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A Low-Carbohydrate Ketogenic Diet Combined with 6-Weeks of Crossfit Training Improves Body Composition and Performance

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Abstract

Background: The purpose of this research was to examine the effects of a 6-week LCKD and CrossFit program on body composition and performance.

Methods: Twenty-seven non-elite CrossFit subjects (mean ± SD age = 34.58 ± 9.26 years) were randomly assigned to a LCKD (males, n = 3; females, n = 9) or control (CON) (males, n = 2; females, n = 13) group. LCKD was instructed to consume an ad libitum diet and restrict carbohydrate intake to less than 50 grams per day and CON maintained usual dietary intake. All subjects participated in four CrossFit training sessions per week during the 6 weeks.

Results: Compared to CON group, the LCKD group significantly decreased weight (0.18 ± 1.30, -3.45 ± 2.18 kg), BMI (0.07 ± 0.43, -1.13 ± 0.70 kg/m^2), percent body fat (% BF) (0.01 ± 1.21, -2.60 ± 2.14 %), and fat mass (FM) (0.06 ± 1.12, -2.83 ± 1.77 kg), respectively. There was no significant difference in lean body mass (LBM) change between or within groups. We found no significant difference in total performance time change between groups; however, both groups significantly decreased total performance time (CON: -41.20 ± 43.17 sec.; LCKD: -55.08 ± 44.29 sec). Carbohydrate intake was significantly lower (11.4 ± 5.6%, 40.06 ± 6.81%) and fat intake was significantly higher (62.88 ± 4.19%, 38.38 ± 4.18%) in LCKD compared to CON, respectively.

Conclusions: Our data show that a LCKD combined with 6 weeks of CrossFit training can lead to significant decreases in %BF, FM, weight, and BMI while maintaining LBM and improving performance.

Keywords

Ketosis, Weight loss, High-Intensity power training, Exercise, Weight-lifting, Interval training, CrossFit

List of Abbreviations

LCKD: Low-Carbohydrate Ketogenic Diet; CON: Control; BMI: Body Mass Index; %BF: Percent Body Fat; FM: Fat Mass; LBM: Lean Body Mass; HIPT: High-Intensity Power Training; WOD: Workout of the Day; CP: Creatine Phosphate; Acac: Acetoacetate; 3HB: 3-β-Hydroxybutyrate; DXA: Dual X-Ray Absorptiometry; FIR: Food Intake Record; MANOVA: Multivariate Analysis of Variance

Introduction

The prevalence of obesity has increased throughout the United States with one in three Americans categorized as obese [1]. Fewer than a quarter of Americans who attempt to lose weight actually follow current recommendations of increasing exercise and reducing caloric intake [2]. Those who attempt losing weight through regular aerobic training by using a treadmill or elliptical often get bored and lose motivation very quickly, leading to decreased exercise adherence [3]. An exercise program that has grown in popularity over the past few years as an alternative to traditional endurance and resistance training is known as CrossFit [3-5].

CrossFit was introduced in 2001 by its founder Greg Glassman and is considered "one of the fastest growing sports in America" with over 13,000 gyms worldwide [3,6]. CrossFit is a high-intensity power training (HIPT) type exercise that consists of a combination of gymnastics, plyometrics, functional movements, anaerobic intervals, weightlifting, sprinting, and Olympic lifting [7,8]. These constantly varied exercises, which are combined into the

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"Workout of the Day" (WOD), allow for training in all three human energy systems: the creatine phosphate (CP) system, anaerobic glycolysis, and oxidative phosphorylation and can be adapted for all levels of age and fitness [4,5].

The majority of CrossFit participants include men and women ranging from 19-60 years old, looking to improve all aspects of health and fitness with a desire to lose weight and increase performance [7]. A popular approach to weight loss that has gained recognition in recent years is the low-carbohydrate ketogenic diet (LCKD). This diet is classified by a decrease in carbohydrates with a subsequent increase in proportions of dietary fat and protein [9]. The reduction in carbohydrates, usually below 50 grams per day, allows a shift from glucose to fat-based metabolism [10] which produces water-soluble ketone bodies known as acetoacetate (AcAC), 3-β-hydroxybutyrate (3HB) and acetone [11]. Ketone body formation, also known as ketogenesis [12], has been shown to aid in the treatment of several diseases such as refractory pediatric epilepsy, cardiovascular disease, Type 2 diabetes, and obesity [9,11]. In addition, ketogenic diets are recognized as one of the more effective treatments for improvements in body weight, body composition, fasting serum lipid levels, and diet tolerability, especially when compared to low-fat diets [2,13-16].

Although there are many benefits to following a LCKD, there has been much controversy surrounding its relationship to exercise performance. While there is a paucity of literature, some studies have reported favorable outcomes in body weight and body fat reductions when following a LCKD and adhering to either an endurance or resistance type training protocol [17-21]. To date, there have been no published investigations supporting changes in body composition or performance in response to a HIPT type exercise program such as CrossFit, while adhering to a LCKD. The purpose of this study is to determine if consuming a 6-week LCKD and participating in a CrossFit training regimen yields significant improvements in body composition while maintaining or increasing performance. Specifically, we hypothesized that a LCKD would be a successful fat loss and weight loss strategy for CrossFit participants while maintaining or improving performance. Our second hypothesis was that those participating in CrossFit training while adhering to their usual dietary intakes would show significant increases in performance with minimal decreases in body mass or body fat content.

