**THIS IS A PREPRINTED VERSION (ONE ROUND OF PEER-REVIEW COMPLETED)**

**Title**

Isoenergetic pre-exercise meals varying in carbohydrate similarly affect resistance training volume performance compared to placebo: a cross-over trial

**Running Title**

Acute feeding before high volume resistance training

**Authors**

Andrew King1, Ivan Jukic1,2, Colby A. Sousa 1, Caryn Zinn1, and Eric R. Helms1,3

**Affiliations**

1Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

2Division of Sport and Exercise Sciences, School of Applied Sciences, Abertay University, Dundee, United Kingdom.

3Department of Exercise Science and Health Promotion, Muscle Physiology Laboratory, Florida Atlantic University, Boca Raton, FL, USA

**ORCID**

Andrew King: https://orcid.org/0000-0002-9332-6506

Ivan Jukic: <https://orcid.org/0000-0002-0900-9410>

Colby A. Sousa: <https://orcid.org/0009-0006-3798-3065>

Caryn Zinn: https://orcid.org/0000-0001-6185-7663

Eric R. Helms: <https://orcid.org/0000-0002-4849-9336>

**Corresponding Author**

Andrew King

PhD Candidate

Sport Performance Research Institute New Zealand (SPRINZ)

Auckland University of Technology

17 Antares Place, Mairangi Bay

Auckland, New Zealand, 0632

Email: andrew.king@aut.ac.nz

*Please cite as:* King, A., Jukic, I., Sousa, C.A., Zinn, C., & Helms, E.R. (2024). Isoenergetic pre-exercise meals varying in carbohydrate similarly affect resistance training volume performance compared to placebo: a cross-over trial. SportRχiv.

**Abstract**

Carbohydrate is an important fuel during moderate-to-high-intensity exercise. We hypothesised that pre-exercise carbohydrate ingestion would improve resistance training (RT) volume performance. In a cross-over design, sixteen resistance-trained participants (male = 13, female = 3) performed 3 sets of back squats, bench press, prone row, and shoulder press to repetition fatigue at 80% of 1-repetition maximum (~90min). Two hours prior, in randomised order, participants ingested high carbohydrate (HCHO; 1.2g/kg body mass), low carbohydrate (LCHO; 0.3g/kg body mass), or low-calorie placebo (PLA), taste and texture matched liquid breakfasts. Linear mixed models were used to analyse volume performance, subjective appetite ratings, and blood glucose and lactate. There were no significant differences between conditions for repetitions completed per session (p = 0.318) or exercise (p = 0.973). Pre- and post-exercise hunger was similar between conditions (p = 0.155). Satiation was greater in HCHO and LCHO versus PLA post-breakfast (p = 0.007 and p = 0.002, respectively) and pre-exercise (p = 0.001 and p = 0.002). Fullness was greater in HCHO and LCHO versus PLA post-breakfast (p = 0.001 and p = 0.001, respectively) and pre-exercise (p < 0.001 and p < 0.001). Blood lactate was greater mid- (p < 0.001) and post-exercise (p < 0.0001) and was similar between conditions (p = 0.897). Blood glucose significantly increased 30-mins after breakfast in HCHO versus LCHO and PLA (p < 0.001) and was similar between conditions post-exercise (p = 1.000).The macronutrient or energy composition of a pre-exercise meal does not enhance upper-body dominant RT volume.

**Keywords** Carbohydrate, resistance training performance, sport nutrition, metabolism, appetite

**Highlights**

* When consuming moderate dietary carbohydrate (≥ 3g/day), acute carbohydrate intake before a primarily upper-body resistance training session might not influence volume performance.
* Improved subjective appetite with energy intake may not influence volume performance.
* Blood glucose concentration is maintained during resistance training, even in the absence of any nutrient provision.

*Introduction*

Dietary carbohydrate (CHO) is an important fuel source for moderate to high intensity exercise and the provision of CHO before and/or during exercise is recommended by current sport nutrition guidelines [1, 2]. Dietary CHO is stored in the liver and skeletal muscle as glycogen, which are important energy sources for high intensity exercise [3]. Standard resistance training (RT) volumes induce modest muscle glycogen store decrements (24 – 40%) [4-7], and greater RT volumes cause greater decrements [8]. Skeletal muscle contains several distinct muscle glycogen depots (e.g., intramyofibrillar, intermyofibrillar, and subsarcolemmal) [9]. Intramyofibrillar glycogen stores are associated with Ca2+ release from the sarcoplasmic reticula during contraction and these stores become selectively depleted after standard RT volumes [10]. The combined impact of a modest decrease in total muscle glycogen and the depletion of intramyofibrillar stores may induce fatigue and limit exercise performance during RT [11-14]. In addition, during periods of fasting, such as the overnight fast, liver glycogen becomes progressively depleted while muscle glycogen stores remain stable [15, 16]. Nonetheless, CHO feeding can modestly increase muscle glycogen stores (10 – 15%) after an overnight fast [17, 18] and acute CHO feeding before RT may augment glycogen stores in preparation for RT.

While there are recommendations for peri-workout nutrition for endurance training that intend to augment glycogen storage, there is less evidence to establish RT-specific recommendations. Acute CHO ingestion improved RT volume performance as reported in a recent meta-analysis [19], where the pre-exercise fast and session duration were longer (≥8 hrs and ≥45 mins, respectively), and the ergogenic effect of CHO was greater as more volume was completed, compared to low or zero energy placebo. In addition, several recent trials reported the potential impact of acute CHO feeding on RT volume performance via psychological (i.e., expectancy) and appetite suppression mechanisms [20, 21].

