Effects of *Ad libitum* Low-Carbohydrate High-Fat Dieting in Middle-Age Male Runners

ALEXANDER J. HEATHERLY[1], LAUREN G. KILLEN[2], ASHTON F. SMITH[2], HUNTER S. WALDMAN[3], CHRISTIE L. SELTMANN[2], ANGELA HOLLINGSWORTH[4], and ERIC K. O'NEAL[2]

[1]*Department of Health and Human Performance, Middle Tennessee State University, Murfreesboro, TN;* [2]*Department of Health, Physical Education and Recreation, University of North Alabama, Florence, AL;* [3]*Department of Kinesiology, Mississippi State University, Starkville, MS; and* [4]*College of Nursing, The University of Alabama in Huntsville, Huntsville, AL*

ABSTRACT

HEATHERLY, A. J., L. G. KILLEN, A. F. SMITH, H. S. WALDMAN, C. L. SELTMANN, A. HOLLINGSWORTH, and E. K. O'NEAL. Effects of *Ad libitum* Low-Carbohydrate High-Fat Dieting in Middle-Age Male Runners. *Med. Sci. Sports Exerc.*, Vol. 50, No. 3, pp. 570–579, 2018. **Purpose**: This study examined the effects of a 3-wk *ad libitum*, low-carbohydrate (<50 $g \cdot d^{-1}$) high-fat (~70% of calories) (LCHF) diet on markers of endurance performance in middle-age, recreationally competitive male runners. **Methods**: All subjects (n = 8) after their normal high-carbohydrate (HC) diet had anthropometric measures assessed and completed five 10-min running bouts at multiple individual race paces in the heat while physiological variables, metabolic variables, and perceptual responses were recorded. After 20 min of rest, participants completed a 5-km time trial on a road course. Subjects then consumed an LCHF diet for 3 wk and returned for repeat testing. **Results**: Body mass and seven-site skinfold thickness sum decreased by approximately 2.5 kg (P < 0.01) and 13 mm (P < 0.05) after LCHF diet. Rectal temperature was higher after the first 10 min of exercise (37.7°C ± 0.3°C vs 37.3°C ± 0.2°C) in the HC diet but did not differ at any other time with LCHF diet. Heart rate and perceptual measures did not display any consistent differences between treatments excluding thirst sensation for LCHF diet. RER and carbohydrate oxidation declined significantly, whereas fat oxidation increased after LCHF diet for every pace (P < 0.01). There was no significant difference (P = 0.25) in a 5-km time trial performance, but LCHF diet (23.45 ± 2.25 min) displayed a trend of improved performance versus HC (23.92 ± 2.57 min). **Conclusion**: Improved body composition and fat oxidation from LCHF diet potentially negate expected performance decrement from reduced carbohydrate use late in exercise for nonelite runners. An acute decrease in training capacity is expected; however, if performance improvement is not exhibited after 3 wk, diet cessation is suggested for negative responders. **Key Words:** METABOLISM, HYDRATION, THERMOREGULATION, CARBOHYDRATES, KETONES

It is commonly recommended that runners should seek to maximize preexercise glycogen stores before competition, restore glycogen content between training bouts, and consume 30 to 60 g of carbohydrates per hour during prolonged endurance exercise (1,2). However, low-carbohydrate high-fat (LCHF) diets have also been proposed to possibly be advantageous for endurance performance due to increased rates of fat oxidation, reduction in glycogen dependence, and loss of body mass or fat (3). The seminal LCHF diet study by Phinney et al. (4) occurred over 3 decades ago. More recent attempts to explore the ergogenic effects of LCHF diet have resulted in equivocal findings with evidence supporting aspects of endurance performance improvement under LCHF diet (5–7), no difference versus high-carbohydrate (HC) intake (8–11), and a lack of performance enhancement when training with an LCHF diet (12) for the endurance population.

Efficacy concerning the ergogenic effect of LCHF diet for endurance athletes continues to be debated; however, there is a paucity of data that actually compares time trial completion after an extended period of low-carbohydrate feeding (8–12). Moreover, the population most likely to benefit from LCHF diet, nonelite endurance athletes that compete at a lower relative percentage of aerobic capacity with higher body fat percentages, has received relatively little attention. Although the responses of nutritional interventions on elite athletes are most certainly interesting, by definition this group represents only a small percent of the running population, and responses to LCHF diet may not be analogous to less elite but recreationally competitive runners. The populations previously examined during LCHF diet studies have primarily consisted of only upper tier endurance athletes (4,8,10–12). Elite endurance athletes are leaner (13) and compete at a higher percentage of $\dot{V}O_{2max}$ (14) than nonelite runners. Hence, the much larger population of recreationally competitive runners most likely to exhibit benefits of LCHF diet intervention have received virtually no attention from the scientific community. Distance running is one of the most popular exercise activities of adults in the United States.

Address for correspondence: Eric K. O'Neal, Ph.D., 1 Harrison Plaza, Florence, AL 35632; E-mail: eoneal1@una.edu.
Submitted for publication May 2017.
Accepted for publication October 2017.

0195-9131/18/5003-0570/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000001477

With consideration of current rates of obesity, the significance of nonelite runner performance improvement is likely important to increase exercise adherence for many runners and should not be overlooked if individuals are able to lose weight by simply eating to satiety without attempting to intentionally reduce caloric intake (15).

Thus, the primary purpose of this study was to investigate the effects of a 3-wk LCHF diet with *ad libitum* food and beverage intake on changes in body composition, running performance, and metabolic profile at multiple race distance intensities in well-trained, recreationally competitive male runners. An additional aim of this study was to examine thermoregulatory, hydration, and perceptual responses after LCHF diet with the assumption that the depletion of glycogen stores would result in decreases in total body water (TBW).

METHODS

Subjects. Eight middle-age (39.5 ± 9.9 yr) trained runners ($\dot{V}O_{2peak}$ = 49.2 ± 4.2 mL·kg^{-1}·min^{-1}) that regularly competed in endurance running events of marathon/ultramarathon to Ironman^{TM} distance triathlons and also participated in shorter distance races from 5-km to half-marathon distance completed all study requirements. Seven runners reported engaging in weekly endurance training of 10–15 h, and one participant reported 5–10 h of endurance training per week. Confirmation that each participant habitually consumed a diet of moderate to HC content was determined by reporting weekly frequency of HC containing food and beverages via a dietary questionnaire. Two participants reported partaking in low-carbohydrate diets in the past but had suspended the diet for at least 12 months before participation. Written informed consent was obtained before testing. The University of North Alabama Institutional Review Board approved all aspects of the project before data collection commenced.

