Effect of Low-and High-carbohydrate Diets on Swimming Economy: A Crossover Study

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Abstract

Background: Swimming economy refers to the rate of energy expenditure relative to swimming speed of movement, is inversely related to the energetic cost of swimming, and is as a key factor influencing endurance swimming performance. The objective of this study was to determine if high-carbohydrate, low-fat (HCLF) and low-carbohydrate, high-fat (LCHF) diets affect energetic cost of submaximal swimming.

Methods: Eight recreational swimmers consumed two 3-d isoenergetic diets in a crossover design. Diets were tailored to individual food preferences, and macronutrient consumption was 69-16-16% and 16-67-18% carbohydrate-fat-protein for the HCLF and LCHF diets, respectively. Following each 3-d dietary intervention, participants swam in a flume at velocities associated with 50, 60, and 70% of their maximal aerobic capacity (VO_{2max}). Expired breath was collected and analyzed while they swam which enabled calculation of the energetic cost of swimming. A paired t-test compared macronutrient distribution between HCLF and LCHF diets, while repeated-measures ANOVA determined effects of diet and exercise intensity on physiological endpoints.

Results: Respiratory exchange ratio was significantly higher in HCLF compared to LCHF (p = 0.003), but there were no significant differences in the rate of oxygen consumption (p = 0.499) or energetic cost of swimming (p = 0.324) between diets. Heart rate did not differ between diets (p = 0.712), but oxygen pulse, a non-invasive surrogate for stroke volume, was greater following the HCLF diet (p = 0.029).

Conclusions: A 3-d high-carbohydrate diet increased carbohydrate utilization but did not affect swimming economy at 50-70% VO_{2max}. Although these intensities are applicable to ultramarathon swims, future studies should use higher intensities that would be more relevant to shorter duration events.

Introduction

Movement economy refers to the rate of energy expenditure relative to speed of movement (*i.e.*, cycling, running, or swimming), and has been identified as a key factor influencing endurance sport performance (1). It is a multifactorial phenomenon reflecting various metabolic, cardiorespiratory, biomechanical, and neuromuscular characteristics of an athlete (2). While economy during running and cycling is commonly measured via indirect calorimetry, it has traditionally been difficult collect a swimmer’s expired breath due to logistical constraints. However, the use of a swim flume allows control of a swimmer’s velocity and enables metabolic measurements to be obtained by keeping the swimmer stationary.

Swimming economy may be a strong predictor of success in long-distance swims such as the 10-km marathon and ultramarathon events (> 10 km) where using less energy at the submaximal swimming speeds is important. Economy may have a greater influence on swimming performance compared to cycling or running economy because swimmers move through water, a fluid 784 times denser than 25 °C air at sea level. Women have better swimming economy than men (3), which may explain the decreasing gap between sexes as swimming distances get longer (4), and the observation that women complete ultramarathon swims as fast as or faster than men (5). Other factors that affect swimming economy include age, training status, body size, hydrostatic lift, and torque (6, 7). Accordingly, research into factors that affect swimming economy may improve performance in these events.

Economy is calculated from the rate of energy expenditure and velocity during steady-state, submaximal exercise. The relationship between the rate of carbon dioxide production (VCO_2) and the rate of oxygen consumption (VO_2) determines the respiratory exchange ratio (RER) and is a direct measurement of substrate utilization (8). Carbohydrate oxidation results in a greater caloric value per liter of O_2 consumed compared with fat oxidation due to the differences in molecular structure of glucose and free fatty acids (8). A number of factors influence substrate utilization during exercise including sex (9), exercise intensity (10), training status (11), exercise duration (12), and dietary pattern (13). Dietary pattern is perhaps the easiest way to modify substrate utilization during submaximal exercise, as just one day of a carbohydrate-rich diet (63% carbohydrate) increased RER during exercise compared with a fat-rich diet (14).