Methods

Experimental approach

This randomized controlled study investigated the effects of a 6-week LCKD on CrossFit members' ages 21-56 years old. Subjects were randomly assigned to follow either a LCKD or maintain normal dietary intake (CON) while participating in four CrossFit workouts per week for 6 weeks. Body composition using a dual x-ray absorptiometry (DXA) scan and performance testing using benchmark CrossFit testing was used to assess baseline measurements for all subjects. Diet adherence was evaluated through urinary ketone measurements and bi-weekly Food Intake Records (FIR). Training compliance was monitored through mandatory check-in procedures at the CrossFit gym. After completion of the study, all subjects were assessed using the same pre-test measurements.

Subjects

Subjects were male and female of all levels of fitness, recruited from and trained at a CrossFit affiliate (Rocktown CrossFit & Sports Performance, Harrisonburg, VA). Inclusion criteria were the following: between 18 and 60 years old and an active member of CrossFit for at least one month prior to the start of recruitment. Subject recruitment began in June 2015 and lasted until August 2015. Subjects were recruited via email, social media, word of mouth, and poster advertisements. Persons interested in participating were screened to see if they met the minimum criteria for entrance into the study. Subjects with current injuries or health conditions that might have affected CrossFit performance or put them at risk for further injuries such as diagnosis of cardiovascular disease were excluded from the study. Additionally, subjects taking any performance enhancing supplements (i.e., creatine, HMB, caffeine, protein powder, weight gainer, thermogenics, etc.), were required to discontinue consumption at least 7 days prior to baseline testing and continue for the remainder of the study. Interested subjects were required to sign a University approved in-

Table 1: Baseline characteristics of subjects participating in a 6-week CrossFit program.

	Control (n = 16)	LCKD[a] (n = 15)	Total (n = 31)
Age (yr.)	33.81 ± 9.33	35.40 ± 9.43	34.58 ± 9.26
Height (cm)	167.60 ± 9.82	170.51 ± 9.12	169.01 ± 9.44
Weight (kg)	74.32 ± 14.58	74.79 ± 12.93	74.55 ± 13.58
BMI (kg/m^2)	26.21 ± 2.96	25.60 ± 2.86	25.91 ± 2.88
Body fat (%)	30.86 ± 7.27	33.45 ± 7.82	32.11 ± 7.53
Lean mass (kg)	49.17 ± 10.94	47.69 ± 10.26	48.46 ± 10.46
Fat mass (kg)	22.16 ± 7.18	24.03 ± 6.88	23.06 ± 6.98
Total performance time (sec)	401.75 ± 75.12	414.93 ± 73.06	408.13 ± 73.19
Vertical jump (cm)	43.26 ± 14.73	42.62 ± 11.18	42.93 ± 12.9
Standing long jump (cm)	210.97 ± 34.98	209.42 ± 28.65	210.24 ± 31.55

[a]Low Carbohydrate Ketogenic Diet (LCKD); Values are means ± SD. No between group differences identified.

formed consent (Table 1).

Procedures

Baseline testing: Data collection during the baseline and post-intervention week included a CrossFit performance test, a power performance test and clinical and anthropometric data. The CrossFit performance and power tests were conducted at the Rocktown CrossFit gym while clinical and anthropometric data were obtained in a private setting in the Health Sciences Human Assessment Lab (Figure 1).

Power and performance testing was conducted over a four day period. Subjects identified an hour and fifteen minute block to participate in the tests. Each block had a maximum of 10 subjects who were split into two cohorts of four to five subjects. Subjects were instructed to arrive at the CrossFit gym 30 minutes prior to testing times and not train for at least 24 hours. Upon arrival,