No previous trial investigating the effect of acute CHO feeding on RT performance has used a comparator placebo condition while equating energy intake within CHO conditions. Where energy is not matched between conditions, an ergogenic effect of CHO feeding may be due to energy provision itself, rather than any specific metabolic influence of CHO on performance. In this sense, energy provision in general could provide varying fuel sources for exercise, a psychological effect (e.g., placebo), or an effect on subjective appetite not necessarily exclusive to CHO that could affect RT volume performance. Thus, we designed a randomised, double-blind cross-over trial investigating the effect of two iso-energetic and isonitrogenous pre-exercise meals with higher (1.2g/kg body mass) and lower (0.3g/kg body mass) CHO content, and a low-calorie placebo, on volume performance during a high-volume, full body, yet ecologically valid RT session. Given the established role of CHO in exercise performance, we hypothesised that HCHO would improve volume performance compared to LCHO and PLA, and that LCHO would improve performance compared to PLA only.

*2 Materials and Methods*

*2.1 Participants*

Using previously published data for session squat repetitions completed [20], an *a priori* power analysis was completed using Power Analysis and Sample Size (PASS; version 15.0.5) software, which revealed 15 participants would be required to achieve a power of 0.8, an effect size of *f* = 0.28, an alpha α = 0.05, and correlation ρ = 0.7. The correlation assumption was checked by a statistician separate to data collection after the first six participants had completed all trials, which was robust (ρ = 0.78).

Resistance trained males (n = 13) and females (n = 3) were recruited via advertisement (posters, social media, and University courses). Their descriptive characteristics are presented in Table 1. Twenty-six participants were initially screened for participation, of which n = 16 were deemed eligible and volunteered to participate in the trial. All participants provided written consent before commencing the study and completed testing with no dropouts. The CONSORT participant flow diagram is presented in Figure 1. The study protocol was approved by the University Ethics Committee (20/312). To be eligible for inclusion, potential participants must have been (a) able to squat 1.5 and 1.25 x bodyweight for males and females, respectively; (b) able to bench press 1.0 and 0.75 x bodyweight for males and females, respectively; (c) between 18-40 years in age; (d) a habitual consumer of breakfast (>5 times per week); (e) not have a pre-existing injury, metabolic disease or condition, or medical condition that would contraindicate safe participation in exercise; (f) not reportedly using ergogenic insulin-like substances and/or anabolic/catabolic steroids, prohormones, or hormones known to affect muscle mass; (g) not reporting dietary requirements contraindicating the ingestion of a breakfast (e.g., reactions or aversions to ingredients); and (h) not previously privy to the contents of the pre-exercise meals (i.e., volunteers who pilot tested were aware of the nutritional composition).

Insert Table 1 about here.

Insert Figure 1 about here.

*2.2 Design*

Thisstudy was a double-blind, randomised, counterbalanced, cross-over trial consisting of, in order, two familiarisation sessions, one 1-repetition maximum session, and three experimental high-volume RT sessions. For each experimental session, participants arrived in the morning after an overnight fast (>10 hrs) and consumed one of three pre-exercise liquid breakfasts which were taste, texture, colour, and volume matched in pilot testing in randomised order (A) high CHO (HCHO; 1.2 g/kg body mass CHO), (B) an isoenergetic and isonitrogenous low CHO (LCHO; 0.3 g/kg body mass CHO), or (C) a low-calorie placebo (PLA) liquid breakfast. HCHO and LCHO primarily contained vanilla Super Mass Gainer (Dymatize, NC, U.S.) and vanilla KetoMeal (KetoLogic, NC, U.S.), respectively. HCHO and LCHO also contained water (350 – 500mL), Butter Powder (Garden of Life, FL, U.S.), and pure maltodextrin (NZ Starch, Auckland, NZ), of varying amounts depending on body mass. PLA contained water, guar gum (Ceres Organics, Auckland, NZ), and vanilla FlavDrops (MyProtein, Manchester, UK). The sample average liquid breakfast nutrition values are presented in Table 2. The participants were told during familiarisation that the three conditions contained the same amount of total energy but differed in macronutrient composition. After the third experimental session was completed, participants learned of the true study design and were asked if they could confidently identify which trial was PLA.

Two hours after consuming the liquid breakfast, participants completed three sets of back squats, bench press, prone row, and shoulder press with 80% 1-repetition maximum (1RM), with repetitions completed to fatigue. Participants were randomised according to the Latin-square method. Possible sequences (i.e., ABC, ACB, BCA, BAC, CAB, CBA) were placed in individual sealed, opaque envelopes. A researcher independent from all data collection kept the sealed envelopes in a locked drawer and during participant sign-up, selected an envelope, assigned the sequence to the participant, then discarded the sequence. Once all six possible sequence combinations were assigned, a new block of six envelopes was generated. All testing was completed between April 2021 and May 2022. This trial was not prospectively pre-registered on a public registry.

Insert Table 2 about here.

*2.3 Familiarisation (visit 1 & 2)*

Participants’ height (cm) and weight (kg) were recorded using a stadiometer (Seca Ltd, Hamburg, Germany) and digital calibrated scale (Tanita HD366, Tanita Corporation, Tokyo, Japan). Participants were verbally informed of the testing protocol for the 1RM and experimental sessions. Participants were familiarised with the RT specific RPE/repetitions in reserve [23] and subjective appetite (hunger, satiety, and fullness) visual analogue [24] scales, and the instruction to lift as fast as possible during concentric phases (with self-selected eccentric tempo), which was implemented for all sessions, with feedback after each set during familiarisation. Participants were also instructed to take at least a momentary pause, but no longer than 2 seconds, between repetitions. Participants were asked what their best, most recent set of each exercise (or closest variation) was, to be used with the Lombardi prediction equation [25] to estimate a conservative 1-repetition maximum for 1RM testing.