It is possible that movement economy may be influenced by dietary pattern. An increase in cycling efficiency (*i.e.*, lower rate of energy expenditure at the same power) has been reported following three days of a high-carbohydrate diet (15). Movement economy has also decreased (*i.e.*, higher rate of energy expenditure at the same velocity) in runners and race walkers following 3–4 weeks of low-carbohydrate dietary interventions (16, 17).

To our knowledge, the effect of diet on swimming economy has not been studied. Therefore, the aim of this research is to determine the influence of three days of high- and low-carbohydrate diets on the energetic cost of submaximal swimming. We hypothesized that a high-carbohydrate diet would result in improved swimming economy (*i.e.*, lower energetic cost of swimming; C_s) due to increased RER and, therefore, greater energy conversion per volume of oxygen consumed when utilizing carbohydrates compared to fats.

Methods

Experimental overview

This study used a randomized, crossover design with participants reporting to the laboratory on three days (Fig. 1). The first visit consisted of an incremental swimming test to volitional fatigue in a swim flume to determine maximal aerobic capacity (VO_{2max}). The second and third visits consisted of submaximal swimming at the velocities at 50, 60, and 70% of VO_{2max} as determined during the first visit. Prior to the second and third visits, participants consumed either a high-carbohydrate, low fat (HCLF) or a low-carbohydrate, high-fat (LCHF) diet. Dietary interventions were randomly assigned and separated by a 4-day washout period.

Participants

Eight healthy, experienced swimmers (4 male, 4 female, 34.6 ± 9.4 years old, BMI 23.8 ± 2.6 kg m^{-2}, VO_{2max} 42.4 ± 8.5 ml kg^{-1} min^{-1}, average swim training volume 5.2 ± 2.3 h per week) were recruited from a local swim club. To be included in the study, participants had to be between the ages of 18–59 years old, swimming > 3 km per week, and be willing to manipulate their dietary patterns for two weeks. Participants were informed of the risks and benefits of participating and provided written informed consent before participating in the study. This study was approved by the California State University, Los Angeles Institutional Review Board (protocol #1419221).

Procedures

Height and weight were collected on their first visit using a high-capacity column scale (Seca 703, Hamburg, Germany). Participants were instructed to refrain from vigorous exercise for 24 hours prior to each visit. All swim tests were completed using a 4.27 × 2.13 m outdoor swimming flume (Endless Pools, Aston, PA, USA). The water depth was maintained at 1.14 m. Water temperature was maintained at 27 °C.

During the first visit, subjects completed an incremental swimming test to exhaustion for determination of VO_{2max}. Following a self-selected 5–10 min warm-up in a 22.9-m outdoor pool, participants transitioned to the flume for a 1–2 min familiarization swim. For the graded exercise test, the initial intensity was set at 0.93 m s^{-1} (1:47 per 100 m) with the speed increasing by 0.09 ± 0.01 m s^{-1} every 2 min. The test was terminated when participants could no longer maintain pace or when they reached volitional fatigue. Heart rate (HR) was continuously monitored via telemetry (Polar T31, Kempele, Finland). Breath-by-breath gas exchange data were continuously measured using a metabolic cart (Quark CPET; Cosmed, Rome, Italy). The VO_{2max} was determined as the highest 10-s average. The gas analyzers on the metabolic cart were calibrated to ambient air and certified standard gas of known concentration (16% O_2, 5% CO_2, 79% N_2) and gas volume was calibrated with a 3-L syringe.

For the second and third visits participants arrived in a fasted state, with trials performed in the morning at the same time of day following both diet interventions. Participants were allowed a self-selected 5–10 min warm-up in the pool prior to the start of the test. Swimming speeds were established based on the speeds eliciting 50, 60, and 70% of their VO_{2max} during the incremental test on the first visit. The subjects swam at each speed for five minutes and each trial was separated by a brief rest period to drain the snorkel of any collected fluids and provide water ad libitum. Heart rate and breath-by-breath respiratory measurements were continuously collected throughout the exercise trial. Average values over the last two minutes of each 5-min stage were used for analysis of VO_2 and VCO_2. Rate of energy expenditure (EE) was calculated according to the equation of Péronnet & Massicotte (18) and assumed negligible protein oxidation:

EE ($J\ s^{-1}$) = 281.67 (VO_2; $L\ min^{-1}$) + 80.65 (VCO_2; $L\ min^{-1}$) (Eq. 1)

The rate of EE was divided by the swimming speed to determine C_s. Oxygen pulse, a non-invasive estimate of stroke volume was calculated for each participant by dividing VO_2 by heart rate (19).