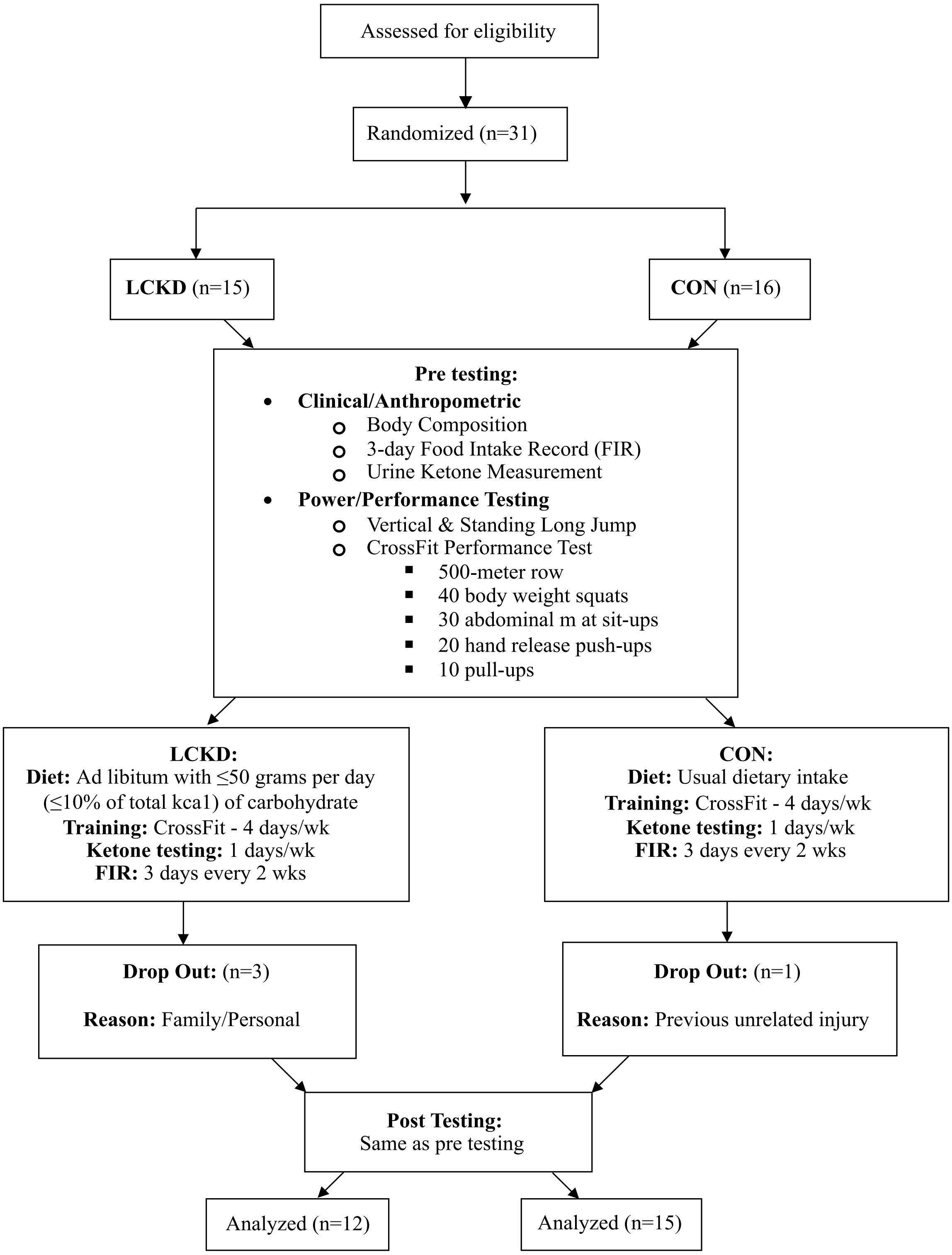

Figure 1: CONSORT diagram of subjects participating in a 6-week CrossFit program while consuming a Low Carbohydrate Ketogenic Diet (LCKD) or normal diet.

the primary researcher explained the testing procedures and protocols and demonstrated each test. Subjects were instructed to warm up by participating in a 250-meter row, 10 body weight squats, and 7 push-ups followed by a standard dynamic/static stretching protocol. Power and performance test administrators and personal researchers were blinded to the randomized group allocations. Subjects were blinded to all testing results until the end of the study.

Each cohort, separately, participated in a vertical jump test and standing long jump test to assess power. The vertical jump test was performed using a standard wall Vertec and expressed as centimeters. Each subject measured their standing reach, in shoes, on the Vertec. Subjects were instructed to stand with both feet flat on the floor with their legs and torso straight. Subjects raised their right arm straight and with their outstretched fingers, touched the highest point on the vane. Before the measured jump, subjects could freely flex the lower limbs, as well as prepare the upper limbs for a sudden upward jump, in effort to promote the highest vertical jump possible. The subject then performed a maximal vertical jump and touched the highest vane. The jump height was the difference between the two points marked on the Vertec. All subjects jumped three times, with an interval of 90 seconds between the jumps and only the highest jump was considered.

The standing long jump test was performed on the gym floor using a standard tape measurement for recording and expressed as centimeters. Subjects stood behind a line (marked 0 centimeters) with feet parallel and approximately shoulder width apart. A two foot take-off and landing was used, with swinging of the arms and bending of the knees to provide forward force. Each subject attempted to jump as far as possible, with measurements taken from start line to back of heels. All subjects jumped three times, with an interval of 90 seconds between the jumps and only the longest jump was considered.

The performance test was designed to mimic the movements and pace of a standard CrossFit workout and consisted of a 500-meter row, 40 body weight squats, 30 abdominal mat sit-ups, 20 hand release push-ups, and 10 pull-ups. Each subject had a personal researcher to record time splits and provide encouragement. Data was expressed as seconds.

Body weight and height measurements were taken with minimal clothes, no shoes, and measured to the nearest 0.5 kg or 0.5 cm using a calibrated balance scale and stadiometer (Detecto, Webb City, MI). A trained researcher took these measurements in duplicate and took the average of the two. These measurements were used to calculate body mass index (kg/m^2). Dual x-ray absorptiometry (DXA) scan was used for the assessment of body composition and included fat mass (FM), lean mass (LBM), and percent body fat (%BF). The DXA assessment took place using a GE Prodigy Lunar Whole Body Scan (GE Medical Systems, Madison, WI).

