International Journal of Kinesiology & Sports Science
ISSN: 2202-946X
www.ijkss.aiac.org.au

The Effects of a Six-Week Ketogenic Diet on CrossFit Performance Parameters: A Pilot Study

Steven Vitti[1]*, Emily Miele[2], Michael L. Bruneau Jr.[3], Laura Christoph[4]
[1]*Department of Health Sciences, Drexel University Three Parkway Building, 9129, Philadelphia, Pennsylvania*
[2]*CVS Heath Corporation Woonsocket, Rhode Island*
[3]*Department of Health Sciences, Drexel University Three Parkway Building, 9114, Philadelphia, Pennsylvania*
[4]*Canyon Ranch Lenox 165 Kemble St, Lenox, Massachusetts*
Corresponding Author: Steven Vitti, E-mail: sv675@drexel.edu

ARTICLE INFO

Article history
Received: February 11, 2022
Accepted: April 21, 2022
Published: April 30, 2022
Volume: 10 Issue: 2

Conflicts of interest: None.
Funding: None

ABSTRACT

Background: CrossFit is a popular high-intensity functional training method. Despite the importance of muscle glycogen in fueling such high-intensity efforts, research exploring the use of a ketogenic diet in CrossFit practitioners is limited. **Objectives:** To conduct an experimental trial examining the effects of a 6-week ketogenic diet on CrossFit performance parameters. **Methods:** Eight men and seven women (N = 15; 30.2 ± 4.11 years) were recruited for this experimental study design and were randomly assigned to either the ketogenic diet (KD; n = 8) or the control group (CON; n = 7) for 6 weeks. Several measures of anaerobic performance were assessed at baseline and after 6 weeks utilizing the following series of standardized exercise tests: timed 500 m row, Wingate Anaerobic Test, and 3-repetition maximum (3-RM) deadlift. Aerobic capacity was also assessed by measuring VO_{2peak}. In addition, body composition was assessed via BodPod. **Results:** Multiple 2 X 2 mixed factorial analyses of variance were performed for measures of body composition and aerobic and anaerobic performance variables. No significant differences in body composition ($p < 0.05$), anaerobic performance ($p < 0.05$), or aerobic performance ($p < 0.05$) were observed between groups. **Conclusion:** A 6-week ad libitum KD had no effect on exercise performance or body composition in CrossFit practitioners. Our findings demonstrate that a KD does not impair CrossFit performance, which may be of interest to those considering a KD when participating in CrossFit.

Key words: CrossFit, Low Carbohydrate, Performance, High-Intensity Exercise, Ketogenic, Body Composition

INTRODUCTION

High-intensity interval training (HIIT) is one of the most popular methods of exercise training. According to a worldwide fitness trends survey conducted by the American College of Sports Medicine, HIIT ranks 2nd among the most popular fitness trends (Thompson, 2019). In previous years, CrossFit participation was attributed to a rise in HIIT participation (Thompson, 2013). CrossFit is a relatively new training paradigm that has seen meteoric growth since its inception in the early 2000s. Moreover, annual CrossFit competitions have drawn the attention of athletes everywhere, where they perform CrossFit-specific workouts for time, for number of repetitions, or for maximal weight lifted (Bergeron et al., 2011; Claudino et al., 2018).

CrossFit is a non-traditional style of training that generally employs high-intensity efforts with little rest between sets (Bergeron et al., 2011). Considering the metabolic demands of this particular training style, sports nutrition recommendations prioritize dietary carbohydrates to elicit optimal performance (Escobar et al., 2016). However, despite current recommendations from international committees (Aragon et al., 2017; Kerksick et al., 2017; Rodriguez et al., 2009) whereby numerous subtypes fall under each major dietary archetype. 2 the founders and trainers of CrossFit generally recommend adhering to diets lower in carbohydrates and higher in proteins and fats (Gogojewicz et al., 2020).

The ketogenic diet (KD) is an example of a diet that follows similar parameters. Low-carbohydrate, high-fat diets like the KD increase the release and utilization of fatty acids, which increase the biosynthesis of ketone bodies (Nasser et al., 2020). Increases in circulating ketone bodies, primarily beta-hydroxybutyrate, occur within days of adopting a KD. These ketone bodies can be used as alternative fuel sources for the central nervous system and peripheral tissues, such as the heart and skeletal muscle (Burke, 2021). Though the macronutrient composition of a KD is variable in the literature, it is generally accepted that ~75-80% of energy intake comes from fat, 15-20% protein, and <5%

Published by Australian International Academic Centre PTY.LTD.

http://dx.doi.org/10.7575/aiac.ijkss.v.10n.2p.25

carbohydrate (and/or 20-50 g/day) energy sources (Burke, 2021). Similar to the popularity of CrossFit, a high-fat KD has too surged in popularity. Interest in KD originated from research demonstrating reductions in total body mass and fat mass, which is of interest to athletes participating in sports favoring an increase in relative strength and power (e.g., CrossFit athletes). In one of the earliest studies investigating the effects of a KD on strength and power performance, Paoli et al. (2012) reported that a 4-week KD decreased body weight while preserving muscular strength in elite gymnasts. Moreover, researchers have shown that KD promote the increase of fat oxidation and inhibit carbohydrate oxidation, which is believed to enhance exercise performance through the sparing of glycogen stores (Burke & Hawley, 2002; Cox & Clarke, 2014). However, reduced rates of glycogen utilization may be due to reductions in overall glycogen content, which has been shown to impair exercise performance at high intensities (Murphy et al., 2021).