Dietary intervention

Prior to enrollment participants were asked to complete a 3-day dietary food recall on three consecutive weekdays (Wednesday – Friday). Participants were provided with diet record sheets and instructed to accurately record all food and drinks consumed with estimates based on basic household portion sizes. Based on their individual eating behaviors and dietary preferences, individualized HCLF (70% carbohydrate, 15% fat, 15% protein) and LCHF (15% carbohydrate, 70% fat, 15% protein) diets were created using dietary analysis software (ESHA Food Processor Nutrition Analysis, Salem, OR, USA) and provided to each participant. Total energy intake was determined as the average of the Harris-Benedict and Mifflin-St. Jeor resting energy expenditure equations (20, 21), multiplied by an activity factor of 1.55. Participants received individualized counseling and instruction on how to follow the diets, as well as basic kitchen measuring equipment and a food-safe digital scale (Etekcity, Digital Kitchen Scale, EK6015, Anaheim, CA, USA). Diet instructions were provided on a Monday and participants were told to follow them as closely as possible for the subsequent Wednesday–Friday, before arriving in the fasted-state on Saturday morning for testing. Subjects noted any deviations from their prescribed diets. Seven participants followed the standard protocol with a 4-day washout period between dietary interventions, but due to scheduling conflict one participant had an 11-day washout period.

Statistical analysis

All data are reported as means and standard deviations. Dietary intake is reported as the average over three days and analyzed with a paired t-test, after confirming normality of the data. Repeated measures analysis of variance (2 diets x 3 exercise intensities) determined main effects for diet and exercise intensity on physiological endpoints with Bonferroni corrections used for post hoc testing. The Greenhouse-Geisser correction was used when sphericity was not met. Analyses were performed using Jamovi (Version 1.2.16.0, www.jamovi.org) with statistical significance at $p < 0.05$.

Results

The macronutrient distribution (carbohydrate-fat-protein) consumed by participants was 68.6-15.5-16.0% for the HCLF group and 15.6-66.7-17.6% for the LCHF group (Table 1). Overall energy intake did not differ between diets ($p = 0.363$). Carbohydrate intake was greater and fat intake was lower (both $p < 0.001$) with the HCLF diet. Protein intake was greater with the LCHF diet ($p = 0.013$).

Table 1
Macronutrient intake for the high-carbohydrate, low fat (HCLF) and low-carbohydrate, high-fat (LCHF) diets (N = 8).

Diet	Daily energy intake		Carbohydrate			Fat			Protein		
	kcal	kcal kg^{-1}	g d^{-1}	g kg^{-1}	% EI	g d^{-1}	g kg^{-1}	% EI	g d^{-1}	g kg^{-1}	% EI
HCLF	2567 ± 463	34.1 ± 3.4	430 ± 82.6	5.7 ± 0.6	68.6 ± 1.4%	42.3 ± 8.5	0.6 ± 0.1	15.5 ± 1.1%	98.3 ± 14.3	1.3 ± 0.1	16.0 ± 1.2%
LCHF	2611 ± 436	34.7 ± 3.0	100 ± 23.8	1.3 ± 0.2	15.6 ± 1.8%	185 ± 30.1	2.5 ± 0.2	66.7 ± 2.3%	110 ± 19.1	1.5 ± 0.2	17.6 ± 1.2%
p	0.363		< 0.001			< 0.001			0.013		