Experimental design. A graphic depiction of the study time line is presented in Figure 1. Data collection occurred during the late winter/early spring months of February and March (n = 5) and during the hot and humid summer months of July and August (n = 3) to minimize any effects of transitional acclimatization. In brief, the first session (day 1; session 1) consisted of health, training, and dietary screenings; $\dot{V}O_{2peak}$; testing body composition assessment; and running course familiarization. Participants reported to the laboratory four more times. Sessions 2 and 3 occurred 24 h apart and 7–10 d after the first session. Participants consumed their habitual HC diets during this period. After their normal high-carbohydrate (HC) sessions 2 and 3, participants began consuming an LCHF diet for approximately 3 wk before reporting back to the laboratory for sessions 4 and 5 (days 28–31). Sessions 2–5 all began between 0500 and 0600 h. Experimental procedures include exercise interventions (described below) during sessions 2 and 4 and were preceded by 24 h of restriction of exercise, caffeine, and alcohol. Further exercise was prohibited for the next 24 h until participants reported the following morning (sessions 3 and 5) for hydration status and body composition assessments. Treatments were not counterbalanced with HC serving as the first treatment for all participants.

Preliminary testing (session 1; day 1). In the initial screening session, participants completed training and dietary practices questionnaires and estimated goal finishing times for 5-km (rounded to nearest 1 min), 10-km (round to

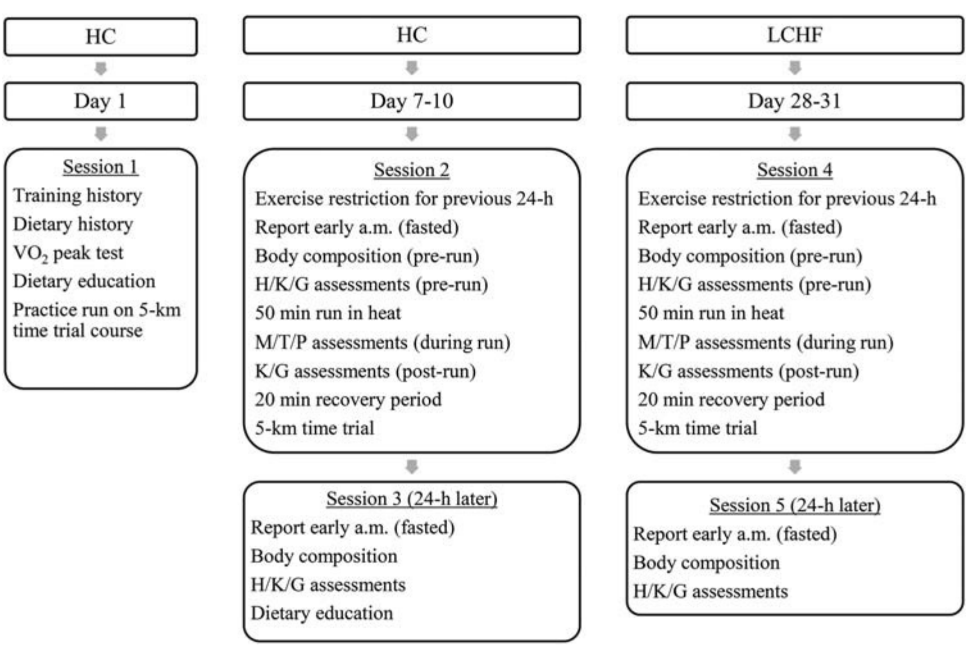

FIGURE 1—Timeline of experimental protocol. During HC, participants consumed their habitual HC diets. After the HC phase (days 7–10), participants began consuming an LCHF diet that ended with 2 d of data collection 28–31 d after the first screening session. H/K/G = hydration/ketone/glucose assessment. M/T/*P* = metabolic/thermoregulatory/perceptual assessments. Sessions 3 and 5 took place the subsequent mornings after sessions 2 and 4.

nearest 2 min), half-marathon (rounded to nearest 5 min), and marathon (rounded to nearest 10 min) distance races under ideal conditions. Body composition and compartmental body water were assessed using bioelectrical impedance analysis (BIA) (mBCA 514; Seca GmbH & Co., Hamburg, Germany). Participants then completed a graded treadmill peak oxygen consumption test. Participants began running at a speed approximately 4.02 $km \cdot h^{-1}$ slower than their estimated 5-km race pace. Every 2 min, the speed of the treadmill was increased by 0.8 $km \cdot h^{-1}$ until volitional exhaustion. The grade was maintained at 1% for the entire test. Expired gas concentrations and volume were measured via indirect calorimetry (TrueOne 2400; Parvo Medics, Sandy, UT). An average of the last minute completed in the final stage was used to represent $\dot{V}O_{2peak}$. Individuals were given a vehicle tour of the 5-km road course that would be used later in experimental procedures. All participants, excluding one nonlocal runner, completed at least one practice run on the course after the initial session, and most had run the course as parts of previous studies in our laboratory. Before leaving, participants were given two 500-mL bottles of water to drink the night before their first experimental session to control for hydration status and a container to collect first morning voids. The day before all remaining experimental sessions, participants ate their evening meal by 1900. After their normal high-carbohydrate (HC) *ad libitum* drinking during this meal, participants drank one 500-mL bottle of water and their second 500-mL bottle of water in the hour before bed. No fluids or food were permitted until reporting to the laboratory the next morning, and participants were asked to collect their first urinary void after waking if the void occurred before reporting to the laboratory.