To date, few studies have examined the effects of a KD on performance in CrossFit athletes. Gregory et al.(2017) reported that male and female recreational CrossFit practitioners following a 6-week KD experienced significant reductions in body fat percentage and increases in CrossFit-specific performance compared to a higher carbohydrate diet group. Kephart et al.(2018) reported that a 12-week KD produced significant reductions in body mass and fat mass without negatively impacting strength, anaerobic or aerobic performance in a small group of male and female CrossFit practitioners. Durkalec-Michalski et al.(2021) recently reported a 4-week KD had no effect on CrossFit-specific performance in male and female CrossFit practitioners. Interestingly, the researchers reported that a KD significantly reduced VO_{2peak} in the female athletes only. Collectively, these studies appear to demonstrate that a KD confers favorable changes in body composition without negatively impacting CrossFit performance. However, despite these findings, the literature does not support using a KD for increasing athletic performance (Harvey et al., 2019). Given that few studies have investigated the use of a KD in a CrossFit population, additional studies are needed to evaluate its efficacy on body composition and CrossFit performance.

Several studies have investigated whether various fitness performance parameters were associated with CrossFit performance. In a study exploring physiological predictors of CrossFit performance, Dexheimer et al.(2019) found that VO_{2max} significantly predicted "Nancy" performance, a CrossFit-specific workout, and that higher peak power values corresponded to greater total body strength. Similarly, Mangine et al.(2020) reported the rate of force development and VO_2 at the respiratory compensation point, an index that demarcates the transition from "heavy" to "severe" intensity, were significant predictors of CrossFit performance. In light of these findings and considering the paucity of data available exploring the effects of a KD on performance in CrossFit practitioners, we aimed to examine the effects of a 6-week KD on performance parameters associated with CrossFit performance, adding to the limited body of evidence investigating the effects of low carbohydrate diets in CrossFit populations. Based on the current literature, we hypothesized that a 6-week KD would decrease body weight without negatively impacting performance.

METHODS

Participants and Study Design

In this experimental design study, a total of 48 participants were recruited from two separate CrossFit affiliates located in Western Massachusetts, 22 of whom were enrolled and completed visit one. Seven participants dropped out due to various reasons (see Figure 1), yielding an attrition rate of 30% in the CON group and 33% in the KD group. Eight men and seven women (N = 15; 30.2 ± 4.11 years) completed the study. All participants were healthy adults between the ages of 20-40 years who had been participating in CrossFit for at least three sessions per week for 3 months. Exclusion criteria included the presence of diabetes, cardiovascular disease (CVD), metabolic disease, pulmonary disease, cancer, or kidney disease; the presence of any signs and/or symptoms of CVD, the presence of two or more risk factors for CVD, a history of gout, consumption of a KD in the previous 6 months, experienced weight loss greater than 10 pounds in the previous 2 months or was unable to participate in strenuous exercise for any reason. All participants were asked to maintain CrossFit training at their respective affiliate for at least 3 times per week during the 6-week intervention. Training attendance at each session was self-reported by the participants. All participants provided written informed consent and all study procedures were performed in accordance with the Helsinki Declaration and approved by the Institutional Review Board at Springfield College.