Relative swimming intensity during each submaximal stage corresponded to 56.7 ± 1.1%, 63.1 ± 0.3%, and 73.6 ± 1.1% VO_{2max} for stages 1, 2 and 3, respectively, with no differences between diets (p = 0.970). Actual swimming speeds were 0.95 ± 0.10 m s^{-1}, 1.05 ± 0.11 m s^{-1}, and 1.12 ± 0.10 m s^{-1}. Rate of O_2 consumption increased with exercise intensity (F(1.18,8.23) = 23.79, p < 0.001), but there was no difference between diets (Fig. 2a). Participants had a higher RER following the HCLF diet (F(1, 7) = 19.59, p = 0.003) and RER differed with exercise intensity (F(1.20,8.43) = 7.67, p = 0.020, Fig. 2b). Energetic cost of swimming ranged from 649 J m^{-1} at 50% VO_{2max} on the LCHF diet to 755 J m^{-1} at 70% VO_{2max} on the HCLF diet. There was a significant effect of exercise intensity (F(1.21,8.48) = 8.49, p = 0.015) but not diet (F(1, 7) = 1.12, p = 0.324) on C_s (Fig. 2c)

One female participant's HR monitor malfunctioned during the LCHF testing, so her data was excluded from all HR and O_2 pulse aggregate data. Heart rate increased with exercise intensity (F(2, 12) = 59.7, p < 0.001), but there were no differences in HR between diets (F(1, 6) = 0.15, p = 0.712, Fig. 3a). Oxygen pulse was greater in the HCLF diet (F(1, 6) = 8.17, p = 0.029), with significant main effects of exercise intensity (F(1.16, 6.99) = 10.02, p = 0.014), and a significant interaction between diet and intensity (F(2, 12) = 7.03, p = 0.010, Fig. 3b).

Discussion

The purpose of this study was to determine the influence of a 3-day, high- or low-carbohydrate diet on swimming economy in recreationally-trained swimmers. It was hypothesized that the HCLF diet would increase carbohydrate utilization relative to a LCHF diet, resulting in an increase energy conversion per volume of O_2 consumed. Although RER was greater during exercise following three days of a HCLF diet, no differences in VO_2 or C_s were detected. Therefore, these data do not support our original hypothesis because there was no improvement in swimming economy (*i.e.*, a reduction in C_s) with the HCLF diet. In addition, HR did not differ between diets, although O_2 pulse, a non-invasive estimate of stroke volume, was greater following the HCLF diet. To our knowledge, this is the first study investigating the effects of diet on swimming economy.

Results from the present study are in contrast with previous research reporting an effect of diet on movement economy in cyclists, runners, and race walkers (15–17). It is possible that exercise intensities used in our study may have been lower than in the previous studies and, therefore, more reliant on fat oxidation. In support of this, Shaw et al. (16) reported that running economy was impaired at intensities over 70% VO_{2max}, but preserved at intensities lower than 60% VO_{2max}, following 31 days of a low-carbohydrate diet in trained runners. Additionally, four weeks of a LCHF diet had no impact on cycling economy in endurance-trained athletes cycling at ~ 63% VO_{2max} (22). Other research has shown that a LCHF diet impaired movement economy during exercise at 70–90% VO_{2max} following 3-week diet and training interventions in elite male race walkers (17) and in recreationally-trained male runners (23). Additionally, three days of a high-carbohydrate diet (70% of energy intake) increased cycling gross efficiency (*i.e.*, improved cycling economy) at 70–75% VO_{2max} compared with both low- and moderate-carbohydrate diets in trained cyclists (15).

Differences in training status may also have affected our results, as higher-caliber athletes generally have better running economy (2) and cycling efficiency (24). The VO_{2max} values of our participants averaged 42.4 ml kg^{-1} min^{-1} whereas other studies showing an effect of diet on economy used participants with a mean VO_{2max} of 56–66 ml kg^{-1} min^{-1} (15–17). However, swimmers tend to have lower VO_{2max} values measured while swimming compared to running (25, 26) and triathletes record higher VO_{2max} values when cycling or running compared to swimming (26, 27), so we likely underestimated the true VO_{2max} of our subjects. Previous research has also shown that 5–7 days of a LCHF diet reduced cycling efficiency in sedentary subjects, but not in trained athletes, possibly due to lower levels of uncoupling proteins found in the trained athletes (28, 29). Therefore, it is possible that differences in subject training status underpin the lack of differences observed between diets in our study.