Dietary interventions. All food and beverage intake was completely *ad libitum* by participants, except restricted carbohydrate intake and targeted goals for fat intake during LCHF diet. Seven to 10 d after the initial preliminary screening session, participants continued their normal HC dietary habits based on reported weekly eating habits from the questionnaire completed in the screening session. This served as the HC phase of the experiment. After their normal high-carbohydrate (HC) diet in the third session, extensive education efforts were made before implementation of the LCHF diet phase to prepare participants to adjust to the LCHF diet phase (began the day after session 3). After completing the initial screening session testing procedures in session 1, participants were provided with a popular LCHF diet book (16) to familiarize themselves with the basic tenets of the LCHF diet. Participants also received a set of detailed dietary instructions that included information concerning how to interpret food labels, an extensive list of foods/beverages to eat or avoid during LCHF diet, examples of daily menu items for LCHF diet, links to LCHF recipe websites, and explanation of the target 70% caloric intake to be from fat with limitation of daily carbohydrate intake to not exceed greater than 50 g of carbohydrate excluding fiber or sugar alcohols. Investigators coached participants on these areas during both the initial screening session and after the last day of the HC phase (session 3). Once LCHF diet commenced, investigators examined food items eaten by participants for the first 3–5 d of the study to confirm if LCHF diet was being followed. Daily correspondence was maintained with participants during LCHF diet to remind runners about recording food/activity logs, to spot-check food logs, and to answer questions regarding food choices. Investigators analyzed 3-d food logs (myfitnesspal.com) leading up to sessions 2 and 4. Absolute net carbohydrates (carbohydrate − fiber) and percentage of total calories from carbohydrates equaled 309 ± 155 $g \cdot d^{-1}$ and 43% ± 11% (HC) and 30 ± 13 $g \cdot d^{-1}$ and 7% ± 4% (LCHF). Fat increased from 121 ± 47 $g \cdot d^{-1}$ and 38% ± 7% of total calories (HC) to 137 ± 53 $g \cdot d^{-1}$ and 64% ± 9% of total calories (LCHF). Protein intake also increased by ~20 $g \cdot d^{-1}$ with LCHF (HC = 111 ± 50 $g \cdot d^{-1}$ and 17% ± 8% of calories; LCHF = 133 ± 43 $g \cdot d^{-1}$ and 29% ± 9% of daily calories). Although there is a potential for inherent error regarding the exact mass of nonmeasured food items from self-reported logs, the most unexpected finding was *ad libitum* LCHF diet resulted in nearly <1000 $kcal \cdot d^{-1}$ during LCHF diet (HC = 2820 ± 955, LCHF = 1886 ± 520 $kcal \cdot d^{-1}$).

Running sessions (sessions 2 and 4). Upon arriving for exercise treatment sessions, participants provided investigators with their first morning urine voids container or made a void, quickly drank a 500-mL bottle of water, and then rested in a reclined position for 10 min for venous blood collection for assessment of biomarkers not discussed in this manuscript. Whole blood was collected from an ethylenediaminetetraacetic acid tube in three 100-μL microcapillary tubes and centrifuged before hematocrit was assessed in triplicate and averaged. Verbal confirmation regarding food and water intake and abstinence of physical activity and caffeine for the previous 24 h were obtained. Urine mass, specific gravity (Pen-urine S.G., Atago Co., Tokyo, Japan), and color (17) were assessed by the same research team member for every session. Nude body mass to the nearest 0.1 kg was measured (BWB 800; Tanita Corp., Tokyo, Japan). Participants then were instructed to insert a rectal thermistor (ThermaLert Th-8; Physitemp Instruments Inc., Clifton, NJ) ~8 cm beyond their anal sphincter. Body composition and fluid volume/distribution were then assessed (mBCA 514, Seca GmbH & Co.). Participants were fitted with a heart rate monitor (Team 2; Polar Electro, Kempele, Finland) and a soft, flexible face mask (V2 mask, Hans Rudolph, Inc., Shawnee, KS) for indirect calorimetry assessment.

Participants then entered an environmental chamber where they sat quietly for 5 min. The environmental chamber was maintained at approximately 29°C and 60% humidity. At 3 min, resting glucose and ketones (Precision Xtra; Abbott Laboratories, Abbott Park, IL) were measured from whole blood collected from a finger stick. These procedures were replicated at 3 min postexercise. Participants ran for a total of 50-min split into five 10-min periods with 2 min of rest separating each bout in the environmental chamber at varying race paces on a treadmill (TMX 425C; Trackmaster, Newton, KS). A box fan was placed in front of the treadmill to increase air circulation and to better replicate outdoor running conditions. The first 7 min of each phase took place at 0.8 $km \cdot h^{-1}$ slower than estimated marathon pace at 0% grade. The subsequent 3 min of running was completed at 1% grade at multiple goal race paces rounded to the nearest 0.8 $km \cdot h^{-1}$. All paces were determined during the initial stages of testing based on the runners' goal finishing times for the 5-km marathon, the 10-km marathon, and the half-marathon and 0.8 $km \cdot h^{-1}$ slower than marathon pace in this order, respectively. Metabolic data were continuously measured during the entire running session with the data averaged over the last minute of each race distance pace used in statistical analysis. Fat ($1.718[\dot{V}O_2] - 1.718[\dot{V}CO_2]$) and carbohydrate ($4.170[\dot{V}CO_2] - 2.965[\dot{V}O_2]$) oxidation rates were estimated using stoichiometric equations (18). Thermal (0 = comfortable; 100 = extremely hot) and thirst (0 = not thirsty at all; 100 = extremely thirsty) sensations were assessed on a 100-mm visual analog scale during the 2-min recovery period between each running bout. RPE for legs, breathing, and overall were assessed using a running based pictorial scale (19) in a random order during the last 30 s of each stage. Heart rate from the last 10 s of each stage was also recorded.

Upon completion of the run, the participants remained seated in a chair placed on the treadmill for 5 min. At 3 min, glucose and ketones were measured. Participants then immediately dried off with a towel, and sweat loss was assessed by change in nude body mass. During summer testing, all participants consumed a 500-mL bottle of water after these procedures. The recovery period was standardized to last 20 min. Participants changed into a dry set of running shorts then ran a 5-km time trial (5TT) on an outdoor road course. The course was considerably challenging with multiple steep hills in the first third of the course, a continuous slight decent in the second third, and a continuous slight assent for the last third of the course. Completion time and pre- or postrectal temperature were recorded. Overall, leg and breathing RPE in regard to the 5TT as a whole were collected 5 min after 5TT completion. A final nude body mass was also measured to determine 5TT trial sweat losses.

Nonrunning/recovery sessions (sessions 3 and 5). Participants repeated their hydration schedules, abstained from caffeine for the evenings after their running sessions, and collected their first morning voids the next morning before reporting back to the laboratory. All prerun procedures (e.g., blood collection, urinalysis, body composition assessment, etc.) were replicated from the previous morning. The only additional assessment made was measurement of skinfold thickness (Lange, Beta Technology Inc., Cambridge, MD) at seven sites (chest, triceps, midaxillary, subscapular, abdominal, suprailiac, and midthigh) to estimate body fat percentage (20).