Participants performed a standardised dynamic warm-up and completed sets of 5, 3, and 1 repetition with 20, 40, and 60% of the estimated 1RM, in the back squat, bench press, prone row, and shoulder press, with self-selected rest. After a mandatory 3-minute rest, participants completed 10 repetitions with 60% estimated 1RM. A 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Viking, Wellington, NZ) were used in all sessions. The squat and bench press were performed in accordance with International Powerlifting Federation regulations using only approved “unequipped” lifting material aids (i.e., knee sleeves and weightlifting belt). Briefly, the back squat required a depth where the hip crease passed the top of the knee when viewed laterally. For bench press, the necessary contact points were maintained (head, upper back, buttocks, and flat feet). The prone row and seated shoulder press were performed as outlined previously [22]. The chest had to maintain contact with the bench and the barbell to touch the bottom of the bench for the prone row, during which participants always wore lifting straps (VersaGrips, Maine, USA). The seated shoulder press was performed off safety pins in a squat rack and required the buttocks and upper back to remain in contact with the chair throughout the movement. A successful seated shoulder press repetition required the participant to raise the barbell off the safety pins to full elbow extension overhead, before controlling the eccentric movement of the barbell back onto the safety pins. All participants completed two familiarisation sessions, which were separated by at least 72 hrs.

*2.4 Pre-trial standardisation*

The participants were asked to track and record their daily food intake using the My Fitness Pal (various versions). During the two familiarisation sessions, the participants were provided a digital food scale, downloaded My Fitness Pal, practised inputting various food selections into My Fitness Pal, and received verbal instruction from a researcher on best practice for weighing/measuring and recording daily food intake. The participants were instructed to consume a daily CHO (4 – 7 g/kg BM) and protein (at least 1.6 g/kg BM) intake in line with current sport nutrition recommendations for RT athletes [23, 24] during participation in the study. Participants were not instructed regarding food selection but were provided food suggestions where necessary to enable adherence to the daily carbohydrate and protein intakes. In addition, participants were instructed not to intentionally increase or decrease their total daily energy intake and to maintain their current supplement habits (i.e., not to introduce or stop taking supplements, and to maintain the dose). Where the participant was habituated to pre-workout supplementation, they were asked to consume the same dose of supplement, at the same time-point, prior to all sessions in the study. This was co-ordinated with a researcher and required the supplement to be low in total energy (<10 kcal). Participants were required to meet the daily CHO and protein recommendations for at least three days preceding each experimental trial, which was verified by a researcher who had access to the participants’ My Fitness Pal logs. Participant’ water intake was not quantified during the pre-trial period. Participants were asked to maintain their normal training habits between each experimental trial and to refrain from physical activity for 48-hrs preceding 1RM and experimental trials. Experimental sessions were separated at least 4, and up to 10 days, to provide adequate recovery and time to meet the standardised pre-trial nutrition requirements between experimental sessions.

*2.5 1RM (visit 3)*

The 1RM protocol consisted of 3 repetitions at 20, 40, and 60%; 1 repetition at 80% and 90%, followed by up to five 1RM attempts [25, 26]. Mean concentric velocity, as measured by linear position transducer (Gymaware Kinetic Performance, Canberra, Australia), was used in concert with participant reported RPE/RIR to guide attempt selection. If a 1RM attempt was successful, the load was increased 1 to 12.5kg in consultation with the participant. A 1RM was recorded if the participant successfully completed the lift at 10 RPE, or successfully completed an attempt at a lower RPE but failed a subsequent attempt. Three minutes and 3-5 mins rest were given between submaximal sets and 1RM attempts, respectively. Barbell velocity feedback was not provided to participants during the 1RM session, or at the subsequent experimental sessions. Constant verbal encouragement was provided by researchers. 1RM for all four exercises were completed on the same day.

*2.6 Experimental trials (visits 4-6)*

After an overnight fast (>10 hrs), participants arrived at the laboratory at the time they habitually ate breakfast (all participants were between 0700 and 0900). The elected start time was kept consistent for each participant. Upon arrival, participants verbally confirmed adherence to the overnight fast (>10 hrs) and abstinence from physical activity (48-hrs), then body mass was recorded. Thereafter, participants consumed the pre-exercise meal within 15-mins, which was prepared and delivered in an opaque container by a researcher independent from all data collection. To aid with blinding, participants were asked not to look in the opaque container and were required to wear a nose peg during its ingestion and for 2-mins following. A 10-sec water mouth rinse was performed after its ingestion, which was expectorated. Participants remained in the seated position for 2-hrs after completing the meal. Water was provided *ad libitum* throughout each experimental trial, which was measured and recorded by a researcher.

Two hours after the pre-exercise meal, participants began the RT session. Participants completed the same standardised warm-up before completing 3 sets of back squats, bench press, prone row, and seated shoulder press with repetitions completed to 10RPE (i.e., no repetitions left in reserve) at 80% of 1RM. Exercise order was consistent for all participants and experimental trials. Rest before and between 10RPE sets was 3-mins. Rest between exercises was 5-mins. Each exercise was preceded by exercise specific warm-ups of 5, 3, and 1 repetition with 50, 70, and 90% of working load with 60-90 secs interset rest. Music was permitted at the discretion of the participant and the same playlist and volume was used for all experimental sessions. Participants were reminded by researchers to complete the concentric muscle action as fast as they could for all lifts and standardised verbal encouragement was given to participants throughout all experimental sessions.

Performance outcomes of interest were total session repetitions completed, and total repetitions completed per exercise, which were silently counted by a researcher. Secondary outcomes were blood glucose and lactate, and subjective appetite (hunger, satiety, and fullness). The researcher that recorded all performance, metabolic, and subjective appetite values did not provide verbal encouragement to the participant.

Blood glucose was recorded at baseline (PREbreakfast) and 30 (POST30mins), and 60 (POST60mins) mins after the liquid meal; and before (POST120mins) and after (POST210mins) the RT session. Blood lactate was recorded immediately before (PREexercise), midway (MIDexercise; after bench press), and at completion (POSTexercise) of the RT session. Capillary blood glucose and lactate were drawn and analysed using a glucose (StatStrip Xpress2, Nova Biomedical, Germany) and lactate (Lactate Pro 2 LT-1730, Arkray, Japan) meter, respectively; and recorded by a researcher not providing verbal encouragement.