Differences in mode of exercise may also explain the lack of effect of diet in the present study. For swimming, minimizing drag force and maximizing propelling efficiency (*i.e.*, maximizing useful power and minimizing wasted power) are adaptations of higher-caliber swimmers that improves swimming economy (30). In addition, swimming technique likely plays a greater role in swimming economy than cycling or running technique do for economy in those sports as the swimmer moves through water. Therefore, any diet effects on swimming economy may have been masked by slight changes in external factors between trials.

There is also the potential that anaerobic metabolism was greater following the HCLF diet that could explain the increased economy as measured by indirect calorimetry. We did not assess blood lactate at the end of each submaximal swimming trial. However, Cole et al. (15), Burke et al. (17), and Shaw et al. (16) all measured blood lactate concentration and found no differences between diets during submaximal exercise intensities. In the present study, we found VO_2 stabilized between 2–3 min into each 5-min stage (*data not shown*), indicating subjects were below their critical swimming velocity, above which VO_2 and lactate will not stabilize (31).

Aggregate C_S in our study ranged from 649–755 J m^{-1}. Higher C_S values (690–1310 J m^{-1}) have been reported while swimming at faster speeds (32), while lower values (593 J m^{-1}) have been reported when swimming with legs held together by an ankle strap and supported by a pull buoy (33). In comparison, the energetic cost of running and race walking are approximately half of C_S values reported in the present study (16, 17). Therefore, the values for C_S are consistent with previous research, and swimming is more costly than running or race waking.

Oxygen pulse was higher following the HCLF diet. Although body weight and hydration status were not measured in this study, it is likely that the high-carbohydrate group had an increase in total body water when performing the swimming test due to increases in muscle glycogen (34). However, water stored with muscle glycogen would increase intracellular but not extracellular water content (35), though it is possible that this extra water may have played a role in the increased oxygen pulse observed during submaximal exercise in following the HCLF diet.

A strength of this study is that the diets were individually tailored for each participant, based on their habitual food choices. Participants were required to shop for and prepare all of their own food in the quantities specified, and could communicate with the researchers about food choices and potential substitutions if needed. This design increases the ecological validity of this study as most recreationally-active swimmers do not have access to the same resources as collegiate and professional swimmers whose diet and exercise volume can be more closely monitored. It is possible that participants could have been untruthful in recording their diets, although the difference in RER between diets suggests acceptable adherence. Protein intake was significantly different between groups (16.0 for HCLF *vs*. 17.6% for LCHF), but this difference is likely too small to impact the results of this study.

Conclusions

To our knowledge, this study was the first to examine the effects of macronutrient intake on swimming economy. The high-carbohydrate diet increased carbohydrate utilization but did not improve swimming economy. Future research should focus on how diet affects swimming economy during long-duration swims where combating fatigue and maintaining swimming economy are important for success in marathon and ultramarathon swimming events.

Abbreviations

HCLF
High-carbohydrate, low-fat
LCHF

Low-carbohydrate, high-fat
VO_{2max}
Maximal aerobic capacity
VCO_2
Rate of CO_2 production
VO_2
Rate of O_2 consumption
RER
Respiratory exchange ratio
EE
Rate of energy expenditure
C_S
Energetic cost of swimming

Declarations

Ethics approval and consent to participate.

Participants were informed of the risks and benefits of participating and provided written informed consent before participating in the study. This study was approved by the [[NAME OF UNIVERSITY]] Institutional Review Board (protocol #1419221).

Consent for publication.

Not applicable.

***Availability of data and materials*.**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests.

The authors declare that they have no competing interests.