In addition, each subject was required to submit a 50 ml urine sample to assess baseline ketone levels. Urinary ketones were tested every week to check compliance and subjects were instructed to provide a urine sample at the Rocktown CrossFit gym that was kept in a cooler and then refrigerated and tested within 24 hours. Ketone assessment was made by a Siemens CLINITEK Status + Analyzer (Siemens Medical Solutions USA, Inc. Malvern, PA) where the threshold for determining ketosis > 15 mg/dl. The height/weight measurements, DXA scan, and urine assessment took place in a private setting.

Diet protocol: Subjects were randomly assigned based on premeasures of BMI, performance, and % body fat to either the CON or a LCKD intervention group for this 6-week, randomized controlled trial. Subjects had a mandatory dietary instruction session prior to the beginning of the study which provided detailed instructions on accurately keeping dietary food intake records (FIR). All subjects were required to provide a three-day FIR (two weekdays and one weekend) every two weeks during the study. All food record data were entered and analyzed using the Nutrition Data System for Research (Minneapolis, MN). Dietary records were assessed for quality assurance. The CON maintained its usual dietary intake throughout the study. The LCKD group was instructed to consume an ad libitum diet while restricting carbohydrate intake to no more than 50 grams per day (< 10% of energy) in order to induce and maintain ketosis. The LCKD group was given a detailed guide on acceptable low-carbohydrate foods as well as a recommended list of nutritious fat and protein rich foods. In addition, subjects were given a 6-week low-carbohydrate meal plan but were advised to use this meal plan as a guide rather than a strict protocol.

Training protocol: Each subject was required to participate in four CrossFit training sessions per week at the Rocktown CrossFit gym. Each workout was posted on the Rocktown CrossFit website the night before training. Although workouts changed daily, they generally consisted of four main components: warm up, dynamic and static stretch, strength, and the "Workout of the Day" (WOD) (Table 2). After each workout, member's names and respective workout times were recorded by the CrossFit coach and saved to assure each individual attended four classes per week. Subjects were prohibited from engaging in any other excessive physical activity during the 6-week study.

Post-intervention testing: Data collection procedures were the same as baseline testing procedures. To ensure reliability, power measures and performance testing were completed by the same researcher as baseline for each subject. In addition, subjects conducted their testing at the same time, with the same cohort, and with the same personal researcher as pretesting. Results from all tests were compared to the individual's baseline values and provided to the subjects after data analysis.

Statistical analysis

All statistical analysis was performed using SPSS (version 23.0; SPSS, Inc., Armonk, NY, USA). All data are presented as mean ± SD. Significance was set a priori with an alpha of 0.05. Intraclass correlations were used to determine the test-retest of the dependent variables. The sample size calculation $[(z^{*}p(1-p))/e^{2}]/1 + [(z^{*}p(1-p))/e^{2}N]$ was used to determine that to be 95% confident that the true value of the estimate will be within 5 percentage points of 0.5 the minimum sample size is 28. A one-way multivariate analysis of variance (MANOVA) was performed on all dependent variables in table 1 for identifying differences between and within groups at baseline. MANOVA is used to look at the relationship between one categorical independent variable and more than one quantitative dependent variable [22].

To examine statistical differences between and within groups, change scores were computed for each dependent variable (post minus pre-study value) and two one-way MANOVAs were used to compare body composition and performance variables between the LCKD group and the CON. The independent variable was the 6-week low-carbohydrate ketogenic diet. For the first MANOVA, the dependent variables were measures of body composition (body fat %, weight, BMI, lean body mass, and fat mass). Change in BF% and FM was skewed slightly, potentially due to two outliers (one in the CON group and one in the LCKD group); however, when eliminating these two outliers from the model, it improved even more, yielding a smaller p value. We included the two outliers in final analysis. For the second MANOVA, the dependent variables were measures of performance (total performance time) and power (vertical jump and standing long jump). Additionally, Pearson correlation tests were used to evaluate the relationships between the different dependent variables.

Furthermore, to assess the change in total performance time, vertical jump, and standing long jump from pre to post testing for both groups combined, one sample t-tests were performed. Additionally, to assess the components of power together from pre to post testing for both groups combined, a multivariate Hoteling T Test was used since there was a correlation between the power variables. In addition, four separate MANOVAs were used to examine statistical differences between groups for dietary analysis of total kilocalories, carbohydrate, fat, and protein intake at baseline, week two, week four, and week six of the study. Significance level was set at ($P < 0.05$).

Table 2: Sample workout of subjects participating in a 6-week CrossFit program while consuming a LCKD* or normal diet.

Strength	**Back squats:**
	1 × 3@60%
	1 × 3@70%
	1 × 3@75%
	1 × 2@80%
	1 × 2@85%
	1 × 2@80%
WOD	**3 Rounds for time:**
	500 m row
	10 Overhead squats
	(Rx: Men -155 lb.)
	(Rx: Women -105 lb.)

