significantly reduced starting glycogen levels. Validation of this finding is important, especially considering the relatively low number of subjects ($n = 5$) in this study. Since many sports involve relatively short bouts of high-intensity exercise that rely heavily on anaerobic energy sources, it is important to further examine the effects of high-fat diets on high-intensity exercise performance in addition to endurance capacity. Thus, the primary purpose of the present investigation was to examine the effects of a 6-week high-fat diet on a variety of exercise performance measures, including maximal oxygen consumption, power output during high-intensity exercise, and prolonged endurance exercise.

Methods

Subjects

This study included 20 men between the ages of 19 and 56 who were screened using medical, nutrition, and exercise history questionnaires. In order to be eligible, subjects had to be recreationally active, habitually consume greater than 45% carbohydrate in their diet (assessed via 7-day food records), have no medical problems, not smoke, and have no goals of weight loss.

Experimental Design

This study utilized a two-group design with pre- and post-testing. Subjects were assigned to either a high-fat/moderate-protein (HFMP) diet or their habitual moderate- to high-carbohydrate diet for 6 weeks. Subjects logged their regular training during the 6-week training period. A maximal oxygen consumption test, two 30-s Wingate anaerobic tests, and a 45-min timed ride were performed prior to and after 6 weeks of diet and training. Initially, we determined each subject’s maximal oxygen consumption on a cycle ergometer and body composition via dual-energy X-ray

Table 1 Physical Characteristics of the Subjects

Variable	High-fat group	Control group
Age (yrs)	36 ± 12	35 ± 13
Weight (kg)	79.2 ± 8.3	85.4 ± 12.8
Fat mass (kg)	16.7 ± 5.6	19.9 ± 9.9
Lean body mass (kg)	60.4 ± 5.6	62.9 ± 5.5
VO_{2max} (L/min)	3.5 ± 0.49	3.84 ± 0.45
VO_{2max} (ml/kg/min)	44.2 ± 2.0	46.2 ± 3.8

Note. Values are means ± *SD.*

absorptiometry. The physical characteristics of both groups are shown in Table 1. No significant differences existed between groups in any variables at the start of the study.

Diet Intervention

The intervention diet was designed so that fat comprised approximately 60% of energy with no restrictions on the type of fat from saturated and unsaturated sources or cholesterol levels similar to previous studies in our laboratory (28, 29). We chose a diet intervention that would maximize metabolic adaptations favoring fat utilization. In order to obtain a diet with 60% fat that was palatable to subjects, the diet was also moderate in protein. The actual diets consumed were mainly comprised of beef (e.g., hamburger, steak), poultry (e.g., chicken, turkey), fish, oils, cheese, eggs, various nuts/seeds and peanut butter, vegetables, salads with low-carbohydrate dressing, protein powder, and water or low-carbohydrate diet drinks. Foods avoided or consumed infrequently included fruits and fruit juices, most dairy products (with the exception of hard cheeses and heavy cream), breads, cereals, beans, rice, desserts/sweets, or any other foods containing significant amounts of carbohydrate. A portion of the foods consumed during the intervention diet (approximately 30–40% of total energy) were provided to subjects during weekly meetings to review compliance with the registered dietitian. These foods included pumpkin seeds, roasted cheese, low-carbohydrate bars, shakes, and bake mix (Atkins Nutritionals Inc., Hauppauge, NY, USA) and protein shakes. Subjects were also provided with a daily multi-vitamin/mineral complex (Daily One Caps With Iron™, Twin Laboratories, Hauppauge, NY, USA).

Each subject received individual weekly dietary instruction on how to consume meals within the specified nutrient goals and to assess compliance. Subjects were provided with a packet outlining specific lists of appropriate foods, recipes, and sample meal plans that were compatible with their individual preferences and the nutrient profile goals of the intervention diet. Food measuring utensils and scales were provided to all subjects prior to the study to assist in the estimation of portion sizes of foods and beverages. Subjects kept records each day of the experiment (7 days during baseline and 42 days during the very low carbohydrate diet), and the control group kept 7-day records during Weeks 1 and 6. All recorded days were analyzed for nutrient content (*Nutritionist V*, v. 2.3, N-Squared Computing, First Databank Division, The Hearst Corporation, San Bruno, CA, USA).