Statistical analyses. Dependent *t*-tests were used to compare data at such as points in time (e.g., absolute $\dot{V}O_2$ at a 10-km pace during LCHF vs HC) between sessions that incorporated the same protocols (e.g., body masses were compared between the two running trials but not between a running trial and a recovery trial session). All statistical analyses were conducted using Statistical Package for the Social Sciences v. 22 (IBM, Chicago, IL). Data are presented as mean ± SD. An alpha level of 0.05 was determined to represent statistical significance *a priori*.

RESULTS

Body composition. Body mass was lower ($P < 0.01$) for LCHF versus HC for both running and recovery sessions (Table 1). Skinfold estimated body fat percentage and cumulative skinfold thickness both decreased after LCHF diet ($P < 0.05$) with statistically significant lower thickness for chest, subscapularis, abdominal, and suprailiac sites, respectively (Table 1). As expected, BIA produced considerably more variance in estimation of body fat, and the validity of these measurements is questionable when such great shifts in body water occur. Body fat percentage and fat mass assessed by BIA were both lower for LCHF diet before running, but contrastingly neither differed 24 h later (Table 1). Skeletal muscle mass only differed in the recovery session with an estimated increase of just over 1 kg of skeletal muscle mass for HC (Table 1).

Compartmental water distribution and hydration markers. The estimated percentage of TBW was greater for LCHF diet before the running session, but the percentage of TBW did not differ during the recovery session (Table 1). Inversely, there was no difference in estimated absolute TBW before the running session, but absolute TBW was greater for HC 24 h after the running session. Both absolute extracellular

TABLE 1. Anthropometric and hydration responses after 3 wk of LCHF diet versus habitual HC diet (n = 8).

	Running Trials (Sessions 2 and 4)		Recovery Trials (Sessions 3 and 5)	
	HC	LCHF	HC	LCHF
Body mass (kg)	81.6 ± 7.1**	79.5 ± 6.4	81.1 ± 7.0**	78.4 ± 6.2
BIA fat (%)	20.0 ± 5.3**	17.9 ± 4.9	19.1 ± 6.7	19.0 ± 5.5
BIA fat (kg)	16.6 ± 5.7**	14.4 ± 4.9	15.9 ± 6.8	15.2 ± 5.5
Lean mass (kg)	31.7 ± 2.4	31.6 ± 2.0	32.1 ± 2.6*	31.0 ± 2.2
Skinfold thickness (mm)				
Chest	NA	NA	13.9 ± 4.4*	12.0 ± 4.9
Midaxillary	NA	NA	10.9 ± 4.0	9.6 ± 4.5
Tricep	NA	NA	9.9 ± 3.6	9.6 ± 4.1
Subscapularis	NA	NA	15.1 ± 4.0*	12.9 ± 4.3
Abdominal	NA	NA	22.5 ± 6.6*	19.1 ± 6.7
Suprailiac	NA	NA	10.5 ± 5.2*	8.5 ± 4.1
Thigh	NA	NA	13.0 ± 4.2	11.1 ± 4.1
Sum	NA	NA	95.8 ± 28.2*	82.9 ± 29.4
Skinfold BF (%)	NA	NA	18.0 ± 3.5*	16.3 ± 3.5
Waking USG	1.013 ± 0.005*	1.020 ± 0.007	1.020 ± 0.006	1.021 ± 0.006
Urine color	4.0 ± 1.3	4.1 ± 1.7	5.4 ± 1.2	4.9 ± 1.1
Hematocrit	51.0 ± 1.8***	52.6 ± 1.3	52.4 ± 2.1	51.5 ± 2.4
TBW (%)	58.0 ± 4.2**	59.5 ± 3.8	58.6 ± 5.2	58.4 ± 4.3
TBW (L)	47.6 ± 3.2	47.4 ± 2.9	47.8 ± 3.3*	46.2 ± 2.8
Extracellular water (%)	23.6 ± 1.5***	24.1 ± 1.8	23.4 ± 1.7	23.2 ± 1.8
Extracellular water (L)	19.3 ± 1.2	19.2 ± 1.4	19.1 ± 1.1*	18.3 ± 1.0
Intracellular water (L)	28.3 ± 2.1	28.3 ± 1.8	28.7 ± 2.4*	27.8 ± 1.9

Data are presented as mean ± SD.
*$P < 0.05$.
**$P < 0.01$.
***Approached significance ($P < 0.10$).

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water and intracellular water did not differ before the initiation of running, but both extracellular and intracellular water were greater ($P < 0.05$) for HC during the recovery sessions (Table 1). Waking USG was higher for LCHF diet and hematocrit approached significance ($P = 0.054$) in the running session, but no statistical differences were detected for either variable during the recovery session (Table 1). Urine color did not differ for either comparison point.

Physiological, perceptual, and metabolic responses. Ketones were elevated both preexercise (0.70 ± 0.52 vs 0.25 ± 0.09 mmol, $P = 0.047$) and postexercise (0.69 ± 0.44 vs 0.24 ± 0.07 mmol, $P = 0.017$) for LCHF versus HC, respectively. Preexercise, fasting glucose approached significance (LCHF = 103 ± 9, HC = 114 ± 8 mg·dL^{-1}, $P = 0.063$) but did not differ postrun (LCHF = 137 ± 24, HC = 144 ± 21 mg·dL^{-1}, $P = 0.29$). Temperature (LCHF = 29.2°C ± 0.7°C, HC = 29.3°C ± 0.7°C, $P = 0.44$) and relative humidity (LCHF = 64 ± 8, HC = 63% ± 5%, $P = 0.57$) did not differ between treatments. Sweat losses for LCHF diet during controlled paced runs and 5TT equaled 1.582 ± 0.342 and 0.888 ± 0.247 L and did not differ versus HC (1.517 ± 0.321 and 0.882 ± 0.248). Rectal temperature was lower during LCHF diet after the 5-km pace bout but did not differ at any other time point (Table 2). Mean heart rate was 2–4 bpm higher for LCHF diet during all intensities but did not differ statistically at any point. Thermal sensation did not differ for any pace intensity bout. Thirst sensation was reduced or approached ($P < 0.075$) a lower level for LCHF diet after four of the five race pace intensity bouts (Table 2). No differences in any leg or overall RPE were reported for any pace, but breathing RPE was rated lower for the 5-km pace ($P = 0.02$) and neared significance for the 10-km pace ($P = 0.086$) during LCHF diet. Absolute $\dot{V}O_2$, relative $\dot{V}O_2$, and percentage of relative $\dot{V}O_{2max}$ did not differ at 5-km pace but were higher at 10-km through marathon pace intensities versus HC (Table 2). RER and carbohydrate oxidation were depressed, and fat oxidation rate was increased ($P < 0.01$) at all intensities for LCHF diet (Table 2). Individual fat and carbohydrate oxidation at each pace are presented in Figure 2. Respiratory rate did not differ at any pace.