*Low Carbohydrate Ketogenic Diet (LCKD); WOD = Workout of the Day; Rx = Prescribed weight for workout.

Results

Thirty-one subjects were recruited for the study, and 27 completed baseline and post testing. Of the four subjects that withdrew, three were for family/personal reasons and one withdrew due to injury. Descriptive characteristics of all subjects are presented in table 1. There were no significant differences between groups for age, body mass, fat mass, lean body mass, BMI, % body fat, performance, or power measures at baseline. Compliance for nutritional intervention and weekly workouts was confirmed through daily workout logs, weekly urinary ketone assessments, and bi-weekly food records.

Body composition

Changes in body composition after the 6-week inter-

Table 3: Changes in body composition & performance for subjects participating in a 6-week CrossFit program.

	Control (n = 15)			LCKD[a] (n = 12)		
	Pre	**Post**	**Chg**	**Pre**	**Post**	**Chg**
Body composition						
Weight (kg)	72.44 ± 12.93	72.62 ± 12.95	0.18 ± 1.30	76.63 ± 13.76	73.18 ± 12.51	-3.45 ± 2.18[b]
BMI (kg/m²)	25.89 ± 2.77	25.97 ± 2.89	0.07 ± 0.43	25.98 ± 2.94	24.86 ± 2.6	-1.13 ± 0.70[b]
% Body fat (%)	30.85 ± 7.52	30.86 ± 7.72	0.01 ± 1.21	34.0 ± 7.38	31.4 ± 9.12	-2.60 ± 2.14[b]
Fat mass (kg)	21.59 ± 7.05	21.65 ± 7.30	0.06 ± 1.12	24.9 ± 6.49	22.08 ± 7.26	-2.83 ± 1.77[b]
Lean mass (kg)	47.87 ± 9.97	47.96 ± 9.96	0.09 ± 0.84	48.64 ± 11.20	48.27 ± 11.04	-0.37 ± 1.27
Power						
Vertical jump (cm)	43.26 ± 14.73	44.70 ± 13.36	1.44 ± 5.64	42.62 ± 11.18	45.86 ± 13.33	2.22 ± 2.87
Standing long jump (cm)	210.97 ± 34.98	212.71 ± 35.47	1.74 ± 8.29	209.42 ± 28.65	209.63 ± 36.60	0.212 ± 10.08
Performance						
Total performance (sec.)	404.00 ± 77.20	362.80 ± 43.27	-41.20 ± 43.17[c]	412.00 ± 78.34	356.92 ± 56.91	-55.08 ± 44.29[c]

Values are means ± SD; [a]Low Carbohydrate Ketogenic Diet (LCKD); [b]Significant between group difference (P < 0.001); [c]Significant within group difference (P < 0.001).

vention are presented in table 3. The LCKD group significantly decreased weight, BMI, %BF, and FM compared to the CON group. There was no significant difference in LBM change between or within groups. There were no significant changes in any body composition variables in the CON group. In general, for all body composition variables (excluding lean body mass) there was a downward trend in the LCKD group versus the CON group (Figure 2).

Performance

We found no significant difference in total performance time change between the CON group and the LCKD group; however, both groups significantly decreased total performance time. Pearson correlation tests showed a significant correlation (r = 0.48, $P < 0.01$) between vertical and standing long jump variables, but no significant correlations between these two variables and total performance time (r = 0.24, P = 0.78; r = 0.32, P = 0.68, respectively). Analysis of the ICCs revealed a high test-retest reliability for vertical jump, standing long jump, and total performance time (r = 0.96, 0.98, 0.95), respectively.

Additionally, there were no significant differences in vertical jump and standing long jump change between or within groups (Table 3). For both groups combined, the overall change in vertical jump (2.31 ± 4.55 cm) was significant ($P < 0.05$) but the change in standing long jump was not; however, when looking at vertical jump and standing long jump power together, the change from pre to post testing was significant ($P < 0.04$). Subjects participated in an average of 4.0 ± 0.20 (LCKD 4.01 ± 0.42, CON 4.0 ± 0.03) days of CrossFit training per week during the 6-week study (Table 3).

Dietary intake

All subjects were 100% compliant turning in biweekly FIR. Analysis of the food intake records revealed no significant group differences in total kilocalories, carbohydrate, protein, or fat intake at baseline. Carbohydrate