Exercise Training

Subjects regularly participated in a variety of different exercise routines including walking, running, cycling, and cross-training. Approximately half of the subjects also participated in resistance exercise workouts at 2–4 sessions per week. Subjects were required to maintain their regular training routines and record the mode, duration, and intensity of each workout performed during the experimental period.

Procedures

Subjects reported to the laboratory on 2 nonconsecutive days prior to beginning the diet intervention and at the conclusion of the diet. Subjects were provided with standardized pre-exercise meals prior to all exercise tests to control for the effects of pre-exercise feedings on exercise performance (9). Subjects consumed a high-fat/low-carbohydrate meal consisting of 361 kcal (53% protein, 10% carbohydrate, and 37% fat) 2 h prior to the maximal oxygen consumption test and 221 kcal (40% protein, 5% carbohydrate, and 55% fat) 2 h prior to the Wingate anaerobic test and 45-min timed ride. Subjects were also instructed to refrain from vigorous exercise 24 h prior to the exercise test and to avoid caffeine 3 h prior to the exercise test. Subjects were weighed prior to each test. In order to ensure maximal effort, subjects were verbally encouraged by the same members of the research team during each exercise test.

Maximal Oxygen Consumption

A maximal oxygen consumption test was performed on an electronically braked Lode cycle ergometer (Instrumenten Lode, Groningen, Holland) previously described (27). Resistance was increased by 50 W every 3 min for the first 9 min and 25 W every 2 min thereafter until subjects could no longer maintain a pedaling frequency of 80 revolutions per minute. Heart rate was recorded at each stage by means of radiotelemetry using the Polar Vantage XL heart rate monitor (Polar, Kempelle, Finland). Ratings of perceived exertion (RPE) were recorded at each stage using the 6–20 scale (5). Inspired air volume was measured with a Parkinson-Cowen dry gas meter (Instrumentation Associates, New York, NY, USA) and expired gases were continuously sampled from a mixing chamber for analysis of oxygen (Applied electrochemistry, Sunnydale, CA, USA) and carbon dioxide (Beckman LB-2, Schiller Park, IL, USA). Gas analyzers were calibrated prior to each test with standard gases of known concentrations. The gas meter was calibrated with a 5-L syringe.

Wingate Sprints

Prior to the Wingate sprints, subjects warmed up for 5 min on a Cybex cycle ergometer (Cybex Norm, Rokankoma, NY, USA). They then performed two 30-s Wingate sprints with 2 min rest in between exercise bouts on a modified Monark cycle ergometer (Monark Inc., Varberg, Sweden), equipped with a lever arm to allow resistance to be added. The cycle ergometer was interfaced with a personal computer that allowed for determination of power output and percent fatigue during each 30-s sprint (Sports Medicine Industries Inc., St. Cloud, MN, USA). A load equal to 7% of the subject's body weight was added for resistance. Peak power was determined as the highest 1-s value recorded during each 30-s sprint. Mean power was determined as the average power during each 30-s sprint. Percent fatigue was determined as the percent decline from the highest to lowest power values during each 30-s sprint. Repeat performance tests on the cycle ergometer in our laboratory have an intraclass correlation coefficient of > 0.95.

Timed Ride

After the Wingate sprints, the subjects were given a 30-min rest before beginning a 45-min timed ride on a Cybex cycle ergometer (Cybex Norm, Rokankoma, NY, USA). The cycle ergometer was set on isokinetic mode at a speed of 80 rpm and interfaced with a computer using a Cybex emulator and data acquisition program. Steady state gas exchange was measured every 15 min. The mouthpiece and nose clips were placed on the subject approximately 2 min before the reading to ensure a steady state VO_2. Metabolic data was calculated using a 30-s rolling average of the data after subjects reached a steady-state VO_2 for approximately 1 min. Heart rate was recorded every 15 min using a Polar Vantage XL heart rate monitor. Work output (kJ) was collected cumulatively and recorded every 15 min. The coefficient of variation in work output during prolonged exercise (105 min) performed on repeated occasions in our laboratory was shown to be 0.5%.