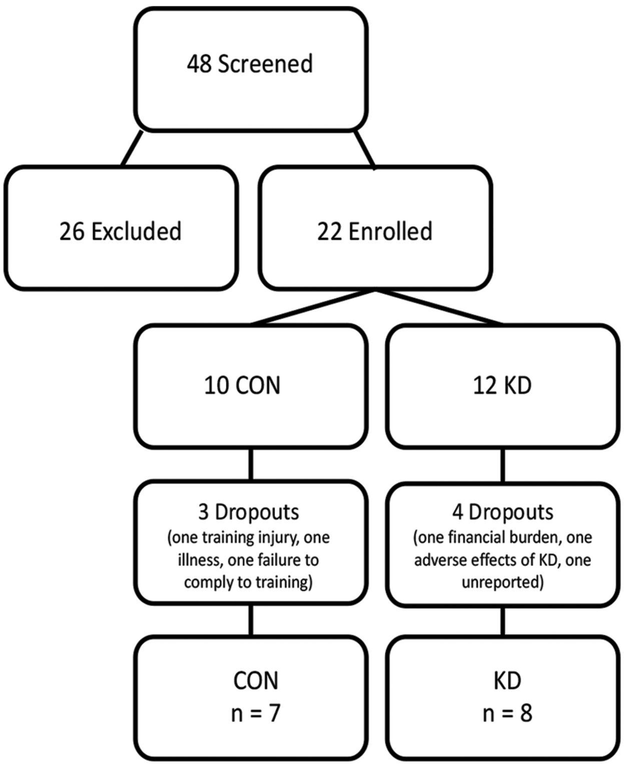

Figure 1. Flow diagram of participant recruitment

Experimental Procedure

Participants reported to the Human Performance Laboratory at Springfield College on two separate occasions. All testing was performed by the same two technicians, in the morning. All equipment was calibrated according to manufacturer standards prior to each testing session. Participants were asked to provide a record of the breakfast consumed the morning of testing. During visit one, weight and height were measured using a Physician Beam Scale (Detecto;Webb City, MO), and body composition was estimated using a BodPod (COSMED USA, Inc., Concord, CA). Participants then performed a standardized dynamic warm-up, followed by a series of four exercise tests (detailed in *Exercise Testing* section). Following completion of the exercise testing protocol, participants were randomized to either the control group (CON) or the KD group using a random number generator (Urbaniak & Plous, 2013). Those assigned to the CON group were instructed to maintain their current diet for the following six weeks. Those assigned to the KD group were instructed to adhere to a 6-week, ad libitum KD. Participants assigned to the KD group attended an educational session at their CrossFit affiliate where they were provided written and verbal instructions on how to follow the diet by a nutrition specialist and given a sample meal plan (Figure 2). The 6-week diet period began on the first morning after the dietary counseling session. The nutrition specialist was available to the KD participants throughout the entire study for nutrition counseling. Prior to visit two, participants in the CON group were provided a copy of the breakfast they recorded on the morning of visit one. On the morning of visit two, the participants were required to replicate the timing and composition of the breakfast from visit one. Participants in the KD group were provided with the total kilocalorie (kcal) count of their breakfast from visit one and were asked to consume an isocaloric ketogenic breakfast. Participants recorded their breakfast on the morning of visit two as a quality and compliance measure. For visit two, participants reported to the laboratory at the same time as visit one and completed the same measurement and testing protocol, in the same order with the same time increments between tests.

Exercise Testing

Exercise testing was conducted prior to and following the 6-week dietary intervention. The following exercise tests were performed in the order as they are listed below. Participants were given 10 min of rest following each test. If requested, participants were given additional time to rest, and the extra time was recorded and repeated on visit two. Instructions for each test were provided to participants verbally, and any questions were addressed prior to performing each test. Verbal encouragement was provided by study technicians for all tests, consistent across all visits and participants.

500 m row

The 500 m row was chosen because it is a staple exercise in many CrossFit workouts (de Souza et al. 2021). Participants were instructed to row at maximal effort on an indoor rowing ergometer (Concept 2, Inc. Morrisville, VT) for 500 m. Breath-by-breath analysis was conducted using a metabolic cart (Max II, Physio-Dyne, Quogue, NY) and a two-way breathing mouthpiece (Hans Rudolph, Survivair Blue 1, Comasec, Inc., Kansas City, MO) for the entirety of the test. The drag factor (10-6 N m s2) was set at 130 for males and 120 for females. The time displayed on the ergometer at the completion of the 500 m row was recorded for analysis.

Wingate test of anaerobic power

Participants performed a 3-min warm-up on an indoor cycle ergometer (Velotron DynaFit, RacerMate, Seattle, WA) at a self-paced work rate equal to 75 Watts (W). The warm-up was followed by a 6-s acceleration phase, where participants were instructed to pedal at maximal exertion to attain peak

Meal Description	Food Items	Amount	Calories	Protein g	Fat g	Net Carb g	Mg mg	Zn mg	Sodium mg
Breakfast: 3 poached eggs, 1 avocado sliced, 6 oz coffee blended with 1 tbsp. coconut oil	Egg, whole, cooked, poached	3 large	214	19	14	1	18	1.94	446
	Avocados, raw, California	1 fruit (without skin and seed)	227	3	21	3	39	0.92	11
	Beverages, coffee, brewed, breakfast blend	6 ounces	4	1	0	0	7	0.04	2
	Oil, coconut	1 tbsp.	121	0	14	0	0	0	0
Snack: 2 stalks celery with 2 Tbsp. peanut butter	Celery, raw	2 stalk, small (5" long) 34g	5	0	0	1	4	0.04	27
	Peanut butter, chunk style, with salt	2 tbsp.	188	8	16	4	51	0.89	156
Lunch: 6 oz canned salmon over 1 cup spinach tossed in with 2 Tbsp. Olive oil	Fish, salmon, pink, canned, total can contents	6 ounces	219	33	8	0	51	1.29	685
	spinach, raw	2 cups	14	2	0	1	47	0.32	47
	Oil, olive, salad or cooking	2 tbsp.	238	0	28	0	0	0	0
Snack: 1 cup cucumber slices and 1 oz almonds and 1 cup chicken broth	Cucumber, with peel, raw	1 cup slices	16	1	0	3	14	0.21	2
	Nuts, almonds, dry roasted, with salt added	1 ounce	170	6	14.9	3	79	0.94	141
	Soup, chicken broth, ready-to-serve	1 cup	15	2	1	1	2	0.17	924
Dinner: Beef burger topped with 1 oz cheddar and 1/4 cup sliced tomatoes	Beef Patty, 20% Fat, broiled	6 ounces	460	44	30	0	34	10.62	128
	Cheese, cheddar	1 ounce	115	6	9	1	8	1.02	183
	Tomatoes, red, ripe, raw, year round average	1/4 cup sliced	8	1	0	1	5	0.08	2
Totals			2014	126	156	19	359	18.48	2754

Figure 2. Sample day ketogenic meal plan

cadence. Immediately after the acceleration-phase, a load equal to 7.5% of the participant's body weight was applied to the flywheel and participants were instructed to pedal at maximum effort for 30 s (Maud & Shultz, 1989). Following the 30 s, the flywheel load was removed, and the participants completed a 2-min cold-down at a self-selected pace with no resistance. Peak power output (PPO; W/kg), mean power output (MPO; W/kg), relative PPO (W/kg), relative MPO (W/kg), and fatigue index (FI; W/sec) were recorded. Seat height was measured and set at the same height during both the first and second visits.