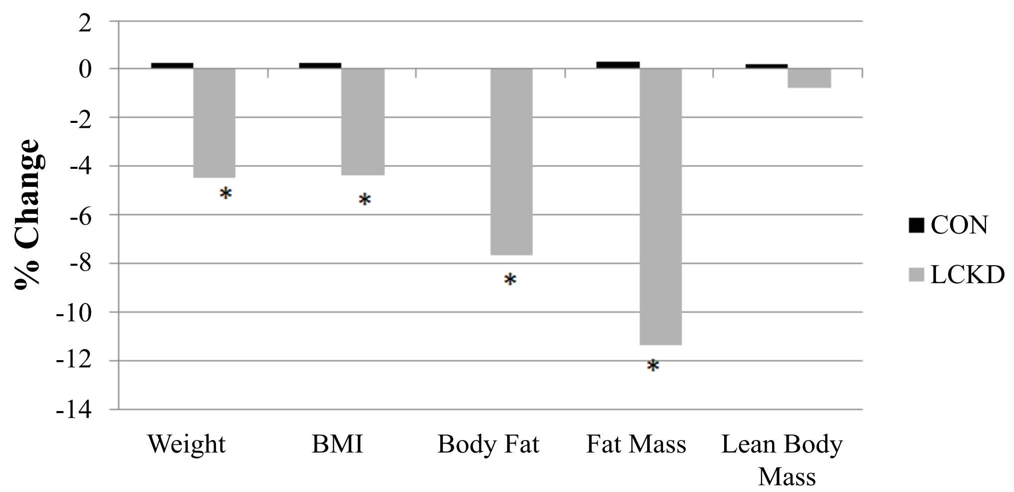

Figure 2: Changes in body composition for subjects participating in a 6-week CrossFit program. Low Carbohydrate Ketogenic Diet (LCKD); *Significant between group difference ($P < 0.001$).

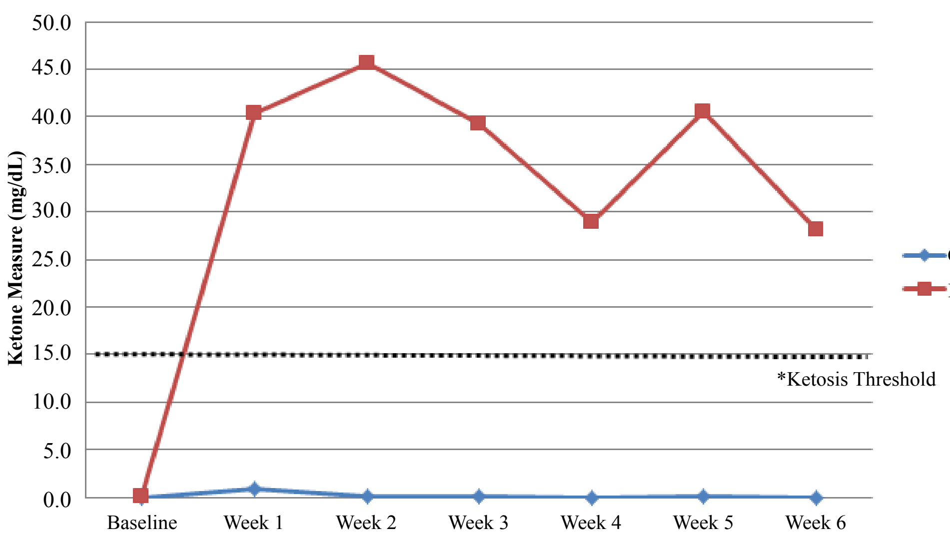

Figure 3: Mean ketone measures in subjects participating in a 6-week CrossFit program while consuming a Low Carbohydrate Ketogenic Diet (LCKD) or normal diet.

Table 4: Macronutrient intake for subjects participating in a 6-week CrossFit program.

	Control (n = 15)				LCKD[a] (n = 12)			
	Pre	Wk 2	Wk 4	Wk 6	Pre	Wk 2	Wk 4	Wk 6
Carbohydrate (g)	214.67 ± 101.17	195.77 ± 109.66	172.23 ± 69.79	193.56 ± 102.76	203.45 ± 90.59	37.80 ± 10.13[c]	41.52 ± 19.15[c]	53.91 ± 31.15[c]
Fat (g)	80.81 ± 25.68	78.11 ± 21.11	67.44 ± 20.35	74.87 ± 22.64	88.01 ± 26.84	135.60 ± 25.19[b]	109.62 ± 36.25[b]	98.40 ± 27.82[b]
Protein (g)	81.60 ± 26.76	86.19 ± 25.30	74.90 ± 17.72	80.27 ± 27.60	78.38 ± 16.42	103.84 ± 20.10	83.32 ± 22.15	87.40 ± 23.85
Kilocalories	1834.43 ± 555.60	1835.87 ± 691.91	1600.29 ± 462.70	1804.03 ± 655.75	1891.46 ± 550.94	1786.13 ± 287.37	1485.84 ± 362.04	1470.00 ± 327.74

Values are means ± SD.; [a]Low Carbohydrate Ketogenic Diet (LCKD); [b]Significant between group difference ($P < 0.05$); [c]Significant between group difference ($P < 0.001$).

Table 5: Average bi-weekly macronutrient intake for subjects participating in a 6-week CrossFit program.

	Control (n = 15)	LCKD[a] (n = 12)
Carb (g)[c]	187.19 ± 68.01	44.42 ± 16.46
Fat (g)[b]	73.47 ± 18.86	114.54 ± 25.23
Protein (g)	80.45 ± 18.61	91.52 ± 17.34
Kilocalorie (g)	1746.73 ± 485.45	1580.66 ± 283.37

Values are means ± SD; [a]Low Carbohydrate Ketogenic Diet (LCKD); [b]Significant between group difference ($P < 0.05$); [c]Significant between group difference ($P < 0.001$).

intake was significantly lower and fat intake was significantly higher in the LCKD group at weeks 2, 4, and 6 compared to the CON group (Table 4 and Table 5). Mean carbohydrate (%) intake in the LCKD group was 11.4 ± 5.6 compared to 40.06 ± 6.81 in the control group ($P < 0.001$). Mean fat (%) intake in the LCKD group was 62.88 ± 4.19 compared to 38.38 ± 4.18 in the control group ($P < 0.05$). There were no statistical differences in total kilocalories or protein intake between or within groups throughout the study. Additionally, there were no significant changes in dietary macronutrient intake in the CON group from baseline and throughout the study (Table 4 and Table 5).

