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The effect of the ketogenic diet on resistance training load management: a repeated-measures clinical trial in trained participants

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ABSTRACT

Background: The effect of low-carbohydrate high-fat dietary manipulation, such as the ketogenic diet (KD), on muscle strength assessment in resistance-training (RT) participants has focused on the one-repetition maximum test (1-RM). However, a pre-specified 1-RM value during an exercise training program disregards several confounding factors (i.e. sleep, diet, and training-induced fatigue) that affect the exerciser's "true" load and daily preparedness. We aimed to evaluate the effect of a 6-week RT program on load control-related variables in trained subjects following a KD intervention.

Methods: Fourteen resistance-trained individuals (3F, 11 M; 30.1 [6.2] years; 174.2 [7.6] cm; 75.7 [10.8] kg; BMI 24.8 [2.1] $kg{\cdot}m^{-2}$) completed this single-arm repeated-measures clinical trial. Load management variables included volume load, number of repetitions, perceived exertion (RPE), movement velocity loss, and exertion index. These primary outcomes were assessed weekly before, during, and at the end of a 6-week RT program that included traditional RT exercises (bench press, femoral lying down, lat pulldown, leg extension, and back squat).

Results: There was a significant difference in RPE between weeks ($p = 0.015$, $W = 0.19$) with a slight trend in decreasing RPE. We found differences in the volume load per week ($p < 0.001$; $W = 0.73$ and $p < 0.001$, $W = 0.81$, respectively), with an increase in the last weeks. In the control of the load based on movement velocity, we did not find significant differences between weeks ($p = 0.591$, $W = 0.06$), although significant differences were found in the effort index ($p = 0.026$, $W = 0.17$).

Conclusions: A KD diet in recreational strength participants does not appear to lead to performance losses during a RT program

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aimed at improving body composition. However, the lack of adherence and familiarity with the ketogenic diet must be considered specially during first weeks.

1. Background

The ketogenic diet (KD) is characterized by a reduction in daily carbohydrate intake to less than 50 grams, which represents less than 10% of total calories, coupled with an increased intake of fats and possibly proteins [1]. The KDs have been assessed in various sports athletic contexts, showing no negative effects on performance, particularly in long-distance athletes [2], and sometimes even improving VO_{2max} [3]. In strength training, studies have reported that *ad libitum* KD combined with resistance training (RT) does not lead to decreases in muscle strength or power levels, especially when accompanied by high-protein intake [4]. However, it is essential to note that some contradictory findings have suggested adverse associations between KD and muscle strength levels [5]. In fact, a recent systematic review with Bayesian meta-analysis and meta-regression concluded that the KD may prove beneficial for achieving overall weight loss and reducing body fat, but a small negative effect on fat-free mass has been observed. Also, KD have not demonstrated effectiveness in improving one-repetition maximum (1-RM) strength or high-intensity cyclic performance [6].

The impact of KD on muscle power or RT performance has been assessed through various methods, including the Wingate test, sprint or plyometric tests [7], or relative indices like load-to-body mass ratio [8]. Nonetheless, in KD research, the 1-RM has been frequently employed to evaluate muscle strength performance in different weight RT exercises such as the bench press, squat [8,9], snatch, clean, jerk, and deadlift [10,11]. In general, most studies have focused on men, with only one study incorporating resistance-trained women. In this particular study, conducted by our research group, it was found that an 8-week KD intervention led to a significant decrease in 1-RM values [12]. It appears that sex-related factors may contribute to these differences in response to KD [6].

It is important to highlight that the aforementioned studies have primarily employed methodological procedures focusing on the assessment of pre- and post-maximum efforts. While performing RT exercises for muscle hypertrophy often involves 12 and 20 sets [13], and even reaching up to 20 repetitions [14], evaluating 1-RM may not fully capture the effectiveness of musculoskeletal adaptations in recreational or advanced individuals. In line with McSwiney et al.. (2019), the transient effects on muscle strength during a low-carbohydrate dietary intervention might not be adequately assessed using conventional analyses (1-RM) in recreational or advanced RT participants [15]. Consequently, monitoring within-exercise variables related to load management (e.g. repetitions to failure, load displacement/velocity, time under tension, inter-set rest, perceived effort) could provide a more precise assessment of the RT-induced adaptations in muscle strength or body composition [16].