VO_{2Peak} Test

A maximal, symptom-limited test was performed on a motorized treadmill (Noramco Fitness, HS-Elite, Willis, TX) using the Bruce protocol (Bruce et al., 1973). Participants were instructed to continue the graded treadmill protocol until volitional exhaustion. Relative volume of oxygen consumption (VO_2; ml/kg/min), heart rate (HR; bpm; Polar Electro Inc., Lake Success, NY), and blood pressure (BP; mmHg) were recorded at baseline and in the last minute of each stage of exercise. Rate of perceived exertion (RPE) was recorded in the last minute of each stage of exercise using the Borg scale (Borg, 1998).

3-Repetition Maximum (3RM) Barbell Deadlift

A warm-up progression consisting of 4 sets was completed using 65%, 75%, 85%, and 87% of the participant's predicted 1-RM, which was self-reported based on their previous training experience. Participants rested for 2 min between each set. Following the warmup, attempts at a 3-RM continued until the participants reached volitional fatigue (Haff & Triplett, 2015). The heaviest weight lifted for 3-RM was recorded and analyzed.

Dietary Analysis

Three-day dietary logs were completed by all participants at baseline, and at weeks 1, 3, and 5. For each dietary log, participants were instructed to record every food, beverage, and supplement consumed over a 3-day period, including two weekdays and one weekend day. The dietary data in our analysis was performed as the average across all weeks. Dietary logs and pre-testing breakfast logs were analyzed for macronutrient and micronutrient content using the Food Processor Nutrition Analysis software (ESHA Research, Salem, OR). Compliance to the KD was assessed through the daily analysis of urinary ketones using Ketostix reagent strips (Bayer Corporation, Elkhart, IN).

Statistical Analysis

Descriptive statistics were computed as means ± standard deviation, unless otherwise noted. Physical characteristics of the study sample were compared at baseline using independent sample t-tests. All inferential statistics computed for each dependent variable were analyzed using a 2 X 2 (Group X Time) mixed factorial analysis of variance with repeated measures. Post-hoc pairwise comparisons and simple effects tests were performed with Bonferroni correction adjustments to control for multiple comparison testing. Partial eta^2 (ηp^2) effect sizes, significance values approaching statistical significance, and paired sample t-tests are also reported to investigate whether the findings from our small and homogenous sample confer practical benefit. All parametric statistical analyses were checked and verified for their basic statistical assumptions and were performed with an *a priori* $\alpha = p < .05$ with the Statistical Package for Social Sciences (SPSS), version 28.0.

RESULTS

No significant differences in baseline characteristics or body composition were observed between KD and CON ($p > 0.05$; Table 1). Both groups attended a similar number of CrossFit sessions per week (KD: 4.75 ± 1.03; CON: 4.57 ± 1.17, $p > 0.05$). Urinary analysis confirmed all participants in the KD group complied with the study protocol dietary guidelines.

Diet Information

A significant increase in total calories was observed only in the KD but not CON group following the 6-week diet intervention, $F(1, 13) = 5.623$, $p = 0.037$. Additionally, the KD group significantly increased fat, $F(1, 13) = 9.662$, $p = 0.010$, and protein, $F(1, 13) = 8.469$, $p = 0.014$, intake across the intervention, and reduced carbohydrate intake $F(1, 13) = 16.359$, $p = 0.002$. All dietary information for the total sample and for each group are listed in Table 2.

Performance

All performance variables are displayed in Table 3. No significant main effects or interactions were observed for VO2peak, $F(1, 13) = 0.145$, $p = 0.709$, 500 m row time, $F(1, 13) = 0.467$, $p = 0.507$, PPO, $F(1, 13) = 0.374$, $p = 0.551$, MPO, $F(1, 13) = 0.536$, $p = 0.477$, relative PPO, $F(1, 13) = [0.950]$, $p = 0.348$, relative MPO, $F(1, 13) = 0.113$, $p = 0.742$, or FI, $F(1, 13) = 0.812$, $p = 0.384$ between the KD and CON groups. However, a trend was identified for 3-RM deadlift with a moderate effect size, $F(1, 13) = 3.131$, $p = 0.100$, $\eta p2 = 0.194$, whereby the CON exhibited a 5 kg increase in the 3-RM deadlift. A significant interaction was observed for heart rate, $F(1, 13) = 8.658$, $p = 0.011$, $\eta p2 = 0.400$.

DISCUSSION

The current study aimed to examine the effects of a 6-week KD on performance parameters associated with CrossFit performance in a group of recreational CrossFit practitioners. The primary findings revealed that 6 weeks of a KD did not affect measures of strength and power, or aerobic capacity associated with CrossFit performance. Additionally, a KD did not result in any changes in body compo-

Table 1. Baseline characteristics and body composition

	Baseline		Post	
	CON	**KD**	**CON**	**KD**
Males/Females (n)	4/3	4/4	—	—
Age (years)	28.14±3.76	32.00±3.70	—	—
Height (cm)	167.07±10.76	173.87±9.01	—	—
Body mass (kg)	75.62±16.25	83.54±14.41	75.85±16.94	82.28±13.76
Fat mass (%)	22.05±8.85	22.03±9.06	23.11±6.63	20.13±9.50
Lean mass (%)	77.94±8.85	77.96±9.06	76.88±6.63	79.86±9.50