5TT. Ambient temperature during winter trials ranged from 8°C to 18°C for HC and 17°C to 24°C for LCHF diet, resulting in near significance for overall temperatures (LCHF = 24.4 ± 4.2, HC = 19.6 ± 8.3, $P = 0.08$), and summer sessions ranged from 25°C to 32°C. There were no differences in humidity (LCHF = 52 ± 23, HC = 50 ± 16, $P = 0.75$). There were no differences in 5TT performance ($P = 0.25$) (Table 3). Individual finishing results are displayed in Figure 3. All five participants completing their time trials in the winter testing session improved with LCHF diet. Of the three participants who were tested during the summer, one had no difference in performance, whereas the other two participants both exhibited impaired performance.

DISCUSSION

The primary purpose of the current study was to examine changes in body composition; metabolic, physiological, and perceptual responses at multiple race paces; and outdoor running time trial performance in recreationally trained male runners after a 3-wk period of LCHF dieting. The secondary

TABLE 2. Physiological, metabolic, and perceptual responses at multiple race paces after 3 wk of LCHF diet versus habitual HC diet ($n = 8$; mean ± SD).

Distance Pace	Pace (km·h^{-1})	Heart Rate (bpm) HC	Heart Rate (bpm) LCHF	Respiratory Rate (bpm) HC	Respiratory Rate (bpm) LCHF	Ventilation (L·min^{-1}) HC	Ventilation (L·min^{-1}) LCHF	Rectal Temperature (°C) HC	Rectal Temperature (°C) LCHF
5 km	14.0 ± 1.4	168 ± 11	172 ± 10	42 ± 7	40 ± 7	110 ± 24	106 ± 21	37.7 ± 0.3*	37.3 ± 0.2
10 km	13.1 ± 1.4	174 ± 11	177 ± 11	44 ± 8	42 ± 5	111 ± 23	109 ± 22	38.2 ± 0.3	38.1 ± 0.6
21 km	12.1 ± 1.3	177 ± 10	179 ± 11	43 ± 8	43 ± 9	106 ± 23	109 ± 28	38.8 ± 0.4	38.8 ± 0.6
42 km	11.2 ± 1.2	178 ± 11	181 ± 10	43 ± 8	44 ± 8	102 ± 23	103 ± 24	39.2 ± 0.6	39.2 ± 0.5
Sub-42 km	10.2 ± 1.2	179 ± 13	181 ± 9	43 ± 6	40 ± 4	94 ± 21	97 ± 24	39.4 ± 0.6	39.5 ± 0.6

Distance Pace	$\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) HC	$\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) LCHF	% Relative $\dot{V}O_{2max}$ HC	% Relative $\dot{V}O_{2max}$ LCHF	RER HC	RER LCHF	Fat Oxidation (g·min^{-1}) HC	Fat Oxidation (g·min^{-1}) LCHF	Carbohydrate Oxidation (g·min^{-1}) HC	Carbohydrate Oxidation (g·min^{-1}) LCHF
5 km	45.8 ± 5.6	47.1 ± 4.4	93.1 ± 6.4	97.4 ± 9.1	1.02 ± 0.06**	0.95 ± 0.03	−0.16 ± 0.41**	0.32 ± 0.19	4.9 ± 1.4*	3.7 ± 0.5
10 km	45.7 ± 5.5*	47.9 ± 7.6	92.8 ± 5.3*	98.7 ± 11.3	0.99 ± 0.05**	0.90 ± 0.03	0.05 ± 0.29**	0.64 ± 0.24	4.3 ± 1.1**	3.0 ± 0.7
21 km	42.9 ± 5.2**	45.7 ± 7.1	87.2 ± 7.1**	94.1 ± 11.8	0.96 ± 0.05**	0.88 ± 0.04	0.20 ± 0.29**	0.73 ± 0.21	3.7 ± 1.0**	2.5 ± 0.8
42 km	40.5 ± 5.4*	43.0 ± 7.1	82.4 ± 8.2*	88.7 ± 12.7	0.95 ± 0.05**	0.86 ± 0.04	0.24 ± 0.23**	0.78 ± 0.21	3.4 ± 0.9**	2.2 ± 0.8
Sub-42 km	38.2 ± 5.1*	41.0 ± 7.2	77.8 ± 7.8*	83.5 ± 12.5	0.94 ± 0.06**	0.84 ± 0.04	0.29 ± 0.27**	0.81 ± 0.24	3.0 ± 1.0*	1.9 ± 0.7

Distance Pace	Thermal Sensation[a] HC	Thermal Sensation[a] LCHF	Thirst Sensation[b] HC	Thirst Sensation[b] LCHF	RPE Legs HC	RPE Legs LCHF	RPE Breathing HC	RPE Breathing LCHF	RPE Overall HC	RPE Overall LCHF
5 km	31.1 ± 16.8	29.3 ± 10.2	35 ± 19***	25 ± 17	5.3 ± 2.1	5.1 ± 1.0	6.5 ± 2.1*	5.3 ± 1.7	5.9 ± 1.9	5.4 ± 1.2
10 km	45.0 ± 12.3	40.9 ± 11.2	46 ± 22*	36 ± 18	5.9 ± 1.2***	5.1 ± 0.8	6.8 ± 2.0***	5.8 ± 1.0	6.0 ± 1.2	5.8 ± 1.0
21 km	63.6 ± 9.9	53.3 ± 16.4	58 ± 26***	47 ± 20	5.9 ± 1.2	6.0 ± 1.6	7.0 ± 1.9	6.1 ± 1.5	6.3 ± 1.2	6.4 ± 1.1
42 km	69.0 ± 8.7	60.4 ± 15.6	65 ± 30***	52 ± 23	6.5 ± 1.6	6.3 ± 1.7	7.3 ± 2.0	6.9 ± 1.6	7.0 ± 1.5	6.9 ± 1.5
Sub-42 km	75.6 ± 7.1	67.3 ± 16.4	70 ± 31	63 ± 30	6.4 ± 1.3	6.4 ± 1.9	7.1 ± 1.3	7.1 ± 1.8	7.0 ± 0.8	6.9 ± 1.5

*$P < 0.05$.
**$P < 0.01$.
***Approached significance ($P < 0.10$).
[a]0 = comfortable; 100 = extremely hot.
[b]0 = not thirsty at all; 100 = extremely thirsty.