Subjective appetite (hunger, satiety, and fullness) was recorded before and after breakfast (PREbreakfast and POSTbreakfast, respectively) and RT session (PREexercise and POSTexercise, respectively). An overview of the experimental session is illustrated in Figure 2.

Insert Figure 2 about here.

*2.7 Statistical analyses*

All data were normally distributed as determined by graphical inspection and conventional value ranges for skewness and kurtosis [27-29]. Descriptive data are presented as mean ± standard deviation. Outcomes of interest were total number of repetitions completed per set and session; perceptual ratings of hunger, satiety, and fullness; and measures of blood glucose and lactate. To examine the effect of condition (i.e., HCHO, LCHO, and PLA) on the outcome of interest, linear mixed effect models were used. Condition (3 levels) and exercise (four levels) were treated as fixed effects, participants were treated as random effects. Random slopes were introduced to the models when their inclusion did not result in convergence error. Given the incorporation of both fixed and random effects, restricted maximum likelihood estimation was used to fit the models. Hedge’s g effect sizes were calculated and the magnitude of difference was determined by standard thresholds: small (0.2 – 0.49), moderate (0.5 – 0.79), and large (>0.8) [30].

Multi-collinearity was checked by inspecting the variance inflation factors for all predictor parameters included in the linear mixed-effects model. The independence of observations was confirmed by performing autocorrelation diagnostics. For all linear models, a Gaussian distribution was assumed. Goodness of fit was checked by assessing the approximate normal distribution of model residuals. Plotted residuals were checked to ensure homoscedasticity before applying the results of the model, to ensure all assumptions were met.

All statistical analysis was conducted in R language and environment for statistical computing [31] using the *lme4* [32], *emmeans* [33], and *ggeffects* [34] packages. Model assumptions were checked using the *performance* [35]and *DHARMa* [36]packages. The custom-written R script and associated dataset are available on the Open Science Framework repository (URL: <https://osf.io/sc2up/>). The figures in this manuscript present condition (i.e., HCHO, LCHO, and PLA) means with 95% confidence intervals; however, if the reader is interested in individual responses across conditions, these are available on the repository.

*3 Results*

*3.1 Baseline nutrition, session duration, and breakfast perception*

Average 3-day protein (p = 0.545), fat (p = 0.929), CHO (p = 0.739) and total energy (p = 0.843) intake between conditions produced a statistically non-significant result.

The average session duration was 93.4 ± 5.2 mins. *Ad libitum* water intake during the experimental trials produced a statistically non-significant result between conditions (p = 0.783).

Nine of the 16 participants (56%) correctly identified which breakfast was PLA. Six stated that they could not identify which breakfast was PLA. One participant stated they could identify which breakfast was PLA but was incorrect.

*3.2 Performance outcomes*

For total session repetitions completed, there was a non-significant result between conditions (F = 1.192; p = 0.318). For total session repetitions completed per exercise, there was a non-significant interaction between condition and exercise (F = 0.208; p = 0.973). There was a main effect of exercise on total session repetitions completed (F = 6.84; p < 0.001) as more squat repetitions were completed per session than prone row (p < 0.001; g = 0.63) and shoulder press (p = 0.001; g = 0.5). More bench press repetitions were completed per session than prone row (p < 0.001; g = 0.83) and shoulder press (p = 0.001; g = 0.66). Performance outcomes are presented in Figure 3.

Insert Figure 3 about here

*3.3 Subjective appetite*

*3.3.1 Hunger*

There was a non-significant interaction between condition and time-point (F = 1.594, p = 0.155). There was a significant main effect of time on hunger (F = 3.37, p = 0.027), as PREbreakfast was significantly greater than POSTbreakfast (p = 0.002). The results for hunger are presented in Figure 4 (A).

*3.3.2 Satiety*

There was a significant interaction between condition and time-point (F = 2.625, p = 0.02). Compared to PLA, satiety at the POSTbreakfast time-point was significantly greater in HCHO (p = 0.001, g = 0.68) and LCHO (p = 0.002, g = 0.69). Compared to PLA, satiety at the PREexercise time-point was significantly greater in HCHO (p = 0.001, g = 0.78) and LCHO (p = 0.002, g = 0.71). Compared to PLA, satiety at the POSTexercise time-point was significantly greater in LCHO (p = 0.001, g = 1.15), but not HCHO (p = 0.076, g = 0.37). The results for satiety are presented in Figure 4 (B).

*3.3.3 Fullness*

There was a significant interaction between condition and time-point (F = 3.672, p = 0.002). Compared to PLA, POSTbreakfast fullness was significantly greater in HCHO (p = 0.001, g = 0.63) and LCHO (p = 0.001, g = 0.63). Compared to PLA, PREexercise fullness was significantly greater in HCHO (p < 0.001, g = 1.13) and LCHO (p < 0.001, g = 1.33). POSTexercise fullness was significantly greater in LCHO when compared to HCHO (p = 0.026, g = 0.53) and PLA (p = 0.005, g = 0.72). The results for fullness are presented in Figure 4 (C).

Insert Figure 4 about here

*3.4 Metabolic markers*

*3.4.1 Lactate*

There was a significant main effect of time for blood lactate (F = 51.03, p < 0.001). Blood lactate at MIDexercise was significantly greater than PREexercise (p < 0.001, g = 2.58) and POSTexercise (p < 0.001, g = 1.05). Blood lactate at POSTexercise was significantly greater than PREexercise (p < 0.001, g = 2.27). The results for blood lactate concentration are presented in Figure 5 (A).

*3.4.2 Glucose*

There was a significant interaction effect between condition and time-point (F = 31.595, p < 0.001). HCHO blood glucose was higher than LCHO at POST30min (p < 0.001, g = 2.46) and POST60min (p < 0.001, g = 1.35), and higher than PLA at POST30min (p < 0.001, g = 3.11), POST60min (p < 0.001, g = 1.94), and POST120min (p = 0.004, g = 0.59). LCHO blood glucose was higher than PLA at POST60min (p = 0.025, g = 0.27). The results for blood glucose concentration are presented in Figure 5 (B).