Values herein are expressed as mean±standard deviation

Table 2. Energy and macronutrient distribution

	Baseline		Post	
	CON	**KD**	**CON**	**KD**
Total calories	2435.33±448.12	2199.46±454.17	2499.06±426.56	2568.58±532.69**
Carbohydrates (g)	247.22±31.94	177.40±50.07*	300.46±80.77	40.50±20.99***
Fat (g)	95.80±38.25	116.54±41.06	90.64±15.80	186.95±37.40***
Protein (g)	112.02±35.33	112.74±36.62	115.83±28.03	161.08±69.09***
Carbohydrates (%)	47.04±7.59	34.16±8.67	48.86±7.80	8.88±5.27***
Protein (%)	18.84±5.22	20.73±3.76	19.05±3.24	27.25±7.68
Fat (%)	34.47±7.49	47.95±12.89	32.94±5.38	63.02±6.06***

Values herein are expressed as mean±standard deviation. *Significant group differences ($p<0.05$); **Significant differences for the main effect of time ($p<0.05$); ***Significant group x time effect ($p<0.05$)

Table 3. Performance variables

	Baseline		Post	
	CON	**KD**	**CON**	**KD**
VO_{2peak} Test				
VO_{2peak} (ml*kg*min)	41.58±5.20	40.36±9.09	42.61±5.69	40.60±10.46
RER	1.16±0.05	1.12±0.07	1.15±0.10	1.09±0.07
HR_{max} (bpm)	177.26±8.77	177.00±10.66	174.00±10.77	180. 62±11.04*
Row Test				
Row Time (s)	107.70±17.88	100.41±6.32	106.40±15.33	100.48±7.10
Row Peak RER	1.20±0.15	1.2±0.10	1.23±0.12	1.13±0.09
Wingate Test				
PPO (W)	996.14±306.05	979.12±160.97	923.71±323.77	954.87±147.26
MPO (W)	614.00±171.71	656.75±143.13	606.14±181.53	627.12±136.31
PPO (W/kg)	13.07±2.52	11.80±1.26	12.11±2.81	11.78±1.93
MPO (W/kg)	8.08±1.34	8.00±1.81	8.00±1.41	7.78±1.80
FI (W/s)	21.16±7.86	18.74±6.52	18.57±7.24	18.68±5.70
Deadlift				
3RM (kg)	115.58±42.38	124.43±28.63	120.45±43.99	124.41±28.63

Values herein are expressed as mean±standard deviation. RER=respiratory exchange ratio; HR_{max}=maximal heart rate; bpm=beats per minute; PPO=peak power output; MPO=mean power output; FI=fatigue index. *Significant group x time effect

sition compared to a moderate carbohydrate diet. To our knowledge, this is the fourth study to examine the effects of a KD in CrossFit populations, adding to the limited data available and showing that a KD does not affect CrossFit performance.

Strength and Power

Strength and power exercises rely primarily on anaerobic pathways to support the energetic requirements of the exercise task. Thus, muscle glycogen serves as an important sustrate for fueling high-intensity exercise, especially for exercise more than a few seconds (Vigh-Larsen et al., 2021). Given that KD has been shown to decrease muscle glycogen stores and pyruvate dehydrogenase activity, KD may impair strength and anaerobic power performance (Kang et al., 2020; Stellingwerff et al., 2006). However, we found that a non-KD conferred no significant advantage over a KD in strength or other anaerobic parameters. Our statistical analyses revealed that neither KD nor CON experienced significant improvements in any of these performance variables, supporting the premise of several previous studies that found no significant advantage or disadvantage of a KD over CON in strength and power performance in CrossFit (Kephart et al., 2018), soccer (Paoli et al., 2021), and strength-trained athletes (Greene et al., 2018). It is worth noting, however, that the CON group in our study demonstrated greater improvements in 3-RM strength following the 6-week dietary intervention. Although this finding is not statistically significant, the ~5 kg improvement in 3-RM, moderate effect size and trend toward statistical significance may be practically meaningful. An important consideration for the disparity in 3-RM between KD and CON is the timing and the protocol used for determining 3-RM. The phosphagen system contributes to 70% of ATP generation during the first 3 s of muscular contraction. For each subsequent contraction, the phosphagen system's contribution to ATP generation decreases, thereby increasing the reliance on glycolysis (Sahlin, 2014). Because we employed a 3-RM test that permitted multiple attempts, the inter-set rest periods may not have provided sufficient time for intracellular phosphagen stores to completely replenish. Additionally, the 3-RM test chosen for our protocol was performed last in the testing battery after other exhaustive exercise testing. For this reason, lower glycogen content may have inhibited the potential maximal muscle contraction. Nevertheless, our findings support the premise that low carbohydrate availability does not negatively impact acute, low-volume strength performance; however, consuming carbohydrates may be required to maximize training adaptation (Cholewa et al., 2019).