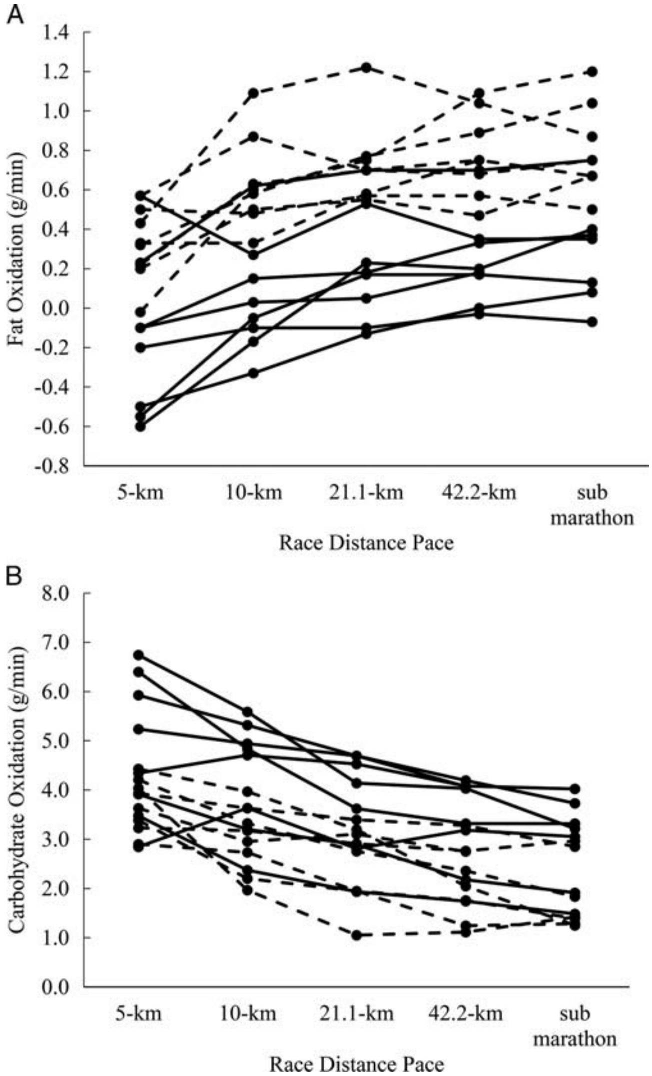

FIGURE 2—Individual runner fat (A) and carbohydrate (B) oxidation rates at multiple race paces. Dashed lines represent LCHF treatment and solid lines represent habitual HC treatment.

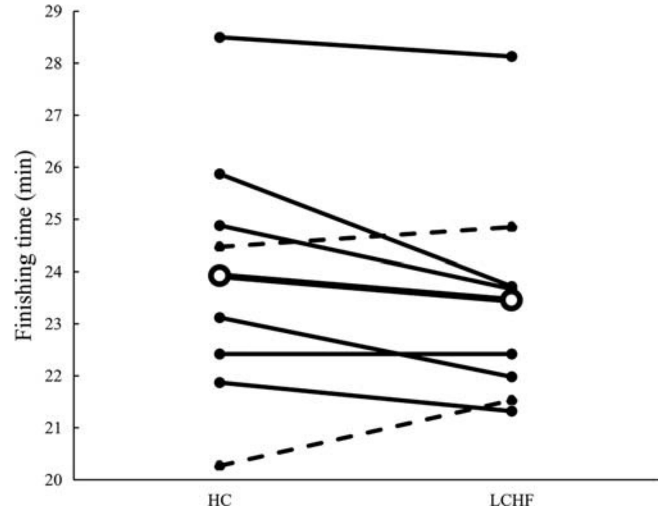

FIGURE 3—Individual finishing times for 5TT. These time trials were completed after 50 min of running in an environmental chamber maintained at ~29°C and 60% relative humidity under fasted conditions. The dashed lines represent runners that failed to match or improve performance during LCHF diet. The bold line with open marker ends represents mean responses.

study purpose was related to thermoregulatory and hydration-related responses of LCHF diet. The main findings were that LCHF diet resulted in 1) a decrease in averaged fasted, morning total body mass of ~2.5 kg (3% of body mass) with a significant decrease in skinfold thickness occurring at multiple sites in the trunk region; 2) no difference in the 5-km running performance after 50 min of running in challenging environmental conditions; and 3) an increase in fat oxidation and decreased RER at all race pace intensities, but few or no differences in cardiorespiratory, thermoregulatory, or perceptual responses excluding thirst sensation.

TABLE 3. 5TT outcomes after 50 min run in the environmental chamber (n = 8; mean ± SD).

		Rectal Temperature (°C)		RPE		
	Time (min)	T-rec pre	T-rec post	Legs	Breathing	Overall
HC	23.92 ± 2.57	38.4 ± 0.6	39.3 ± 0.7**	6.8 ± 1.5*	7.6 ± 1.7	8.0 ± 1.0
LCHF	23.45 ± 2.25	38.7 ± 0.4	39.6 ± 0.7	7.8 ± 1.7	8.1 ± 1.4	8.4 ± 1.2

*$P < 0.05$.
**Approached significance ($P < 0.10$).

One of the commonly promoted advantages of the LCHF diet is the potential for lower racing body mass, but the extent to which loss in body mass after LCHF diet aids performance is unclear. LCHF diet requires near complete restriction of HC low-nutrient dense food items such as sodas and sweets, and there is evidence that LCHF diet may alter hunger sensation (21). A combination of removal of low nutrient density foods, particularly calories from beverages, and possibly a reduction in hunger sensation resulted in a nearly 33% decrease in caloric intake after LCHF diet. Improvement in caloric intake and expenditure balance could be even more critical to improving performance for nonelite athletes because of the higher body fat percentages exhibited in recreationally competitive runners. However, nearly all previous LCHF diet studies with elite athletes have standardized caloric intake (5–9,11) or included an HC refeeding period, which will result in a quick increase in body mass (8,9), diminishing potential improvement in overground running performance because of body mass losses. Evidence concerning the relationship of decrease in non-lean body mass and racing performance is made further unclear as nearly all LCHF diet studies have been conducted on stationary cycle ergometers (4,5,8–10). Stationary cycle ergometers negate any potential performance advantages associated with improved running economy via decreased body mass.