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There was no funding source for this study.

Authors' contributions.

The study was designed by MB, JR and GC; data were collected by MB and GC, data were analyzed by MB, JR and GC; data interpretation and manuscript preparation were undertaken by MB, JR and GC. All authors approved the final version of the paper.

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Figures

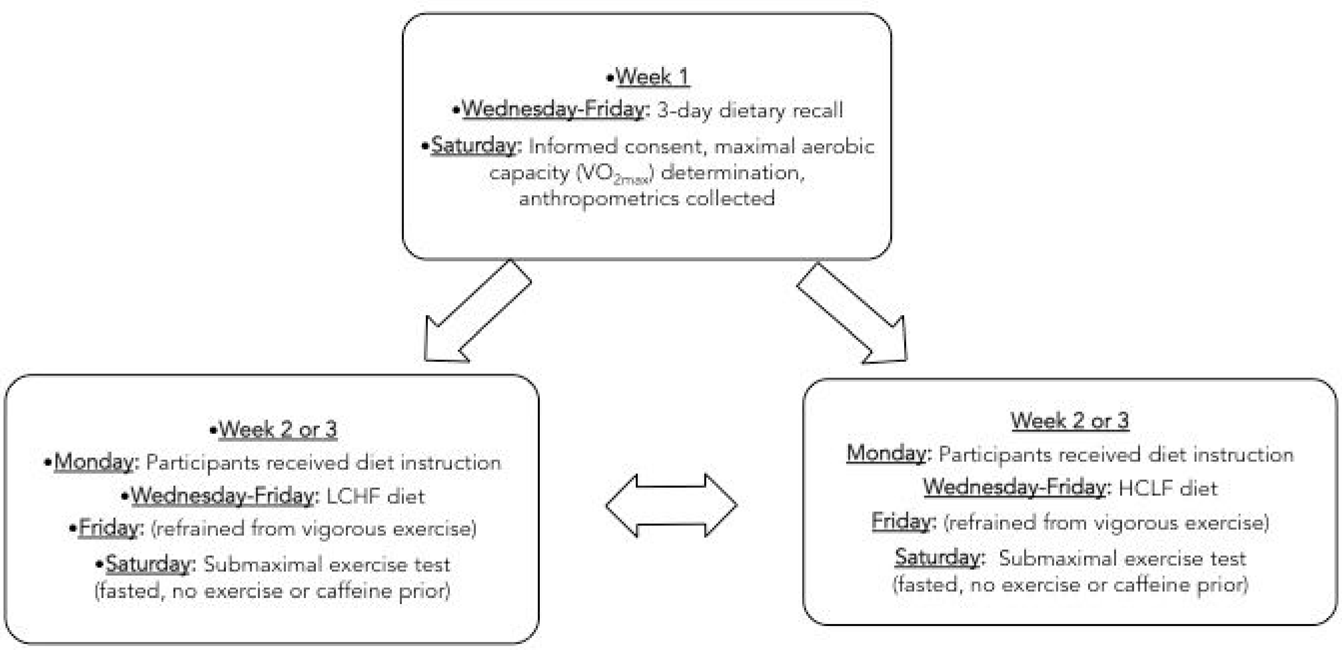

Figure 1

Schematic of study design. VO2max = maximal aerobic capacity; HCLF diet = high-carbohydrate, low-fat diet; LCHF = low-carbohydrate, high-fat diet.