Aerobic Performance

Several studies to date have identified maximal aerobic capacity (VO_{2max}) to be a significant predictor of CrossFit-specific performance (Dexheimer et al., 2019; Gómez-Landero & Frías-Menacho, 2020; Mangine et al., 2020). We found that 6-weeks of KD preserved VO_{2peak}. Our finding is consistent with the findings of others who have examined aerobic capacity following KD in various durations (Kang et al., 2020). Moreover, we observed no differences in peak respiratory exchange ratio (RER) between KD and CON. Considering a reduction in RER at VO_{2max} might reflect impaired glycolytic potential, and thereby, a decline in performance at high intensities, our findings further support the premise that a KD preserves high-intensity exercise efforts (Murphy et al., 2021). We also found the KD group to exhibit a significantly higher peak heart rate during the VO_{2peak} test. Similar findings were reported by Durkalec-Michalski et al., (2014) who found a 4-week KD increased HR_{max} in female participants and HR at anaerobic threshold in male participants during an incremental cycling test. Such changes in peak HR and HR at the anaerobic threshold may reflect enhanced sympathetic activation attributed to low glycogen stores and heightened metabolic stress (Havemann et al., 2006); however, the increase in HR_{max} observed in our study was not associated with changes in performance.

Body Composition

KD has gained much attention as a strategy to promote reductions in fat mass (FM) and thus body composition. Reductions in FM increase the strength-to-mass ratio, which is beneficial for strength and power athletes. Martínez-Gómez et al.(2020) recently found that relative strength to be a strong predictor of CrossFit performance that involved moving their body weight in addition to external loads (e.g., medicine ball cleans, wall balls, front-rack lunges). Numerous studies to date appear to support the favorable changes in body composition following a KD. Specifically, a KD is associated with reductions in body mass (BM) and FM (Ashtary-Larky et al., 2021; Lee & Lee, 2021). However, we found that 6-week of a KD did not result in reductions in BM or FM, which is in disagreement with previous studies that have found reductions in BM and FM following a KD at various lengths. Kephart et al. (2018) reported reductions in BM and FM following 12 weeks of a KD in CrossFit athletes. Gregory et al. (2017) reported similar improvements in BM and FM following a 6-week KD in CrossFit athletes. Reasons for the observed changes in BM can be due to several factors. First, KD diets reduce skeletal muscle glycogen content, which stores an obligatory three molecules of water per gram of glycogen. Consequently, the reductions in BM can be partly attributed to significant reductions in intracellular water. Second, it is thought that reductions in BM and FM following a KD rely on reducing energy intake. A KD may have anorexigenic effects, which could reduce total caloric intake and thus explain the favorable reductions in both BM and FM (Paoli et al., 2021). This is supported by Kephart et al.(2018), who reported a decrease in total energy intake in the KD group, and Gregory et al.(2017), who, though reported no statistically significant differences in kilocalories between the groups, observed that the KD group did consume fewer kilocalories each day (KD: 1580.66 ± 283.37; CON: 1746.73 ± 485.45). Hence, because our study did not observe such reductions in total energy intake, we support the claim that a hypoenergetic KD is needed to elicit reductions in BM and FM.

A major strength of the current study is the generalizability of the findings. Specifically, those interested in adopting a KD may do so without it negatively impacting exercise performance at various intensities. From a practical perspective, this study demonstrated the feasibility of a KD in a CrossFit population such that those interested in pursuing a KD may do so without experiencing deleterious effects in CrossFit performance. Some limitations should be considered when interpreting the result, however. First, we acknowledge that we recruited a small sample of CrossFit athletes from Western Massachusetts, and a larger, more representative sample will be needed to reveal meaningful differences in body composition and CrossFit performance variables. Second, while all participants attended a similar number of CrossFit sessions, we did not control for exercise intensity or volume of these activities. Lastly, CrossFit exercise programming generally includes a combination of aerobic and resistance exercise training in the same session. Therefore, because we tested each performance parameter independently, we cannot confidently state that KD impairs or does not impair CrossFit performance alone on the basis of our findings reported.

CONCLUSION

Our findings demonstrate that a 6-week ad libitum KD does not significantly impact exercise performance in CrossFit practitioners when compared to a moderate carbohydrate diet. Furthermore, our findings demonstrate the feasibility of adhering to a KD while CrossFit training. However, unlike previous studies, we found a KD did not lead to reductions in BM and FM. The results herein suggest an energy deficit brought on by a KD, not a KD per se, may be needed to experience favorable changes in body composition.

CONFLICT OF INTERESTS

We report no conflicts of interest.

FUNDING

No funding was provided for this study.

ACKNOWLEDGEMENTS

The authors would like to thank Richard Wood for spearheading this project, Tracey Matthews for her preliminary work on the statistical analyses, and the participants for their efforts.

REFERENCES

Aragon, A. A., Schoenfeld, B. J., Wildman, R., Kleiner, S., VanDusseldorp, T., Taylor, L., Earnest, C. P., Arciero, P. J., Wilborn, C., Kalman, D. S., Stout, J. R., Willoughby, D. S., Campbell, B., Arent, S. M., Bannock, L., Smith-Ryan, A. E., & Antonio, J. (2017). International society of sports nutrition position stand: Diets and body composition. *Journal of the International Society of Sports Nutrition, 14*(1), 16. https://doi.org/10.1186/s12970-017-0174-y

Ashtary-Larky, D., Bagheri, R., Asbaghi, O., Tinsley, G. M., Kooti, W., Abbasnezhad, A., Afrisham, R., & Wong, A. (2021). Effects of resistance training combined with a ketogenic diet on body composition: A systematic review and meta-analysis. *Critical Reviews in Food Science and Nutrition*, 1–16. https://doi.org/10.1080/10408398.2021.1890689

Bergeron, M. F., Nindl, B. C., Deuster, P. A., Baumgartner, N., Kane, S. F., Kraemer, W. J., Sexauer, L. R., Thompson, W. R., & O'Connor, F. G. (2011). Consortium for Health and Military Performance and American College of Sports Medicine Consensus Paper on Extreme Conditioning Programs in Military Personnel: *Current Sports Medicine Reports, 10*(6), 383–389. https://doi.org/10.1249/JSR.0b013e318237bf8a

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Human kinetics.