In the current study, when no attempt was made to control caloric intake, mean body mass loss during LFHC equaled 2.1 kg (2.6% body mass) and 2.7 kg (3.4% body mass) in comparison with HC before the exercise session and subsequent morning recovery session, respectively (Table 1). These findings are supportive of Zajac et al. (7) and

Klement et al. (22), who reported losses of ~2.3% and 3% of body mass, respectively, in a variety of physically active adults after 4–7 wk of LCHF diet with *ad libitum* food consumption. Determining whether body mass loss is derived from decrease in fat mass, glycogen mass, or retained fluid is difficult. Dual x-ray absorptiometry estimation of lean body mass is greatly skewed by hydration status (23) and carbohydrate intake (24). Body composition assessment from BIA (used by Zajac et al. (7), Klement et al. (22) and the current study) is even further distorted as outcomes are determined by water-dependent electrical current conduction resistance. Findings of Webster et al. (25) suggest that glycogen storage in endurance athletes undergoing prolonged LCHF diet reduce glycogen storage by close to 50%. From this basis, it is difficult to not assume that at least some of the loss in body mass was due to a decreased retention in TBW and is somewhat supported by BIA of TBW during recovery. Using BIA, Zajac et al. (7) and Klement et al. (22) both found similar decreases in body fat percentage as the current study (Table 1), but the discrepancies of body fat percentage within a single day in the current study cast doubt on the validity of these findings. However, based on the decreased thickness of skinfold measurements and substantial reduction in daily calories, it is also difficult to not attribute some of the loss in body mass to decreased fat mass. When viewed in combination, these three investigations of physically active adults support that an estimated mean loss in body mass of ≥2.5% at least partially attributed to fat loss can be expected in regularly physically active adults after LCHF diet.

A prominent theory for LCHF diet advocates is that performance can be improved by enhanced use of fatty acids and ketones. Volek et al. (26) and Burke et al. (12) have recently reported that sustained LCHF dieting can increase fat oxidation rate in excess of 1.5 $g \cdot min^{-1}$ in elite distance runners and race walkers. In comparison, a sampling of some of the world's best ultrarunners consuming HC diets fail to exceed 0.5 $g \cdot min^{-1}$ in regard to maximal fat oxidation (26). Mean oxidation rates in the current study did not exceed that of Volek's elite runners, but three runners were able to exceed 1.0 $g \cdot min^{-1}$ (Table 2 and Fig. 2). The nonuniformity in substrate use responses to LCHF and TT performance highlights that metabolic fuel shifts cannot be solely responsible for shifts in running performance. Interestingly, the participant with the highest average fat oxidation rates during LCHF diet exhibited the lowest fat oxidation rates during HC. He also exhibited one of the highest carbohydrate oxidation rates during HC and lowest carbohydrate oxidation rates during LCHF diet (Fig. 2). This participant was highly familiarized with the route used in the study and able to take nearly 1.5 min off his HC time. However, all three of the participants who failed to improve in their time trial on LCHF diet were also in the top half of subjects in regard to fat oxidation rates across paces distorting the strength of the relationship between improvement in fat oxidation rates and actual improvement in competition performance.

Current findings support past studies that highlight the major reduction in RER after LCHF diet (4,5,8,9,22), and that those differences are fairly uniform with an approximately 0.07–0.1 drop with LCHF diet across nearly all popular race distance pace intensities. It has been suggested that LCHF diet can reduce ventilation rate by decreasing circulating $\dot{V}CO_2$ and drop in pH (16). If true, change in breathing frequency and depth could potentially influence RPE. Although there was a trend for decreased breathing RPE for LCHF diet during the first few stages of the run in the heat, statistical significance was approached but not reached, and the pattern becomes uncoupled later in exercise and even reversed during the 5TT (Tables 2 and 3). Again, subjective evaluation of individual data suggested that although respiratory rate and ventilation did not differ, there was a high interindividual variability possibly linked to shifts in substrate use (Table 2).

Burke et al. (12) highlight the lack of recognition of the disadvantage of reduced efficiency for fat to produce ATP versus carbohydrates due to differences in ratios of NADH and $FADH_2$ production for each substrate in recent LFHC diet studies. In the current study, absolute $\dot{V}O_2$ was increased in LCHF diet at both half- and full-marathon paces (Table 2) despite runners exhibiting decreased body mass. This manifestation is often viewed as a disadvantage, and the current authors agree that it would be if there was no substantial alteration in substrate use that is manifested after LFHC diet. However, although statistical significance was reached for two of the five paces, even in the worst-case scenario (half-marathon pace), there was only a 4% difference in oxygen consumption during LCHF diet. It is well established that elite endurance athletes are capable of extracting a higher percentage of oxygen from arterial blood than less elite athletes. The current authors postulate that for elite endurance athletes nearing maximal capacity for the $A - \dot{V}O_2$ difference, perhaps even a small decrease in carbohydrate oxidation capacity may in fact limit performance capacity. However, for runners matching the characteristics of participants in the current study, knowing that oxygen consumption must increase during LCHF diet and participants have a much higher relative ceiling for being able to extract and potentially use oxygen from the blood stream, perhaps minor increases in absolute $\dot{V}O_2$, is a less dominant factor in performance outcomes. This may be particularly true for runners focusing on longer distance–lower-intensity events as habitually training in a state of low glycogen results in physiological adaptations that increase oxidative ATP production capacity in less than elite but physically active men undertaking endurance training (27). Using the theoretical model that elite runners are more relatively carbohydrate dependent, it is not surprising that the fastest runner in the current study had the highest carbohydrate oxidation rates at nearly all paces (Fig. 3B) and also experienced the greatest percentage decrease in 5TT performance after LCHF diet (Fig. 3). Some of the differences in findings in the current study may be attributable to the elite status of the participants in Burke et al. (8) and the performance test distance (10 km) chosen for that study, which was half as long as the shortest race walk competition distance in the Olympics (20 km) requiring a much higher-intensity effort than the current study participants who were only running slightly faster than their expected half-marathon pace.