To understand the alterations in RT-induced stimuli, it is advisable to consider a set of programming variables related to muscular hypertrophy and strength, such as the total

number of repetitions, the volume load, the loss of movement velocity and the perceived effort. Thus, the aim of this study was to evaluate the impact of a 6-week KD on RT performance as load management in resistance-trained individuals: volume load, number of repetitions, perceived exertion (RPE), movement velocity loss (VL), and exertion index. We hypothesized that a decline in RT performance may occur during the initial weeks of the KD intervention.

2. Materials and methods

2.1. Trial design

This was a single-arm non-randomized own-control clinical trial to evaluate the effects of a 6-week KD intervention on RT performance in resistance-trained individuals. Strength-related variables were assessed before, during and after the dietary intervention (Figure 1).

2.2. Participants

Physically active participants with more than one consecutive year of strength training (minimum 3 days/week) were included in our study. Participants were recruited from fitness centers located in Malaga, Spain. We excluded participants who had used performance and image enhancing drugs, such as anabolic androgenic steroids, within the previous two years. Additionally, individuals who consumed any type of nutritional supplement during the program were also excluded from the study. The participants were informed of the possible risks of the experiment and signed an informed consent form. All participants agreed to follow the

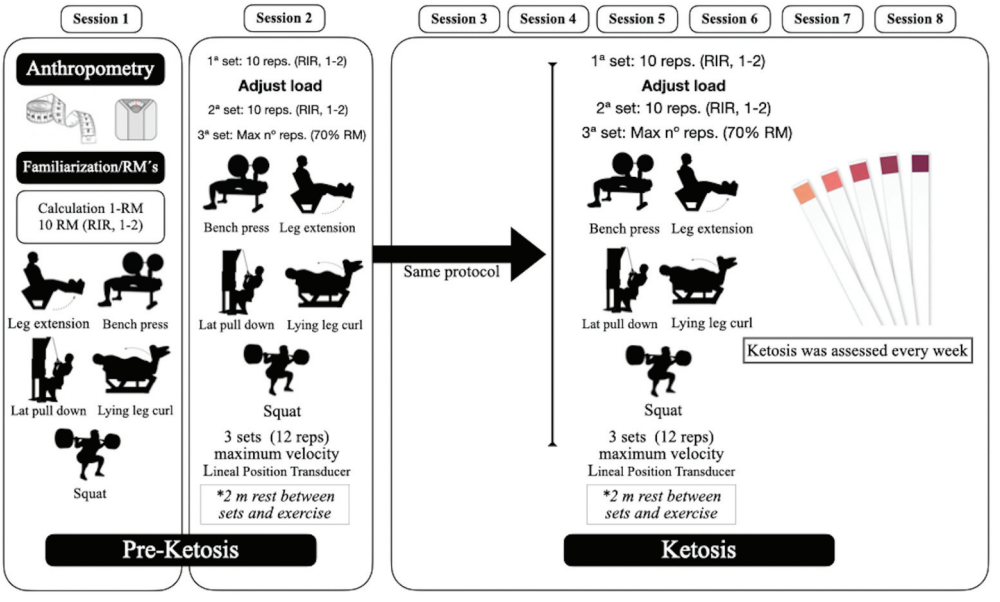


Figure 1. Schematization of the study design.

prescribed diet and scheduled sessions during the intervention period and to refrain from any other physical activity on the day and the day before the sessions. The study was developed in accordance with the ethical guidelines of the Declaration of Helsinki of the World Medical Association and approved by the ethics committee of the University of Malaga (code: 38–2019-H).

2.3. Procedures

2.3.1. Familiarization

A familiarization session was carried out, where the loads were adjusted, a 1-RM was performed, and the exercise technique was supervised. The technique of the exercises used was evaluated, and the 1-RM was measured in the exercises squat, lat pull down, femoral lying, leg extension, bench press (Gervasport, Madrid, Spain) based on our laboratory procedures [17]. Additionally, we proceeded to adjust the loads to 10 repetitions with reps in reserve (RIR) (1–2) and perform a familiarization in squat using the linear position transducer. Additionally, the nutritional protocol was explained by the sports nutrition specialist, and anthropometric measurements were carried out.