Bruce, R. A., Kusumi, F., & Hosmer, D. (1973). Maximal oxygen intake and nomographic assessment of functional aerobic impairment in cardiovascular disease. *American Heart Journal, 85*(4), 546–562. https://doi.org/10.1016/0002-8703(73)90502-4

Burke, L. M. (2021). Ketogenic low-CHO, high-fat diet: The future of elite endurance sport? *The Journal of Physiology, 599*(3), 819–843. https://doi.org/10.1113/JP278928

Burke, L. M., & Hawley, J. A. (2002). Effects of short-term fat adaptation on metabolism and performance of prolonged exercise: *Medicine & Science in Sports & Exercise, 34*(9), 1492–1498. https://doi.org/10.1097/00005768-200209000-00015

Cholewa, J. M., Newmire, D. E., & Zanchi, N. E. (2019). Carbohydrate restriction: Friend or foe of resistance-based exercise performance? *Nutrition*, *60*, 136–146. https://doi.org/10.1016/j.nut.2018.09.026

Claudino, J. G., Gabbett, T. J., Bourgeois, F., Souza, H. de S., Miranda, R. C., Mezêncio, B., Soncin, R., Cardoso Filho, C. A., Bottaro, M., Hernandez, A. J., Amadio, A. C., & Serrão, J. C. (2018). CrossFit overview: Systematic review and meta-analysis. *Sports Medicine - Open, 4*(1), 11. https://doi.org/10.1186/s40798-018-0124-5

Cox, P. J., & Clarke, K. (2014). Acute nutritional ketosis: Implications for exercise performance and metabolism. *Extreme Physiology & Medicine, 3*(1), 17. https://doi.org/10.1186/2046-7648-3-17

Dexheimer, J. D., Schroeder, E. T., Sawyer, B. J., Pettitt, R. W., Aguinaldo, A. L., & Torrence, W. A. (2019). Physi logical performance measures as indicators of CrossFit® performance. *Sports*, *7*(4), 93. https://doi.org/10.3390/sports7040093

Durkalec-Michalski, K., Nowaczyk, P. M., Główka, N., Ziobrowska, A., & Podgórski, T. (2021). Is a four-week ketogenic diet an effective nutritional strategy in CrossFit-trained female and male athletes? *Nutrients, 13*(3), 864. https://doi.org/10.3390/nu13030864

Escobar, K. A., Morales, J., & Vandusseldorp, T. A. (2016). The effect of a moderately low and high carbohydrate intake on Crossfit performance. *International Journal of Exercise Science, 9*(3), 460–470

Gogojewicz, A., Śliwicka, E., & Durkalec-Michalski, K. (2020). Assessment of dietary intake and nutritional status in CrossFit-trained individuals: A descriptive study. *International Journal of Environmental Research and Public Health, 17*(13), 4772. https://doi.org/10.3390/ijerph17134772

Gómez-Landero, L. A., & Frías-Menacho, J. M. (2020). Analysis of morphofunctional variables associated with performance in Crossfit ® competitors. *Journal of Human Kinetics, 73*(1), 83–91. https://doi.org/10.2478/hukin-2019-0134

Greene, D. A., Varley, B. J., Hartwig, T. B., Chapman, P., & Rigney, M. (2018). A low-carbohydrate ketogenic diet reduces body mass without compromising performance in powerlifting and Olympic weightlifting athletes. *Journal of Strength and Conditioning Research, 32*(12), 3373–3382. https://doi.org/10.1519/JSC.0000000000002904

Gregory, R. M., Hamden, H., Torisky, D. M., & Akers, J. D. (2017). A low-carbohydrate ketogenic diet combined with 6-weeks of CrossFit training improves body composition and performance. *International Journal of Sports and Exercise Medicine, 3*(2). https://doi.org/10.23937/2469-5718/1510054

Haff, G. G., & Triplett, N. T. (Eds.). (2015). *Essentials of strength training and conditioning 4th edition*. Human kinetics.

Harvey, K. L., Holcomb, L. E., & Kolwicz, S. C., Jr (2019). Ketogenic diets and exercise performance. *Nutrients, 11*(10), 2296-2311 https://doi.org/10.3390/nu11102296

Havemann, L., West, S. J., Goedecke, J. H., Macdonald, I. A., St Clair Gibson, A., Noakes, T. D., & Lambert, E. V. (2006). Fat adaptation followed by carbohydrate loading compromises high-intensity sprint performance. *Journal of Applied Physiology, 100*(1), 194–202. https://doi.org/10.1152/japplphysiol.00813.2005

Kang, J., Ratamess, N. A., Faigenbaum, A. D., & Bush, J. A. (2020). Ergogenic properties of ketogenic diets in normal-weight individuals: A systematic review. *Journal of the American College of Nutrition, 39*(7), 665–675. https://doi.org/10.1080/07315724.2020.1725686