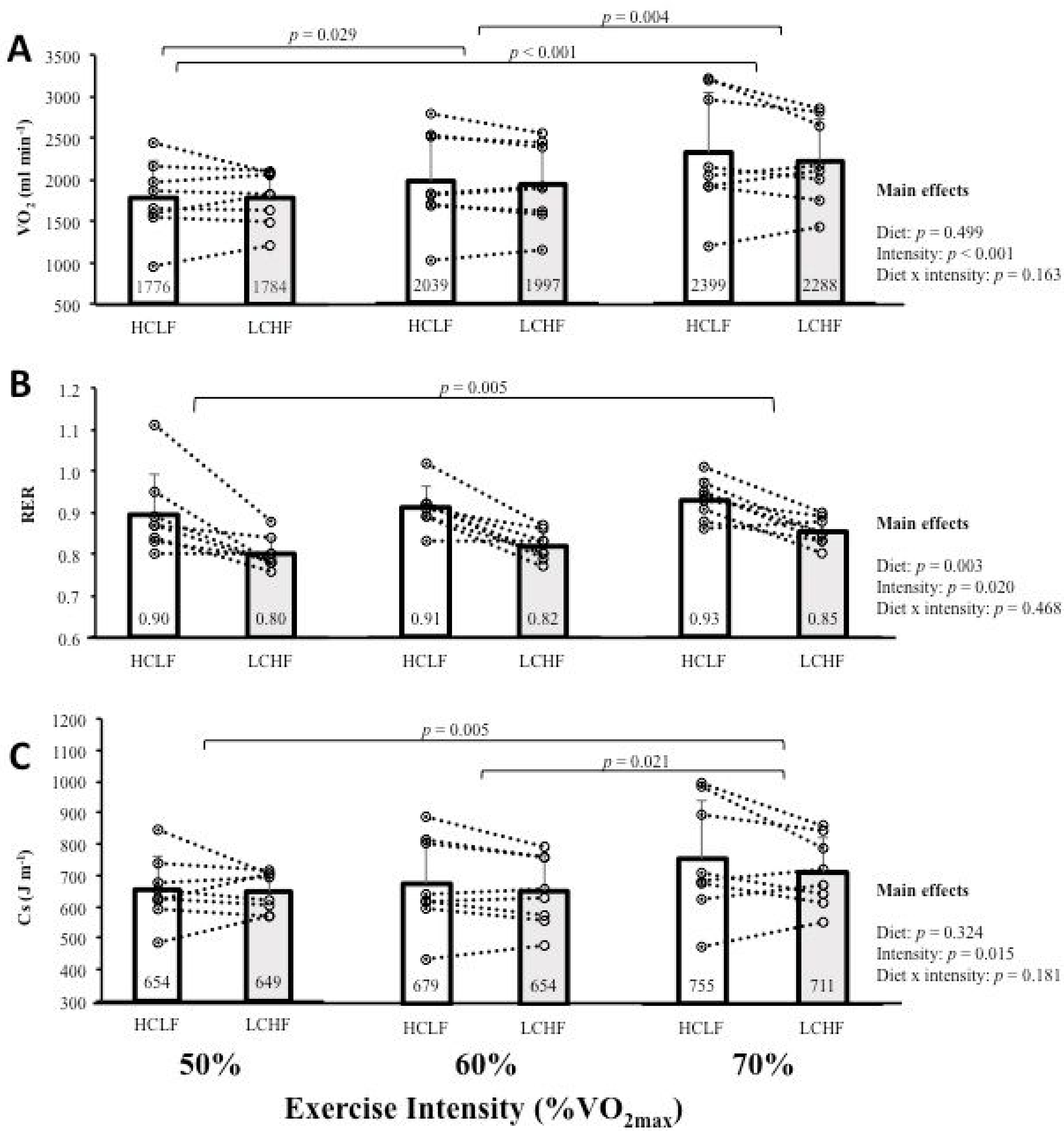

Figure 2

Rate of oxygen consumption (VO2, panel A), respiratory exchange ratio (RER, panel B), and energetic cost of swimming (CS, panel C) at swimming velocities corresponding to approximately 50, 60, and 70% of maximal aerobic capacity (VO2max) following 3 days of high-carbohydrate, low-fat (HCLF) and low-carbohydrate, high-fat (LCHF) diets. Bar graphs denote mean responses and error bars denote standard deviations for 8 subjects. Data points connected by dotted lines denote individual responses.