No statistical differences were detected in running performance (Table 3); however, as displayed by individual performances in Figure 3, there is evidence that LCHF diet may be beneficial to some recreationally competitive male runners. Through continued contact with our participants poststudy, personal records for multiple race distances and the first completion of an Ironman distance triathlon were reported by participants who chose to maintain their LCHF diet. Five of the eight participants tested improved their subsequent 5TT performance by 22–129 s. Each of these individuals completed their experimental trials during late winter or early spring and reported an initial but transient decrease in training run quality that subsided before the second 5TT. All participants completing their trials during the summer either failed to improve their performance or were slower after LCHF diet. Of note, none of those testing in the summer reported their training quality returning to pre-LCHF diet levels, and all three participants explicitly expressed that training quality was suppressed to investigators through informal dialogue or in training logs even after 3 wk of intervention. One participant with a decreased HFLC performance reported a 5-d period without training because of extreme physical fatigue he attributed to a combination of the LCHF diet and very hot regional temperatures.

A common criticism of LCHF diet advocates is that previous investigations are too short in duration to manifest desired changes. Metabolic alterations occur quickly upon initiation of LCHF diet as ≤7 d are needed to diminish glycogen stores and alter fat oxidation and RER (8,9), but there is no question that these adaptations impair short-term performance. Qualitative responses from participants in previous investigations report it is common for endurance athletes to experience difficulty simply completing their normal training regimens in the first week of LCHF diet transition, and the decrements can persist for as long as 5 wk for some individuals (5,8,22). We contend that the most critical application aspect of our study in regard to a performance response is that positive responders to LCHF diet can be identified within ~21 d. If there is no quantitative or qualitative performance improvement after this period, continuing to experiment with LCHF diet does not appear to be warranted.

We caution against the interpretation that our findings are meant to be representative of 5-km race performance. Although our participants reported participating in 5-km race events, the majority of their training was focused on longer duration events. Because of the multifaceted approach taken during the current study, a longer duration time trial was not logistically possible. Besides the collection of physiological and perceptual data, the standardized 50-min runs in the hot environmental chamber were meant to induce a state of fatigue and glycogen depletion that would more closely replicate the latter half of a longer distance race event. The average 5TT pace was around 12.5 $km \cdot h^{-1}$, approximately midway between expected 10-km and half-marathon race pace (Table 2). Although not under the same scenarios, the reliability of outdoor 5TT performance in populations similar to those in the current study that are familiar with the course has been found to have a coefficient of variation of <1% (28).

If carbohydrate loading is undertaken before competition or long training runs, increased fluid retention could potentially mitigate cardiovascular drift and thermal drift via an increase in free water stores as glycogen is metabolized. Conversely, completing a task with reduced body mass at the same intensity may decrease heat stressors from improvement in running economy. To the knowledge of the current researchers, only two other studies have examined the effects of LCHF diet on thermoregulatory responses. Pokora et al. (29,30) found that LCHF diet resulted in the earlier onset of sweating but had no effect on temperature regulation. However, both of these studies used tympanic temperature, in low heat stress environments, and body mass was unaffected by LCHF diet, possibly due to the very short duration of LCHF diet (3 d). Although the onset of sweat production was not assessed in the current study, it should be noted that the only time point that rectal temperature differed was after the first 10 min running bout during non-5TT running (Table 2). However, rectal temperature during LCHF diet was still considerably elevated even after the 20-min recovery period with a trend for higher starting and finishing temperature before and after the 5TT (Table 3). Although limited in number of observations, evidence through correspondence with the runners and observations of runners during the 5-km time suggested that LCHF diet was less well tolerated by the participants who completed testing during the summer.

Multiple limitations should be considered with interpretation of the current study. The first is that an ordering effect could have potentially influenced the 5TT results. Although the authors consider the *ad libitum* food and beverage consumption approach taken to increase ecological validity of our findings, there was no attempt to standardize caloric intake between treatments or control for fatty acid type distribution. It must also be considered that the fasted exercise conditions and no carbohydrate intake during exercise may have been disadvantageous during the HC treatment, and the effects of body mass loss cannot be marginalized. Although highly trained based on weekly volume and experienced in ultramarathon distance running events, one runner was considerably slower than the other participants. The increased variance of this individual in our small sample size likely decreased the potential for a significant difference to be detected in the 5TT. Unlike actual road or trail races where there are no recovery periods, the running tasks required in this study was noncontinuous during the environmental chamber observation period, and a 20-min break was given before the 5TT to allow recovery from the substantial increase in core temperature. Loss in body mass in LCHF diet also potentially influenced multiple physiological variables such as $\dot{V}O_2$ or heart rate because running pace did not differ, but running at a lower body mass resulted in less work actually being completed. As detailed above, the results of this study also represent that of a middle-age, nonelite population of runners. These findings may not translate to more elite runners.

In conclusion, *ad libitum* LCHF diet appears to offer well-trained but nonelite, middle-age male runners the opportunity to eat to satiety while maintaining a more competitive racing weight and body composition versus HC. Responses in performance appear to be highly individualized, and current data do not exhibit a clear relationship to determine whether changes in anthropometric measures or substrate use alteration alone can explain overground running performance changes. Although there is much contention in the scientific and running communities to whether HC or LCHF diet is the best nutritional approach, we contend that LCHF diet may be an option worth experimenting with for recreationally competitive runners, particularly those with less desirable body compositions. If observable performance improvement is not exhibited within 3 wk, LCHF diet is unlikely the best option to optimize running performance. Despite no clear negative thermoregulatory response to LCHF diet, adaptation to LCHF diet appears to be more challenging when training occurs in hot conditions and should be a consideration when choosing to begin an LCHF diet. Further research should examine if decrease in thirst sensation or fluid retention between training bouts may contribute to difficulties in adapting to LCHF diet during the summer and compare endurance performance with a nonfasted carbohydrate intake during exercise scenario against LCHF diet.

The authors thank the University of North Alabama for their funding support and all participants who volunteered to help with the completion of this project.

Funding for the current study was not aided by any grants, awards, or incentives by any outside organizations. The views and data presented in this manuscript are not necessarily that of the American College of Sports Medicine and are in no way under endorsement. All information that is presented in this manuscript is without falsification, manipulation, or fabrication. All data are reported accurately and honestly to the best of the authors' knowledge.

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