Statistics

Data were analyzed using a two-way analysis of variance (ANOVA) with Group (HFMP and control) and Time (pre- and post-diet) as main effects. When a significant main effect or interaction effect was detected, a Fisher's LSD test was used to locate the pair-wise differences between means. The level of significance was set at $p \leq .05$.

Results

Dietary Intake, Body Mass, and Training

Daily intake of dietary energy and nutrients are presented in Table 2. All dietary nutrients were significantly different during the HFMP diet with the exception of dietary energy and alcohol consumption. Dietary protein, fat, and cholesterol were significantly greater, and dietary carbohydrate was significantly lower (8% of total energy) during the high-fat diet. There were no significant changes in dietary nutrient intake in the control group from week 1 to week 6. In the HFMP group, serum β-hydroxybutyrate concentrations were significantly increased at week 6 (0.08 ± 0.07 to 0.29 ± 0.09 mmol/L), and urinary ketones were positive as assessed daily with reagent strips (data not shown). All subjects in the HFMP group demonstrated β-hydroxybutyrate concentrations above 0.20 $\text{mmol} \cdot \text{L}^{-1}$, indicating compliance with the HFMP diet. Subjects in the HFMP group lost an average of 2.2 kg (from 79.2 ±

Table 2 Daily Intake of Dietary Energy and Nutrients

Variable	High-fat group (Week 0)	High-fat group (Week 6)	Control group (Week 0)	Control group (Week 6)
Energy (kcal)	2540 ± 590	2335 ± 375	2029 ± 469	1815 ± 195
Protein (g)	113 ± 40	176 ± 45*	82 ± 16	70 ± 10
Protein (%)	17 ± 4	30 ± 5*	16 ± 2	15 ± 1
Carbohydrate (g)	306 ± 100	46 ± 10*	287 ± 79	271 ± 47
Carbohydrate (%)	48 ± 10	8 ± 3*	55 ± 5	59 ± 7
Fat (g)	91 ± 31	157 ± 27*	65 ± 18	50 ± 14
Fat (%)	32 ± 8	61 ± 4*	29 ± 5	25 ± 8
SFA (g)	31 ± 12	56 ± 11*	21 ± 6	16 ± 6
SFA (%)	14 ± 4	25 ± 2*	14 ± 4	12 ± 4
MUFA (g)	27 ± 11	57 ± 12*	14 ± 5#	12 ± 8
MUFA (%)	12 ± 4	25 ± 3*	9 ± 2	9 ± 5
PUFA (g)	12 ± 6	24 ± 5*	9 ± 3	6 ± 3
PUFA (%)	6 ± 2	11 ± 2*	6 ± 1	4 ± 2
Cholesterol (mg)	332 ± 126	741 ± 254*	130 ± 14#	118 ± 7
Alcohol (%)	3 ± 3	1 ± 2	0 ± 0	0 ± 1

Note. Values are mean ± *SD*. *$p \le .05$ versus corresponding Wk 0 value. #$p \le .05$ versus corresponding high-fat group value.

8.3 kg to 77.0 ± 7.5 kg) ($p \le .05$), while control subjects gained an average of 0.1 kg (from 85.4 ± 12.8 kg to 85.8 ± 12.0 kg). Data from exercise logs indicated that there were no changes in physical activity patterns of subjects.

Maximal Oxygen Consumption

No change was noted in relative maximal oxygen consumption ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) in either group (Table 3). However, a significant decrease was observed in absolute terms (L/min) in the HFMP group. Although not significant, maximal heart rate was lower in the HFMP group after 6 weeks ($p = .052$) while no change was noted in the control group. Maximal RER values declined significantly from week 0 to week 6 in the HFMP group, while the control group remained unchanged. In the HFMP group, the RPE ratings were significantly higher after 6 weeks at 9 min and 11 min (Table 4). There was no significant change in RPE in the control group. No change was noted in total test time in either group.