2.3.2. Exercise protocol

From the first week after the start of ketosis to the sixth week, a previous warm-up was carried out. Subsequently, one set of bench press was performed with the load calculated in the familiarization session, 10 repetitions (RIR, 1–2). In the second set, the load was adjusted according to the participant's needs, the kilos were increased, reduced, or maintained depending on their perceptions, with the intention of maintaining the same number of repetitions and intensity. Finally, the third set was performed counting the maximum number of repetitions with 70% of the 1-RM, and this weight was maintained during all sessions. Participants rested two minutes between sets and a controlled movement velocity of approximately one second in the concentric phase and one in the eccentric phase was maintained. Likewise, the same protocol was carried out in the exercises leg extension, lat pull down and lying femoral, in that order in all sessions. Finally, we proceeded to perform three sets of 12 repetitions in squat using a linear encoder with 70% of the 1-RM based on [18], to assess velocity loss and perceived effort. At the end of the sessions, all the participants reported their perception of the training session on a scale of one to ten.

2.3.3. Nutrition intervention

The participants were instructed to consume 30–40 $g \cdot d^{-1}$ carbohydrates with a protein intake of 2 $g \cdot kg^{-1} \cdot d^{-1}$ protein [19], and the rest in the form of fats *ad libitum*. Participants were advised to eat 3–6 meals a day. They were provided with a list of foods that included sources of proteins and/or fats (eggs, fish, meats, various dairy products, avocados, olive oil, nuts). To assess dietary compliance, urinary ketones concentrations were measured weekly in the early morning using over-the-counter reagent strips (*Ketostix, Bayer Vital GmbH, Leverkusen, Germany*) [20,21]. Furthermore, to facilitate compliance with total calories and macronutrients, they were informed about the use of the MyFitnessPal program [22].

2.4. Outcomes

The performance was evaluated through a training session, before ketosis, one week after ketosis, and in the second, third, fourth, fifth and sixth week of the KD protocol. A full-body session was assessed, including squat, bench press, leg extension, lat pull down and lying femoral exercises. The sessions were carried out in the following order: bench press, leg extension, lat pull down and lying femoral. Each exercise consisted of two sets of 10 repetitions, with two repetitions in reserve (RIR, 1–2), followed by a third set with the maximum number of repetitions. After completing these four exercises, three sets of 12 squat repetitions were performed at maximum movement velocity, which was controlled by a linear position transducer. In between sets and exercises, there was a 2-minutes break. Figure 1 shows the intervention protocol.

2.4.1. Anthropometry

All anthropometric data was collected during the first visit to the laboratory during the familiarization period. Body mass was measured with a digital scale to the nearest 50 grams (Tanita RD-545, Tokyo, Japan). A fixed stadiometer was used to measure the stature (SECA 220, Hamburg, Germany).

2.4.2. Volume load

The training volume was evaluated in terms of sets x repetitions x load. The sets were kept constant during all sessions, while the load moved was adjusted based on the participant's perception during each set and exercise. It has been shown that volume is the variable with the greatest influence on structural adaptations to resistance training [23].

2.4.3. Repetitions to failure

The total number of sets was evaluated in each training session during all the weeks that the research lasted (pre- and post-KD protocol ketosis). For this purpose, the three sets of 12 repetitions used in the squat were added. Also, the first two sets of each exercise performed at 10 repetitions (leg extension, bench press, lat pull down, and lying leg curl) were added. All this added up to a total of 116 repetitions, where the last set of each exercise (except squat) was performed to the maximum number of repetitions, reaching voluntary failure, where it has been shown that a higher number of repetitions generates a higher load volume [24], which may be more optimal for hypertrophy [23].

2.4.4. Rating of perceived exertion

At the end of each session, data on subjective perception of effort were collected using the visual analogue scale of 1 to 10 of the RPE [25].