Urine analysis

All subjects were 100% compliant submitting weekly urine samples throughout the study. In the LCKD group, 6 subjects tested 100%, four at least 50%, and two less than 50% in ketosis during urine ketone measurements throughout the study. Ketone measurements for the CON group showed that no subjects reached ketosis during the study (Figure 3).

Discussion

The aim of the current study was to examine the effects of a 6-week LCKD and CrossFit training on body composition and performance. The present study revealed that adhering to a LCKD during 6-weeks of CrossFit training results in significant decreases in weight, BMI, %BF, and FM compared with an ad libitum diet while maintaining LBM. Additionally, all subjects significantly improved total CrossFit performance time and overall power. To our knowledge, the present study is the first that has assessed the use of a LCKD combined with CrossFit training to evaluate body composition and performance outcomes.

The use of a LCKD to improve body composition measures has been a topic of interest for many years. There have been numerous studies comparing the weight loss effects of following a LCKD versus a low-fat diet, showing far superior results in the former [2,13-16]. Additionally, a recent meta-analysis showed that subjects had significantly greater long-term reductions in body weight following a LCKD as opposed to a low-fat diet [17]. Specifically, Volek, et al. found that greater weight and fat loss was achieved with no significant loss of LBM when following a LCKD versus a low-fat diet [15]. Similarly, in the present study, the LCKD group lost an average of 3.5 kg in weight, 2.6% BF, and 2.83 kg of FM while maintaining LBM. Additionally, Moreno, et al. compared the effects of following a LCKD versus a standard-low calorie diet in 53 otherwise healthy obese men and women. Similar to the present study, results from Moreno's study concluded that a LCKD diet was significantly more effective in inducing weight loss and fat loss without affecting LBM, compared to a standard low-calorie diet. Furthermore, at one-year follow up, 88% of the subjects in the LCKD maintained the weight and fat loss compared to 34.6% of patients in the low-calorie group [23]; however, it is worth noting that the present study evaluated normal weight, physical active adults, whereas the two aforementioned studies evaluated otherwise healthy overweight/obese men and women. Nonetheless, it is evident that a LCKD is just as effective and maintainable for weight and fat loss as a low-fat or low-calorie protocol.

There were no statistical differences in total kilocalories or protein intake between or within groups throughout our study; however, while no statistical difference was found, it is important to note that the LCKD group consumed a lower average energy intake (1580.66 ± 283.37) per day compared to the CON group (1746.73 ± 485.45) even when encouraged to eat ad libitum. This small but non-significant reduction in energy intake may be due to several factors, including the higher satiety value of protein and fat, effects on appetite-related hormones such as ghrelin, and/or the possible direct appetite-blocking effect of ketone bodies [24-26]. Accordingly, a recent meta-analysis revealed that individuals are significantly less hungry and have a reduced desire to eat when adhering to a LCKD [27].

Individuals in the LCKD group were encouraged and given sample food choices/meal plans to replace carbohydrate intake with high quality proteins and fats. Additionally, when consuming carbohydrates, they were advised to focus on limiting them to green vegetables, nuts/seeds, and full fat dairy. In accordance with the present study, Paoli and colleagues investigated the effects of a modified ketogenic diet based on green vegetables, olive oil, fish, and other high quality fats with results showing significant weight and fat loss, reductions in waist circumference, improvements in cardiovascular risk markers, and good overall compliance with diet protocol over a period of 12 months [28,29]. These findings indicate the benefits of restricting carbohydrate and increasing fat intake for satiety, weight loss, and overall health improvements. A low carbohydrate, high fat lifestyle may be an intriguing option in reducing the number of obese Americans. A LCKD has been suggested as an effective strategy for weight loss in the 2013 Guidelines for Managing Overweight and Obesity in Adults [30].

Several hormonal changes occur on a LCKD with the most prominent including a reduction in the circulating levels of insulin, due to decreased blood glucose levels, with a subsequent increase in circulating glucagon [12]. This reduction in insulin levels facilitates the mobilization of FFA from fat stores and it has been proposed that the use of these FFA in combination with ketone bodies spares muscle protein and is thus anti-catabolic [19]. The LCKD group in the present study was able to maintain LBM while also increasing performance. These findings are consistent with the aforementioned studies in which LBM was maintained while following a LCKD. Furthermore, Volek, et al. examined body composition and hormonal changes in 12 normal, healthy weight men following a 6-week LCKD and found significant decreases in weight, %BF, and FM with a subsequent increase in LBM [26]. According to research, LBM is generally conserved during a ketotic state due to the use of ketone bodies and FFA for energy that slows muscle protein catabolism; however, the processes behind this mechanism are not well understood but it is hypothesized that the “sparing effect” of using FFA as an energy source might play a role. Additionally, the relative increase of amino acid uptake in the diet has a distinguished protein synthesis effect via the mTOR signaling pathway, which has also been proposed to be a key reason for the conservation of LBM when following a LCKD [24,31].