Wingate Tests

Peak and mean power output decreased significantly from week 0 to week 6 in the HFMP group for the first of two 30-s Wingate sprints, while the control group remained unchanged ($p = .25$). When analyzed relative to body weight (W/kg),

Table 3 Maximal Oxygen Consumption Data

Variable	High-fat Wk 0	High-fat Wk 6	Control Wk 0	Control Wk 6
VO_{2max} (ml/kg/min)	44.2 ± 2.0	42.8 ± 1.1	45.5 ± 3.3	45.2 ± 3.6
VO_{2max} (L/min)	3.50 ± 0.1	3.27 ± 0.1*†	3.84 ± 0.2	3.82 ± 1.6
Max HR (bpm)	187 ± 3.5	181 ± 3.5	178 ± 3	175 ± 3
RER	1.19 ± 0.02	1.13 ± 0.02*	1.14 ± 0.01	1.14 ± 0.01

Note. Values are mean ± *SEM*. *$p \leq .05$ from corresponding Wk 0 value. †$p \leq .05$ from corresponding control value.

however, only peak power output in the HFMP group decreased significantly. No change was noted in either variable in the HFMP or control group during bout 2. The percent decline in power output was not affected in either group (Table 5).

Timed Ride

During the 45-min cycling bout, work output for the HFMP group was significantly reduced from week 0 to week 6 at 15, 30, and 45 min (Figure 1). These values corresponded with significantly decreased RER values at 15 and 30 min for this group (Figure 2). No change was noted in either of these variables for the control group. Oxygen consumption was unchanged except for a significant decrease at the 15-min time point in the HFMP group. Heart rate responses were not affected in either group.

Discussion

The primary purpose of the present investigation was to examine the effects of a 6-week HFMP diet on a variety of exercise performance measures including peak oxygen consumption, power output during high-intensity exercise, and prolonged endurance exercise. We chose subjects who were physically active but not highly trained in order to capture a wider segment of the population. We have previously shown a high degree of dietary compliance to the HFMP diet used in this study as indicated by increased blood and urine ketone levels (28, 29) and this was the case in this study as well. In our prior high-fat (ketogenic) diet studies we have found it difficult to prevent weight loss despite aggressive dietary counseling (28), which was also the case in this study as subjects lost a mean 2.2 kg over 6 weeks. Nevertheless, our results indicate that adaptation to a HFMP diet in non-highly trained men does not improve exercise performance and may slightly impair maximal aerobic

Table 4 Ratings of Perceived Exertion During the Maximal Oxygen Consumption Test

	3 min		6 min		9 min		11 min	
Variable	Pre	Post	Pre	Post	Pre	Post	Pre	Post
HFMP	8.1 ± 1.8	8.5 ± 1.9	10.1 ± 1.8	11.2 ± 2.8	12.3 ± 1.4	13.8 ± 2.7*	14.7 ± 1.7	16.3 ± 2.8*
Control	8.0 ± 1.9	7.0 ± 1.3	10.0 ± 1.9	8.9 ± 1.5	11.9 ± 1.6	11.6 ± 1.2	13.6 ± 1.1	13.6 ± 0.9

Note. Values are means ± *SD*. *p < .05 from corresponding pre value.

Table 5 Wingate Power Output Data (W)

Variable	High-fat Wk 0	High-fat Wk 6	Control Wk 0	Control Wk 6
Bout 1 PP (W)	878.7 ± 38.9	786.2 ± 36.2*	872.0 ± 49.5	805.6 ± 48.7
Bout 1 MP (W)	537.5 ± 21.4	426 ± 17.8*	543.8 ± 26.0	455.0 ± 11.0
Bout 1 % decline	56.6 ± 2.5	61.1 ± 2.1	54.7 ± 2.5	62.2 ± 2.4
Bout 2 PP (W)	798.7 ± 33.0	751.9 ± 28.6	820.0 ± 44.4	763.6 ± 40.7
Bout 2 MP (W)	501.9 ± 17.8	411.6 ± 14.7	538.0 ± 27.6	456.9 ± 19.8
Bout 2 % decline	55.1 ± 2.6	61.6 ± 2.3	50.8 ± 1.8	55.4 ± 2.3
Bout 1 PP (W/kg)	11.2 ± 0.5	10.2 ± 0.5*	102.2 ± 0.5	9.6 ± 0.6
Bout 1 MP (W/kg)	6.7 ± 0.2	6.5 ± 0.2	6.0 ± 0.4	6.3 ± 0.4
Bout 2 PP (W/kg)	9.4 ± 0.5	9.5 ± 0.4	9.7 ± 1.0	8.9 ± 0.5
Bout 2 MP (W/kg)	5.3 ± 0.2	5.3 ± 0.2	5.4 ± 0.3	5.4 ± 0.4

Note. Values are mean ± *SEM*. PP = peak power; MP = mean power. *$p \le .05$ from corresponding Wk 0 value.