2.4.5. Velocity loss

The velocity loss in the squat was evaluated during three sets performed at the end of each session, as a lower velocity loss is related to better mechanical performance [26,27]. A linear position transducer (SmartCoach Power Encoder SPE-35, SmartCoach Europe AB, Stockholm, Sweden) was used for this purpose.

2.4.6. Exertion index

The Exertion Index of the three squat sets was evaluated using data obtained from the linear position transducer. The average velocity of the first repetition and the percentage of velocity loss were used to calculate this index. This data was obtained from the three sets performed in the exercise as we have conducted previously [18].

2.5. Sample size

Non-probability sampling (convenience sampling) was used as it is often a strategy used in pilot and feasibility studies [28]. After the call to participate in this study, 22 participants were suitable for eligibility from the available population (i.e. resistance-trained men attending the fitness and strength conditioning center Physical Training located in Malaga, Spain).

2.6. Analytical methods

The descriptive statistics are expressed as mean (standard deviation) or median (interquartile range, Q1 – Q3). The normality of the data was contrasted with the Shapiro – Wilk test. The comparison of the variables between the weeks was carried out with the Friedman test, the Kendall's W was considered as a measure of the effect size (W = 0.1 - <0.3, small effect; 0.3 - <0.5, moderate effect, and ≥ 0.5, large effect), and Dunn's pairwise post-hoc tests. In all analyses, a $p < 0.05$ was considered to indicate statistical significance. Statistical analyses were performed using IBM SPSS version 26 (IBM Corp., Armonk, NY, USA) and JASP Team (2020, version 0.12.0), retrieved from https://jasp-stats.org/.

3. Results

Initially, 22 participants started the intervention but four withdrew the research in the second week of ketosis, two in the third week and two more in the fourth week. A total of 14 recreationally trained men and women completed this clinical trial (30.1 [6.2] years; stature 174.2 [7.6] cm; body mass 75.7 [10.8] kg, BMI 24.8 [2.1] $kg{\cdot}m^{-2}$). Figure 2 shows the flowchart of the trial process according to the Consolidated Standards of Reporting Trials (CONSORT) extension to pilot and feasibility trials [29]. Table 1 shows the characteristics of the participants who participated in the study.

Load control analysis during RT showed there was a significant difference on RPE between weeks of training ($p = 0.015$, W = 0.19), specifically between the first weeks of the KD diet (1 and 3) and the last weeks (4, 5 and 6), highlighting that the trend was a slight decrease in RPE in the last weeks of the intervention. Similarly, there were differences in the volume of the load, expressed in the number of repetitions and mass mobilized per week ($p < 0.001$; W = 0.73 y $p < 0.001$, W = 0.81, respectively). In this sense, an increase in these indicators was observed in the last weeks of the intervention. On the other hand, the load control based on movement velocity showed that there was no statistically significant difference in velocity loss between weeks ($p = 0.591$, W = 0.06); however, differences were observed in the effort index ($p = 0.026$, W = 0.17). Figure 3 and Table 2 present these results.