Insert Figure 5 about here

*4 Discussion*

The purpose of this study was to investigate the effect of higher and lower doses of pre-exercise CHO ingestion on RT volume performance in an ecologically valid exercise protocol, while controlling for total calories consumed. The main findings were, (a) RT volume performance was similar between two isoenergetic, isonitrogenous pre-exercise meals differing in CHO dose and a low-calorie PLA, (b) participants were generally more full and sated, in HCHO and LCHO, compared to PLA, (c) pre-exercise blood glucose was significantly higher in HCHO compared to PLA, but not LCHO, and post-exercise blood glucose was similar between conditions, and (d) mid- and post-exercise blood lactate increased compared to pre-exercise, with no interaction effect between conditions at any time-point.

The findings do not confirm our initial hypothesis. We hypothesised that a higher dose of CHO would improve volume performance over a lower dose (LCHO) and a low-calorie PLA due to the established role of dietary CHO as an important fuel source during high-intensity exercise [3]. RT induces modest decreases in total muscle glycogen (24 – 40%) [8] and stores of intra-myofibrillar glycogen in type II muscle fibres can become depleted during RT [10]. In some circumstances, CHO can be ergogenic for RT volume performance, such as where the training duration is longer (> 45 mins) and where the pre-exercise fast is longer (> 8hrs) [19]. Given the longer duration (~90 minutes) and higher volume performed to repetition fatigue (12 sets) in the RT session of the present study, we hypothesized an ergogenic effect of CHO ingestion. However, we found no significant effect of higher or lower CHO doses on RT volume performance, compared to a low-calorie PLA. Possible explanations for the lack of observed results may include exercise selection, training intensity, and the timing of CHO ingestion.

In the present study, three of the four exercises were for the upper body (i.e., bench press, prone row, and shoulder press), which were selected as a representative variety of exercises common to strength and hypertrophy type training. Previously, King et al. [19] reported that acute CHO ingestion had a clearer ergogenic effect on higher volume lower body RT and speculated that this trend may be due to lower body RT recruiting more muscle mass, producing more total work, and incurring greater metabolic fatigue. However, few studies have investigated the effects of acute CHO ingestion on higher-volume upper body RT. Krings et al. [37] reported an ergogenic effect of CHO ingestion on bench press repetitions completed to fatigue compared to a placebo, but no significant performance improvement in the bent-over row, incline press, or close-grip press. In addition, Smith et al. [38] reported no significant effect of a liquid CHO beverage on repetitions to fatigue in a ~60 min upper body RT session, nor did the studies by Naharudin et al., [20, 39] report an ergogenic effect of pre-exercise CHO on bench press volume performance compared to water only or a viscous, energy-less placebo. Overall, the findings from the present study and previous literature suggest that CHO ingestion might be less important for volume performance in a higher-volume, upper body RT session, potentially due to recruiting relatively less muscle mass than lower body RT, resulting in less total work and metabolic fatigue. Future research is necessary to investigate whether isoenergetic pre-exercise meals similarly affect higher-volume, lower body RT.

It has previously been reported that hunger may influence RT performance. Naharudin et al. [20] reported no significant difference in repetitions to fatigue during 4 sets of back squat and bench press following viscous, semi-solid CHO containing and placebo pre-exercise meals. However, the CHO and placebo meals in Naharudin et al. [20] did improve volume performance compared to water only and the authors concluded that this may be due to psychological mechanisms (i.e., a placebo of ingesting, or nocebo of omitting, a pre-exercise meal). Indeed, the participants in that study [20] were hungrier and less full in the water only control, compared to the taste and texture matched CHO and placebo groups, and were similarly hungry and full following CHO and placebo. The findings of the present study are broadly in agreement with Naharudin et al. [20]. In a follow-up study [21], a viscous CHO containing breakfast improved subjective appetite and repetitions performed to fatigue, compared to a liquid CHO breakfast, suggesting hunger can influence RT performance. In the current study, there were no significant differences in hunger between conditions at the pre- and post-exercise timepoints. However, HCHO and LCHO had higher ratings of fullness and satiety at the pre-exercise timepoint, and satiety at the post-exercise timepoint, compared to PLA, indicating that the participants were generally less full and sated after ingesting PLA, compared to HCHO and LCHO. A greater magnitude in the difference of hunger/fullness between conditions of Naharudin et al., [20] may explain the differences in results compared to the current study. Nonetheless, the results from the current study suggest that lower subjective appetite may not always influence RT performance and that greater feelings of hunger may be requisite for pre-exercise feeding to influence volume performance. The discrepancy in results between our study and previous studies [20, 21] may be due to differences in the magnitude of effect on subjective appetite (i.e., the previous studies elicited greater differences in appetite between conditions) and exercise protocol such as training duration, exercise selection (i.e., upper versus lower), and training intensity (i.e., %1RM load) and the addition of pre-exercise supplement practices.

Training intensity (i.e., percentage of 1RM) could have also affected the ability to detect an effect of CHO feeding in the present study. We selected a load of 80% 1RM to lend ecological validity to the design, which resulted in an average of ~7 repetitions being completed in each set of each exercise. An increase of 1 repetition would be a ~14% increase in volume performance and though our power analysis was based on a 16% difference in volume performance, it’s possible differences in study design led to non-significant results in volume performance. Several other studies using lower training intensities (approximately 55 – 75% 1RM) and lower body exercise selection have reported an ergogenic effect of carbohydrate in comparison to water [20, 39] and an energy-less placebo [40-42]. Thus, it’s possible that lower loads and higher repetitions may be required to detect an effect of pre-exercise feeding, though a recent meta-regression did not find an effect of load on the ergogenic effect of CHO [19].