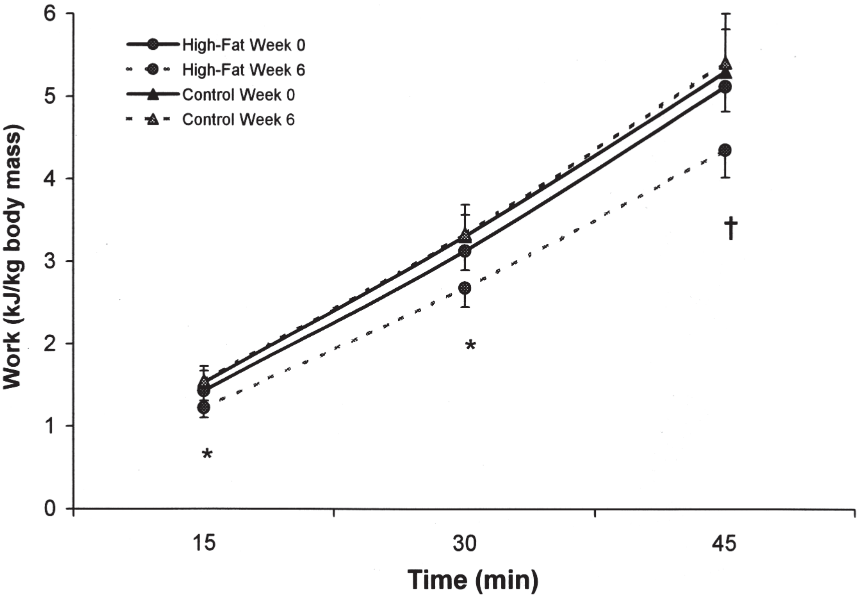

Figure 1 — Work output during the 45-min timed ride. *p £ .05 from corresponding week 0 value. †p £ .05 from corresponding control value.

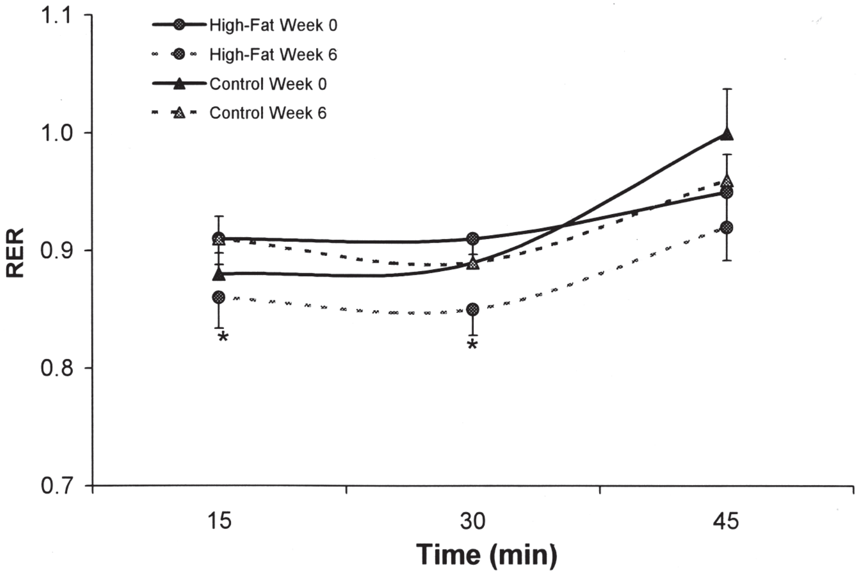

Figure 2 — Respiratory exchange ratios during the 45-min timed ride. *_p_ £ .05 from corresponding week 0 value.

capacity, peak power output, and endurance capacity when associated with a small but significant loss in body mass.