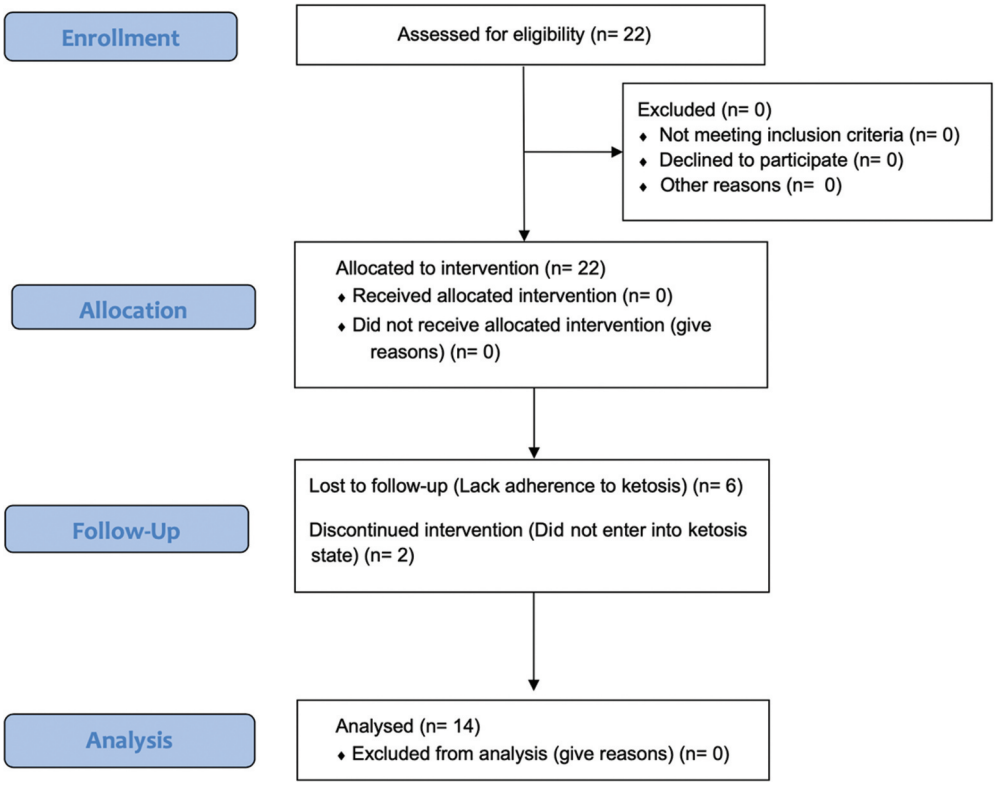


Figure 2. Modified CONSORT flow chart for this single-arm non-randomized own-control study.

Table 1. Participant characteristics.

Characteristics	$n = 14$
Sex (F, M)	3F, 11 M
Age, y	30.1 (6.2)
Body mass, kg	75.7 (10.8)
Stature, cm	174.2 (7.6)
Body mass index, $kg \cdot m^{-2}$	24.8 (2.1)

Data is shown as mean (standard deviation) unless otherwise is indicated.

4. Discussion

The objective of this study was to assess the impact of a 6-week KD on load management in resistance-trained individuals, including parameters such as volume load, number of repetitions, RPE, VL, and exertion index. The results indicated that the RPE was higher in the initial weeks but gradually decreased as the program progressed. The effort index exhibited a significant increase between the pre-ketosis week and the subsequent weeks, with a significant difference compared to the first week of ketosis. Likewise, we observed that both the volume load and the number of repetitions significantly decreased during the first week and gradually increased from the second week onwards. In a similar protocol that induced ketosis and another that