The participants were told that all three breakfast meals contained the same amount of energy (despite PLA containing almost no calories). The breakfasts were taste and texture matched during pilot testing. Nine of the 16 participants were able to correctly identify the PLA breakfast which indicates modest success in masking the true design of the study to the participants. Positive expectancy from ingesting a pre-exercise breakfast which is perceived to contain energy may explain why there was no significant differences in volume performance in the current study. However, without a control condition that omitted the ingestion of anything but water, it is not possible to determine the magnitude of a placebo effect. Nonetheless, previous studies [20, 39] also indicate that psychological factors (i.e., positive, or negative expectancy) of feeding may play a role in mediating RT volume performance.

Another potential mediating factor that could explain the lack of influence of subjective appetite on performance in the present study is that half of the participants (n = 8) used their habitual pre-exercise supplements, which could be sufficient to mask an effect of the pre-exercise meal, or to suppress/mitigate sensations of hunger. These supplements included caffeine (black coffee, n = 4; pre-workout formulation, n = 4), which has known ergogenic effects on indices of muscle strength and endurance [43] without clear evidence for an effect on appetite [44]. Future research should investigate whether habituation to pre-exercise supplementation mediates the effect of a pre-exercise meal on RT performance.

There are several limitations to the present study. The sample size calculation for the present study was based on detecting a moderate effect between a CHO and water only condition for squat repetitions reported in a previous study [20]. Thus, while the sample size of the present study is powered to detect an effect between HCHO and PLA conditions, it might be underpowered to detect a small effect between HCHO and LCHO conditions, if one exists. Commercially available products were used to prepare pre-exercise meals and their nutritional composition was not verified. Several aspects of our study design could have influenced the results (e.g., supplementation, music) and masked the potential effect of a pre-exercise meal on RT volume performance. This adds external validity to our findings, since these aids are used in practice, and while they were kept consistent for each participant across trials, their inclusion prevents the true isolation of the effect of the pre-exercise meal on RT performance. A mixed-sex cohort of participants was recruited in the current study, and it is currently unknown if there are potential sex differences in the response to a pre-exercise meal and RT volume performance. Finally, we attempted to provide metabolic insight with blood measures but did not measure muscle glycogen; thus, future research is necessary to understand the effect of CHO ingestion on muscle glycogen (and its subcellular compartments) during RT.

*5 Conclusion*

The results provide evidence that for primarily upper-body RT volume performance, a higher or lower CHO dose produces comparable performance to a low-calorie placebo. These findings are of practical relevance, as they suggest the macronutrient composition of a meal may not matter per se, and that the perception of energy intake may be sufficient for RT volume performance (at least in the context of similar session lengths, volumes, and exercise selections).

*Author declarations*

None.

*Data availability statement*

The custom-written R script and associated dataset are available on the Open Science Framework repository (URL: https://osf.io/sc2up/).

*References*

1. Thomas D, Erdman K, Burke L Position of the academy of nutrition and dietetics, dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. J Acad Nutr Diet 2016; 116(3):501-28.

2. Kerksick CM, Arent S, Schoenfeld BJ, et al. International society of sports nutrition position stand: nutrient timing. J Int Soc Sports Nutr 2017; 14(1):1-21.

3. Vigh-Larsen JF, Ørtenblad N, Spriet LL, et al. Muscle glycogen metabolism and high-intensity exercise performance: A narrative review. Sports Med 2021; 51(9):1855-74.

4. Koopman R, Manders RJ, Jonkers RA, et al. Intramyocellular lipid and glycogen content are reduced following resistance exercise in untrained healthy males. Eur J Appl Physiol 2006; 96(5):525-34.

5. Tesch PA, Colliander EB, Kaiser P Muscle metabolism during intense, heavy-resistance exercise. Eur J Appl Physiol Occup Physiol 1986; 55(4):362-6.

6. Pascoe D, Costill DL, Fink WJ, et al. Glycogen resynthesis in skeletal muscle following resistive exercise. Med Sci Sports Exerc 1993; 25:349-54.

7. MacDougall JD, Ray S, Sale DG, et al. Muscle substrate utilization and lactate production during weightlifting. Can J Appl Physiol 1999; 24(3):209-15.

8. Robergs RA, Pearson DR, Costill DL, et al. Muscle glycogenolysis during differing intensities of weight-resistance exercise. J Appl Physiol 1991; 70(4):1700-6.

9. Ørtenblad N, Nielsen J Muscle glycogen and cell function–location, location, location. Scand J Med Sci Sports 2015; 25:34-40.

10. Hokken R, Laugesen S, Aagaard P, et al. Subcellular localization- and fibre type-dependent utilization of muscle glycogen during heavy resistance exercise in elite power and Olympic weightlifters. Acta Physiol 2020; 231(2)(e13561).

11. Ørtenblad N, Nielsen J, Saltin B, et al. Role of glycogen availability in sarcoplasmic reticulum Ca2+ kinetics in human skeletal muscle. J Physiol 2011; 589(3):711-25.

12. Jensen R, Ørtenblad N, Stausholm MH, et al. Heterogeneity in subcellular muscle glycogen utilisation during exercise impacts endurance capacity in men. J Physiol 2020; 598(19):4271-92.

13. Nielsen J, Schrøder H, Rix C, et al. Distinct effects of subcellular glycogen localization on tetanic relaxation time and endurance in mechanically skinned rat skeletal muscle fibres. J Physiol 2009; 587(14):3679-90.

14. Nielsen J, Cheng AJ, Ørtenblad N, et al. Subcellular distribution of glycogen and decreased tetanic Ca2+ in fatigued single intact mouse muscle fibres. J Physiol 2014; 592(9):2003-12.

15. Knapik JJ, Meredith CN, Jones BH, et al. Influence of fasting on carbohydrate and fat metabolism during rest and exercise in men. J App Physiol 1988; 64(5):1923-9.

16. Rothman DL, Magnusson I, Katz LD, et al. Quantitation of hepatic glycogenolysis and gluconeogenesis in fasting humans with 13C NMR. Science 1991; 254(5031):573-6.