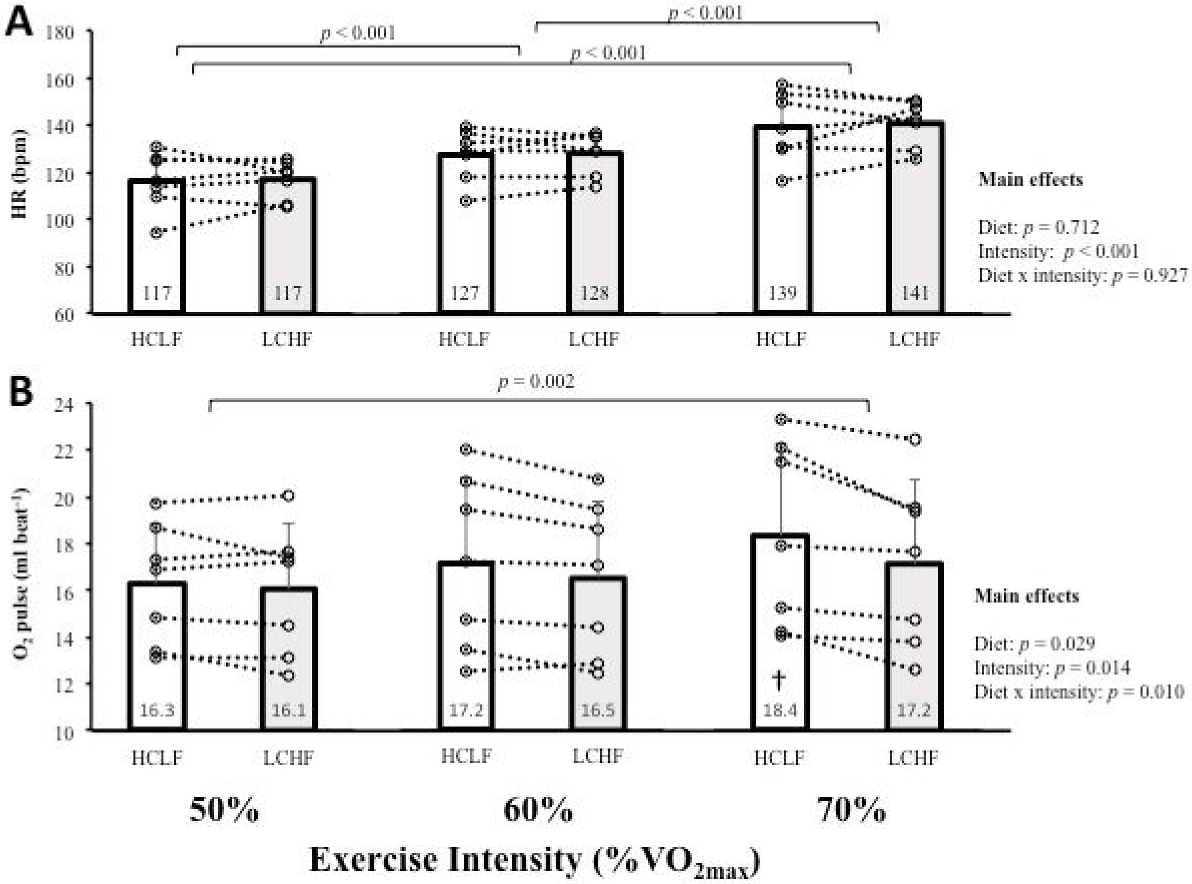

Figure 3

Heart rate (HR, panel A) and oxygen pulse (panel B) at swimming velocities corresponding to approximately 50, 60, and 70% of maximal aerobic capacity (VO2max) following 3 days of high-carbohydrate, low-fat (HCLF) and low-carbohydrate, high-fat (LCHF) diets. Bar graphs denote mean responses and error bars denote standard deviations for 7 subjects (one subject omitted due to technical difficulties with HR measurement). Data points connected by dotted lines denote individual responses. † denotes significantly different from HCLF 50% and different from LCHF at all intensities (p< 0.02).