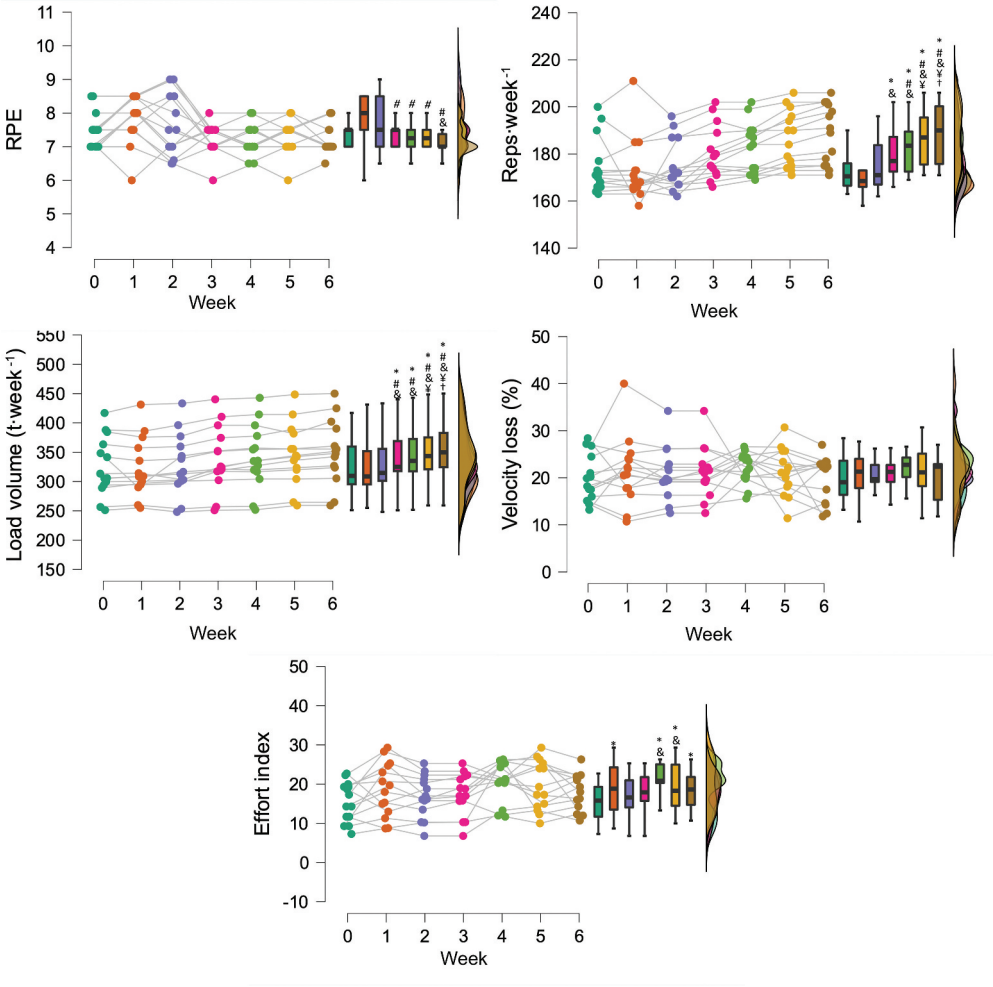


Figure 3. Results of the training load control during the intervention. RPE, rate of perceived exertion; Reps·week-1, number of repetitions per week. * difference with week 0 (pre-ketogenic diet), # difference with week 1, & difference with week 2, ¥ difference with week 3, † difference with week 4, ‡ difference with week 6.

introduced all macronutrients, LaFountain et al.. (2019) also found no significant differences between groups on these parameters in squat, deadlift, bench press, row, clean, and overhead press [8]. However, both repetitions and total tonnage were higher in the non-KD group. Additionally, there were no significant differences in velocity loss between sessions. Previous studies analyzing various velocity losses, similarly did not find differences in the number of repetitions performed in different exercise sets, but these were under normal diet conditions [30]. As for the effects of different percentages of VL, the evidence suggests that a VL of 25%, with intensities of 55% to 70% of 1-RM, provides an optimal training stimulus to maximize neuromuscular adaptations and strength performance in the bench press, while higher VL thresholds tend to promote greater muscle hypertrophy [31].

Table 2. Results of the training load control during the intervention.

	Week								
	0	1	2	3	4	5	6	P	W[a]
RPE	7.5 (7.0–7.6)	8.0 (7.5–8.5)	7.5 (6.9–8.6)	7.5 (7.0–7.5)	7.3 (7.0–7.5)	7.3 (7–7.5)	7.0 (7.0–7.5)	0.015	0.19
Reps reps·week^{-1}	170.5 (166.0–180.3)	168.5 (165.8–176.0)	171.0 (167.0–187.0)	177.0 (171.8–190.3)	183.5 (171.8–190.0)	187.0 (174.8–197)	190.0 (175.0–201.3)	<0.001	0.73
VL, s·week^{-1}	325.6 ± 49.7	322.4 ± 49.6	327.3 ± 51.8	338.8 ± 53.8	342.2 ± 54.1	345.7 ± 52.4	350.4 ± 54.7	<0.001	0.81
LV, %	19.1 (15.8–25.1)	21.3 (17.4–24.4)	19.7 (18.4–23.7)	21.2 (18.4–23.7)	22.7 (20.0–24.4)	21.2 (17.6–25.7)	22.4 (14.5–23.1)	0.591	0.06
Effort Index	15.8 (11.1–19.5)	18.8 (12.6–24.8)	16.6 (12.7–21.5)	17.9 (14.3–22.1)	20.8 (18.6–25.4)	18.3 (14.1–25.6)	18.7 (13.8–22)	0.026	0.17

Data is shown as mean (standard deviation) for VL while other variables are reported as median (interquartile range [Q1 – Q3]). RPE, rate of perceived exertion; Reps, Number of repetitions per week; LV, Load volume per week; VL, Velocity loss; a Kendall's W. Note: The post-hoc analysis between the weeks can be seen in Figure 3.