17. Wee S-L, Williams C, Tsintzas K, et al. Ingestion of a high-glycemic index meal increases muscle glycogen storage at rest but augments its utilization during subsequent exercise. J App Physiol 2005; 99(2):707-14.

18. Chryssanthopoulos C, Williams C, Nowitz A, et al. Skeletal muscle glycogen concentration and metabolic responses following a high glycaemic carbohydrate breakfast. J Sports Sci 2004; 22(11-12):1065-71.

19. King A, Helms E, Zinn C, et al. The ergogenic effects of acute carbohydrate feeding on resistance exercise performance: A systematic review and meta-analysis. Sports Med 2022; 52(11):2691-712.

20. Naharudin M, Adams J, Richardson H, et al. Viscous placebo and carbohydrate breakfasts similarly decrease appetite and increase resistance exercise performance compared to a control breakfast in trained males. Br J Nutr 2020:1-25.

21. Naharudin MN, Yusof A, Clayton DJ, et al. Starving your performance? Reduced preexercise hunger increases resistance exercise performance. Int J Sports Physiol 2021; 17(3):458-64.

22. Spiering BA, Kraemer WJ, Vingren JL, et al. Elevated endogenous testosterone concentrations potentiate muscle androgen receptor responses to resistance exercise. J Steroid Biochem Mol Biol 2009; 114(3-5):195-9.

23. Morton RW, Murphy KT, McKellar SR, et al. A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. Br J Sports Med 2018; 52(6):376-84.

24. Slater G, Phillips SM Nutrition guidelines for strength sports: sprinting, weightlifting, throwing events, and bodybuilding. J Sports Sci 2013; 29(S67-S77.).

25. Jukic I, García-Ramos A, Malecek J, et al. The use of lifting straps alters the entire load-velocity profile during the deadlift exercise. J Strength Cond Res 2020; 34(12):3331-7.

26. Jukic I, García-Ramos A, Malecek J, et al. Validity of load-velocity relationship to predict 1 repetition maximum during deadlifts performed with and without lifting straps: The accuracy of six prediction models. J Strength Cond Res 2020; 36(4):902-10.

27. Gravetter FJ, Wallnau LB, Forzano L-AB, et al. (2020) Essentials of statistics for the behavioral sciences: Cengage Learning.

28. Field A, Miles J, Field Z (2012) Discovering statistics using R: Sage publications.

29. Trochim WM, Donnelly JP (2001) Research methods knowledge base: Atomic Dog Pub. Macmillan Publishing Company, New York.

30. Cohen J (1988) Statistical power analysis for the behavioral sciences: Academic press.

31. Team RC R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2021. <https://www.R-project.org/>.

32. Bates D, Mächler M, Bolker B, et al. Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:14065823 2014.

33. Lenth R, Singmann H, Love J, et al. Emmeans: estimated marginal means, aka least-squares means. 2018; R Package Version 1.8.8.

34. Lüdecke D ggeffects: Tidy data frames of marginal effects from regression models. J Open Source Softw 2018; 3(26):772.

35. Lüdecke D, Ben-Shachar M, Patil I, et al. performance: An R package for assessment, comparison and testing of statistical models. J Open Source Softw 2021; 6(60).

36. Hartig F DHARMa: Residual diagnostics for hierarchical (multi-Level/mixed) regression models. R package version 01 2020; 5.

37. Krings B, Rountree J, McAllister M, et al. Effects of acute carbohydrate ingestion on anaerobic exercise performance. J Int Soc Sports Nutr 2016; 13(1):40.

38. Smith JW, Krings BM, Shepherd BD, et al. Effects of carbohydrate and branched-chain amino acid beverage ingestion during acute upper body resistance exercise on performance and postexercise hormone response. Appl Physiol Nutr Metab 2018; 43(5):504-9.

39. Bin Naharudin MN, Yusof A, Shaw H, et al. Breakfast omission reduces subsequent resistance exercise performance. J Strength Cond Res 2019; 33(7):1766-72.

40. Haff G, Koch A, Potteiger J, et al. Carbohydrate supplementation attenuates muscle glycogen loss during acute bouts of resistance exercise. Int J Sport Nutr Exerc Metab 2000; 10(3):326-39.

41. Lambert CP, Flynn MG, Boone Jr JB, et al. Effects of carbohydrate feeding on multiple-bout resistance exercise. J Strength Cond Res 1991; 5(4):192-7.

42. Haff G, Stone M, Warren B, et al. The effect of carbohydrate supplementation on multiple sessions and bouts of resistance exercise. J Strength Cond Res 1999; 13(2):111-7.

43. Grgic J, Mikulic P, Schoenfeld BJ, et al. The influence of caffeine supplementation on resistance exercise: A review. Sports Med 2019; 49(1):17-30.

44. Schubert MM, Irwin C, Seay RF, et al. Caffeine, coffee, and appetite control: a review. Int J Food Sci Nutr 2017; 68(8):901-12.

*Figures*

A flowchart of a flowchart

Description automatically generated

Fig. 1. CONSORT participant flow diagram through each stage of the randomised cross-over trial.

A diagram of a bench

Description automatically generated

Fig. 2. Experimental session overview. Note that the times are approximations. 1RM = 1-repetition maximum, RPE = the resistance training repetitions in reserve/rating of perceived exertion scale