Maximal Oxygen Consumption

Adaptation to the HFMP diet resulted in a reduction in maximal oxygen consumption that could be attributed to a reduction in body mass. Phinney et al. (23) found no change in VO_{2max} (L/min) after 3 weeks of an isocaloric high-fat (ketogenic) diet in trained cyclists. Similarly, Helge et al. (12) reported no difference in VO_{2max} between a high-fat and a high-carbohydrate group after 7 and 8 weeks of training in previously sedentary subjects. Neither of these studies, however, reported any weight loss. Subjects reported a higher perceived exertion during the maximal oxygen test after the HFMP diet in this study, which could lead to premature termination of the maximal test. However, duration of the test was not affected in either group. Thus, it appears that diet composition has little effect of maximal aerobic capacity independent of weight loss.

Wingate Performance

Adaptation to the HFMP diet resulted in a significant decrease in peak power during bout 1 of the Wingate tests. In contrast, Lambert et al. (17) reported that peak power output was similar after a 2-week high-fat diet compared to a high-carbohydrate diet during a 30-s Wingate sprint. Several potential mechanisms could explain the decreased performance in the Wingate test. The longer adaptation period in the present study (6 weeks) may have resulted in greater glycogen depletion or a decreased ability to utilize muscle glycogen as an energy source, forcing the muscles to rely upon the less efficient process of fat oxidation during high-intensity exercise (13). The HFMP diet presumably resulted in decreased muscle glycogen levels to approximately half after 2 to 4 weeks (17, 23). The effects of reduced muscle glycogen on the rate of glycogenolysis and high-intensity exercise is controversial. Although there are studies demonstrating that lower than normal initial glycogen levels decrease the rate of glycogenolysis and short-term, high-intensity exercise performance (6, 14, 20), several reports indicate that reduced pre-exercise glycogen levels do not impair performance (2, 15, 26). Alternatively, the reduction in body mass could have resulted in reduced force-producing capabilities; however, a significant reduction in peak power remained after correction for changes in body mass (Table 4). The HFMP diet may have resulted in mild acidosis and decreased buffering capacity, leading to decreased power output (11).

Perhaps the most likely explanation is a reduction in the phosphorylation potential after the HFMP diet. This hypothesis is based on data from a study that used 31P-magnetic resonance spectroscopy to study how diet modulates skeletal muscle bioenergetics and short-term exercise capacity. Compared to a diet rich in fat, a high-carbohydrate diet improved exercise efficiency through beneficial effects on intracellular phosphorylation potential independent of changes in intracellular pH (19). Incremental exercise time to exhaustion after 5 days of the high-fat diet was significantly reduced compared to 5 days on the high-carbohydrate diet. Incremental time to exhaustion was related to the slope of skeletal muscle phosphocreatine/Pi ratio, which reflects the phosphorylation potential of the cell (ATP/ADP + P_i).

Timed Ride

During the 45-min timed ride, work output was significantly decreased after the HFMP diet. In agreement, Helge et al. (12) reported that ingestion of a high-fat diet while performing endurance training for 7 weeks resulted in sub-optimal endurance training adaptations. In contrast, Phinney et al. (23) reported maintaining endurance performance after a 4-week high-fat diet in trained cyclists, and Lambert et al. (17) reported increased time to exhaustion at 60% VO_{2max} after a high-fat diet compared to a high-carbohydrate diet. These differences in endurance performance among studies are difficult to reconcile. Training status may play a role, as subjects were untrained in the study by Helge et al. (12) and had a similar VO_2 as subjects in this study. It is questionable whether glycogen depletion played a role in our 45-min timed trial. Even when glycogen and glucose levels are restored after adaptation to a high-fat diet, sub-optimal endurance performance persists (12), indicating that some aspect of a high-fat diet other than carbohydrate availability adversely affects endurance performance in non-highly trained subjects. Although speculative, changes in membrane composition, buffering capacity (11), perceived exertion, reduced body mass, or negative energy balance could be responsible.

Adaptation to a 6-week HFMP diet in non-highly trained men resulted in increased fat oxidation during exercise and small decrements in peak power output and endurance performance. Although this study did not attempt to establish the mechanisms for these performance effects, the deleterious effects on exercise performance may be accounted for in part by a reduction in body mass and/or increased ratings of perceived exertion.

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