This seems to indicate that during the first weeks (especially the first and second), RT performance may be hindered by the stimulus of carbohydrate reduction; however, both overall performance progression and perceived exertion were not affected by the KD program, probably due to periods of physiological adaptation to the use of substrates as an energy source. When insulin levels in our body decrease due to carbohydrate restriction, the liver begins to produce ketones. This adaptation process takes some time in various organs, including the brain, where an alternative molecule must traverse the blood-brain barrier, similar to how glucose does [32]. Beta-hydroxybutyrate primarily substitutes for glucose to supply energy to neurons. Our body is not capable of maintaining its performance state for a few days until this adaptation occurs. This is what is referred to as "keto flu," and among the symptoms that can affect performance are fatigue (17.82%), reduced energy (9.9%), decreased appetite (4.9%), or bodily aches (3.9%) [33].

Slight variations in results emerge when considering the impact of the KD on training programs designed to enhance both endurance and strength. For instance, studies indicate that following high-intensity interval training (HIIT), the group adhering to a low-carbohydrate diet did not exhibit significant performance differences in parameters such as total time to exhaustion, respiratory exchange ratio, and oxygen uptake [34]. Similarly, Dostal et al.. (2019) reported no substantial changes in total time to exhaustion and absolute maximal oxygen uptake after consuming a low-carbohydrate diet [35]. In CrossTraining athletes, it has been observed that similar changes in 400 m sprint and VO_{2peak} occurred in both ketogenic and non-ketogenic protocols [10]. This might be partially explained by the metabolic flexibility reached after full adaptation to the nutritional ketosis [36] which is associated with the mitochondrial dynamics and anti-oxidative capacity [37].

It is essential to note the considerable number of dropouts among participants, particularly in the initial weeks of the KD nutritional intervention. It seems that the first weeks of the KD negatively affect physical performance due to alterations in perceived exertion, directly influencing adherence to the training and nutrition program [36]. Additional research is needed to assess whether this adherence issue occurs when individuals are unfamiliar with carbohydrate restriction. Once this period is overcome, and the metabolic adaptations of the nutritional ketosis state are reached, no differences are anticipated when compared to high-carbohydrate diets. The potential benefits of the KD in terms of body composition and endurance performance may then be realized [38,39]. Moreover, the effects on the hypothalamic – pituitary – adrenal axis in the regulation of the renin – angiotensin – aldosterone system [40] and the effect of these diets on testosterone serum levels [41] warrant further research as potential mechanisms. In the context of skeletal muscle hypertrophy, a training frequency of two days per week [42] with 10 sets per session [43] should be prioritized. As this volume is not particularly high, individuals experiencing difficulties adhering to the KD, especially in the initial weeks, may avoid adverse effects on their RT performance. In fact, recent works suggest that carbohydrate intake itself does not affect strength training performance when in an energy-balanced state for workouts involving up to 10 sets per muscle group [44].

This study has several flaws that should be mentioned. On one hand, the sample size is small, and on the other, the intervention's duration is limited to six weeks. Furthermore, the absence of performance decline when applying the KD for six weeks in trained participants does not necessarily imply that these individuals would have experienced superior effects on the variables measured if they had followed a diet with the same

caloric content but with a higher carbohydrate distribution. For this reason, it is crucial to investigate protocols that compare the effects of a RT program with parameters similar to those evaluated in this research, while equating the total calorie intake but varying macronutrient distribution (ketogenic vs. non-ketogenic). For this reason, we consider the absence of a control group and potential confounding factors (*ad libitum* selection of fats) relevant limitations of this study.

5. Conclusions

Resistance-trained individuals following a 6-week KD might experience performance decrements and increased perceived effort in the initial weeks as they adapt to changes in their dietary habits. Nevertheless, a KD does not appear to affect performance, volume load, number of repetitions, or velocity loss at short term.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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