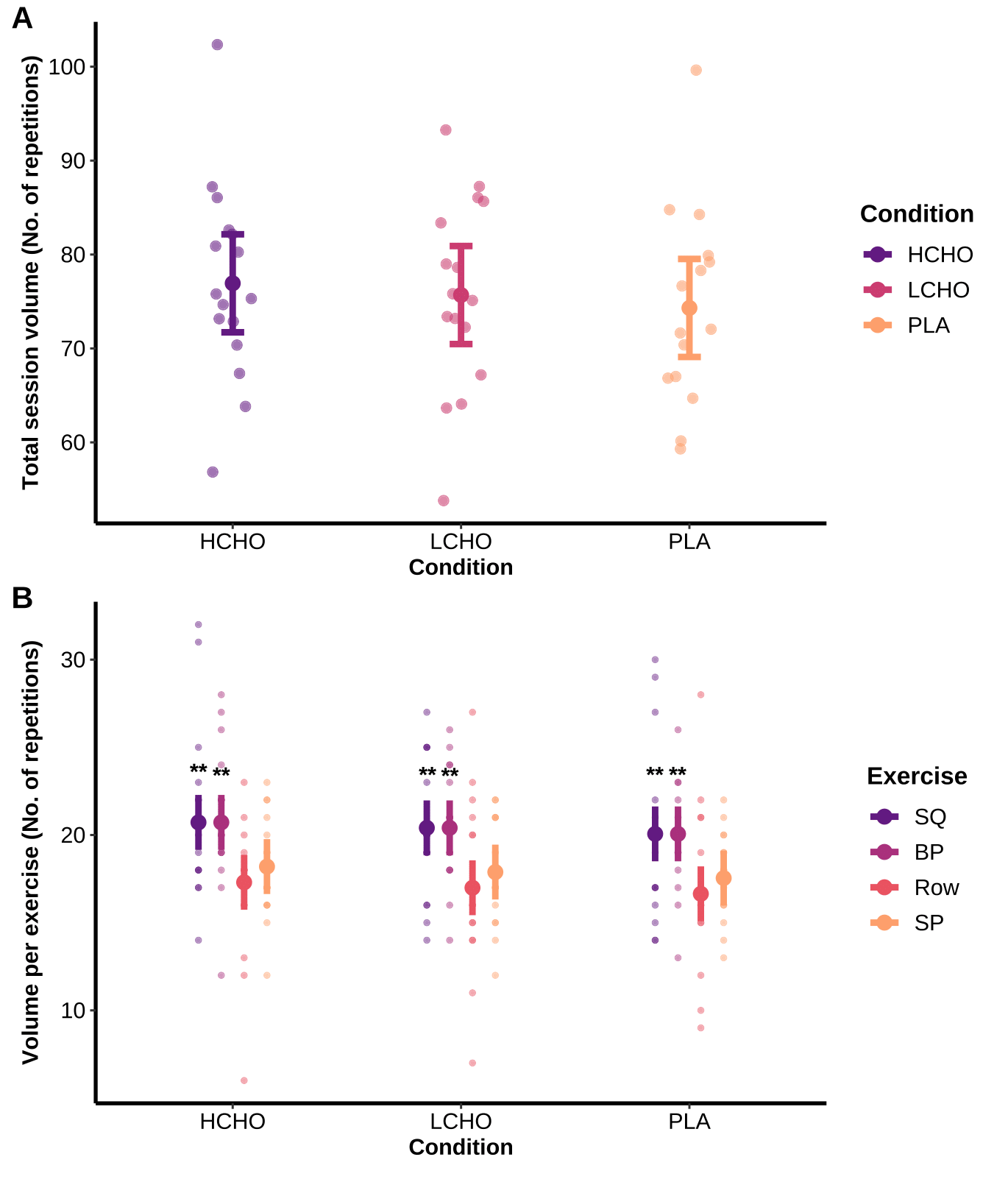


Fig. 3. Comparison between groups (HCHO, LCHO and PLA) for total session repetitions completed (Panel A) and repetitions completed per exercise (Panel B) after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. HCHO = high carbohydrate breakfast, LCHO = low carbohydrate breakfast, PLA = placebo SQ = back squat, BP = bench press, SP = shoulder press. \*\* significantly greater than prone row and shoulder press (p ≤ 0.001)

A graph of different types of food

Description automatically generated with medium confidence

Fig. 4. Comparison between groups for subjective hunger (Panel A), satiety (Panel B), and fullness (Panel C) ratings after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. HCHO = high carbohydrate breakfast, LCHO = low carbohydrate breakfast, PLA = placebo. † significantly greater than POSTbreakfast (p < 0.01); \*\* significantly greater than PLA (p ≤ 0.001); \* Significantly lower than LCHO (p ≤ 0.05)

A graph of blood glucose level

Description automatically generated

Fig. 5. Comparison between groups for blood lactate (Panel A) and glucose (Panel B) concentrations after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. HCHO = high carbohydrate breakfast, LCHO = low carbohydrate breakfast, PLA = placebo. † Significantly greater than PREexercise (p < 0.001); ‡ Significantly greater than PREexercise (p < 0.001) and POSTexercise (p < 0.001); \*\* significantly greater than PLA and LCHO (p ≤ 0.001); \* Significantly greater than PLA (p ≤ 0.05)

|  |  |
| --- | --- |
|  | *Participants* |
| Age (years) | 26 ± 4 |
| Height (cm) | 176.6 ± 7.5 |
| Body mass (kg) | 83.68 ± 15.1 |
| Resistance training experience (years) | 4.8 ± 2.24 |
| Relative squat strength (1RM/body mass) | 1.81 ± 0.4 |
| Relative bench press strength (1RM/body mass) | 1.26 ± 0.3 |

**Table 1.** Participant descriptive characteristics (n = 16).

Data is presented as mean ± standard deviation. *1RM* = 1-repetition maximum.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **High CHO (1.2 g/kg BM)** | **Low CHO (0.3 g/kg BM)** | **Placebo** |
| Total energy (kJ) | 2438 ± 478 | 2412 ± 505 | 11 ± 0 |
| Relative total energy (kJ/BM) | 29 ± 1 | 29 ± 1 | 0.1 ± 0 |
| CHO (g) | 103 ± 20 | 25 ± 5 | 0 ± 0 |
| Protein (g) | 20 ± 5 | 21 ± 4 | 0 ± 0 |
| Fats (g) | 10 ± 2 | 44 ± 9 | 0 ± 0 |
| Water intake (mL) | 1699 ± 608 | 1653 ± 719 | 1805 ± 747 |

**Table 2.** Average nutritional content of pre-exercise breakfasts (n = 16)

*CHO* carbohydrate, *BM* body mass