Despite the significant reduction in carbohydrate intake and slight decrease in caloric intake, the LCKD group was able to adhere to CrossFit training at least 4 times per week with no adverse side effects reported. Additionally, there were no significant differences in performance or power outcomes between the LCKD and CON group after 6 weeks of CrossFit training. While the literature surrounding the effects of following a ketogenic diet and adhering to a specific exercise program is not extensive, some studies have shown positive outcomes [17-19,32]. For example, Jabekk, et al. studied the effect of 10 weeks of resistance training in combination with either a regular diet or an ad libitum LCKD in overweight women. Results from their study showed that the LCKD group lost 5.6 ± 2.9 kg of fat mass with no significant change in LBM and the regular diet group gained 1.6 ± 1.8 kg of LBM with no significant change in fat mass [18].

Similar to our study, Sawyer, et al. examined the effects of switching from a habitual diet to a LCKD on strength and power performance in 31 trained men and women ages 18 to 30. Results from their study showed a significant decrease in body mass with no decrement in strength and power performance as measured by handgrip dynamometry, vertical jump, 1 rep maximum bench press and back squat, maximum repetition bench press, and a 20 second Wingate anaerobic cycling test [32]; however, subjects in their study were assessed after following a LCKD for only 7 days, whereas the subjects in our study adhered to the diet for 6 weeks. Furthermore, a study investigating the influence of a LCKD on explosive strength performance in elite artistic gymnasts showed a significant decrease in body weight and fat mass over a 30-day period with no negative changes in strength and power performance [19]. These findings suggest the powerful effects that a LCKD can have throughout the entire athletic community.

Over the past few years CrossFit training has become very popular as a community based, competitive exercise program for the average person aspiring to get in shape and lose weight. CrossFit exercises are designed to stress each metabolic system by combining various exercise movements, intensities, resistance, repetitions, sets, and rest periods in a HIPT type session [4]. During the current study, significant improvements in total performance time and power were observed in both groups after 6 weeks of CrossFit training. Although the literature surrounding the benefits of CrossFit is scarce, this study supports existing evidence that HIPT training can yield both anaerobic and aerobic improvements [8,33].

In accordance with our findings, Beilke, et al. demonstrated that a 4-week CrossFit training program significantly improved aerobic capacity, sports performance, and muscle endurance and strength in 21 healthy adults ages 19 to 25-years-old [4]. Similarly, Smith, et al. determined that a 10-week CrossFit-based HIPT program significantly improved maximal aerobic capacity and body composition in individuals of varying fitness levels and gender [8]. Furthermore, a recent study showed that 3-months of CrossFit training led to increases in VO_2max, improvements in anaerobic capacity and reduction in % BF in women with increases in LBM in all subjects [34].

Strengths of the present study include the randomized control study design, the 100% compliance of all subjects to attend the prescribed number of CrossFit sessions each week, and the small dropout rate with only one due to a non-severe injury. Limitations of the present study include the lack of control in physical activity outside of the CrossFit training sessions as well as the short intervention period of six weeks; however, the 6-week period is significantly longer compared to previous studies of only 7 days [32] or 4 weeks [4]. Also, data was not collected on previous training level of subjects and a natural adaptation could have occurred. Subjects were randomly assigned based on selected premeasures and it is likely that trained and minimally trained subjects were assigned to the same group. Additionally, because the same performance test was evaluated during pre and post testing, it is possible that a learning curve may have influenced the results. Furthermore, although all subjects were compliant with turning in their bimonthly 3-day food records, it is hard to assess the complete validity of these records due to the possible measurement error associated with self-reported dietary assessment tools.

Conclusions

To our knowledge, no research on the body composition and performance benefits of following a LCKD combined with CrossFit training has been conducted. With the current obesity epidemic overpowering our nation, Americans are constantly searching for the most effective diet protocol to induce weight and fat loss. Additionally, the constantly varied and competitive nature of CrossFit training has made it a popular exercise regimen for all levels of age and fitness.

Our data suggests that adhering to a LCKD can lead to weight loss and improved body composition outcomes without negatively affecting LBM, strength, or power performance. CrossFit athletes looking to explore novel nutritional approaches such as the low carbohydrate ketogenic diet may be able to improve performance while simultaneously improving body composition. These results could also be useful for weight category athletes, such as Olympic weightlifters, powerlifters, boxers, or wrestlers, seeking to lose a significant amount of body fat without compromising performance. Future research should be directed to the long term physiological adaptations which occur with a LCKD and CrossFit training, as well as the hormonal and psychological changes that may also transpire.

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Ethics Approval and Consent to Participate

The Institutional Review Board at James Madison University, Harrisonburg, VA approved the present study and all subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study.

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