Kephart, W., Pledge, C., Roberson, P., Mumford, P., Romero, M., Mobley, C., Martin, J., Young, K., Lowery, R., Wilson, J., Huggins, K., & Roberts, M. (2018). The three-month effects of a ketogenic diet on body composition, blood parameters, and performance metrics in Crossfit trainees: A pilot study. *Sports, 6*(1), 1-11 https://doi.org/10.3390/sports6010001

Kerksick, C. M., Arent, S., Schoenfeld, B. J., Stout, J. R., Campbell, B., Wilborn, C. D., Taylor, L., Kalman, D., Smith-Ryan, A. E., Kreider, R. B., Willoughby, D., Arciero, P. J., VanDusseldorp, T. A., Ormsbee, M. J., Wildman, R., Greenwood, M., Ziegenfuss, T. N., Aragon, A. A., & Antonio, J. (2017). International society of sports nutrition position stand: Nutrient timing. *Journal of the International Society of Sports Nutrition, 14*(1), 1-21. https://doi.org/10.1186/s12970-017-0189-4

Lee, H. S., & Lee, J. (2021). Influences of ketogenic diet on body fat percentage, respiratory exchange rate, and total cholesterol in athletes: A systematic review and meta-analysis. *International Journal of Environmental Research and Public Health, 18*(6), 2912. https://doi.org/10.3390/ijerph18062912

Mangine, G. T., Tankersley, J. E., McDougle, J. M., Velazquez, N., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Predictors of CrossFit open performance. *Sports, 8*(7), 102. https://doi.org/10.3390/sports8070102

Martínez-Gómez, R., Valenzuela, P. L., Alejo, L. B., Gil-Cabrera, J., Montalvo-Pérez, A., Talavera, E., Lucia, A., Moral-González, S., & Barranco-Gil, D. (2020). Physiological predictors of competition performance in CrossFit athletes. *International Journal of Environmental Research and Public Health, 17*(10), 3699. https://doi.org/10.3390/ijerph17103699

Maud, P. J., & Shultz, B. B. (1989). Norms for the Wingate anaerobic test with comparison to another similar test. *Research Quarterly for Exercise and Sport, 60*(2), 144-151.

Murphy, N. E., Carrigan, C. T., & Margolis, L. M. (2021). High-fat ketogenic diets and physical performance: A systematic review. *Advances in Nutrition, 12*(1), 223–233. https://doi.org/10.1093/advances/nmaa101

Nasser, S., Vialichka, V., Biesiekierska, M., Balcerczyk, A., & Pirola, L. (2020). Effects of ketogenic diet and ketone bodies on the cardiovascular system: Concentration matters. *World Journal of Diabetes, 11*(12), 584–595. https://doi.org/10.4239/wjd.v11.i12.584

Paoli, A., Mancin, L., Caprio, M., Monti, E., Narici, M. V., Cenci, L., Piccini, F., Pincella, M., Grigoletto, D., & Marcolin, G. (2021). Effects of 30 days of ketogenic diet on body composition, muscle strength, muscle area, metabolism, and performance in semi-professional soccer players. *Journal of the International Society of Sports Nutrition, 18*(1), 62. https://doi.org/10.1186/s12970-021-00459-9

Rodriguez, N. R., DiMarco, N. M., & Langley, S. (2009). Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. *Journal of the American Dietetic Association, 109*(3), 509-527. https://doi.org/10.1016/j.jada.2009.01.005

Sahlin, K. (2014). Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Medicine, 44*(S2), 167–173. https://doi.org/10.1007/s40279-014-0256-9

de Souza, R., da Silva, A. G., de Souza, M. F., Souza, L., Roschel, H., da Silva, S. F., & Saunders, B. (2021). A systematic review of CrossFit® workouts and dietary and supplementation interventions to guide nutritional strategies and future research in CrossFit®. *International Journal of Sport Nutrition and Exercise Metabolism, 31*(2), 187–205. https://doi.org/10.1123/ijs

Stellingwerff, T., Spriet, L. L., Watt, M. J., Kimber, N. E., Hargreaves, M., Hawley, J. A., & Burke, L. M. (2006). Decreased PDH activation and glycogenolysis during exercise following fat adaptation with carbohydrate restoration. *American Journal of Physiology-Endocrinology and Metabolism, 290*(2), E380–E388. https://doi.org/10.1152/ajpendo.00268.2005

Thompson, W. R. (2013). Now Trending: Worldwide Survey of Fitness Trends for 2014. *ACSM'S Health & Fitness Journal, 17*(6), 10–20. https://doi.org/10.1249/FIT.0b013e3182a955e6

Thompson, W. R. (2019). Worldwide survey of fitness trends for 2020. *ACSM's Health & Fitness Journal, 23*(6), 10-18. https://doi.org/10.1249/FIT.0000000000000526

Urbaniak, G. C., & Plous, S. (2013). *Research Randomizer* (Version 4.0) [Computer software]. Retrieved on June 22, 2013, from http://www.randomizer.org/

Vigh-Larsen, J. F., Ørtenblad, N., Spriet, L. L., Overgaard, K., & Mohr, M. (2021). Muscle glycogen metabolism and high-intensity exercise performance: A narrative review. *Sports Medicine, 51*(9), 1855–1874. https://doi.org/10.1007/s40279-021-01475-0