REVIEW ARTICLE

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L-carnitine supplementation decreases post-exercise blood lactate levels and enhances aerobic capacity in trained individuals: systematic review and meta-analysis

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Abstract

Introduction. A benefit of L-carnitine (LC) supplementation for athletes' performance remains unclear. The present study aimed to evaluate an effect of LC supplementation on a post-exercise blood lactate level and aerobic capacity in athletes/trained individuals. Methods. A systematic review and meta-analysis study was conducted based on the PRISMA guidelines. PubMed, Google Scholar, and ProQuest were searched for relevant studies from database inception to November 2023. An overall effects estimation was performed using random and fixed effects models for a blood lactate level and maximal oxygen consumption ($\dot{V}O_2$ max). Pooled effects were presented as standardized mean difference or mean difference. Results. A total of 257 athletes from 14 studies were included. Pooled analysis demonstrated that a supplementation group had significantly lower blood lactate levels (SMD = –0.52 mmol/L, 95% CI: –0.85 to –0.19, p = 0.002) and higher $\dot{V}O_2$ max (MD = 2.16 ml/kg/min, 95% CI: 0.45 to 3.87, p = 0.01) compared to a placebo group. Subgroup analysis showed that chronic LC supplementation resulted in lower post-exercise blood lactate levels than placebo (SMD = –0.69 mmol/L, 95% CI: –1.16 to –0.21, p = 0.004). Conclusions. This study suggests that athletes may benefit from chronic LC supplementation by decreasing post-exercise blood lactate levels and increasing $\dot{V}O_2$ max. However, acute LC supplementation only resulted in an increase in $\dot{V}O_2$ max. Nevertheless, more scrutinous studies are needed to ascertain its efficacy.

KEYWORDS: carnitine, exercise, recovery, performance, athletes, maximal oxygen.

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Introduction

Athletes frequently consume dietary supplements to maintain their health and optimize their athletic performance. A recent meta-analysis estimated prevalence of dietary supplement use among athletes to be around 60% [19]. One such supplement gaining popularity is L-carnitine (LC). A recent cross-sectional study found that at least 3.9% of competitive athletes had taken LC supplements at any time in the past [42].

LC is a naturally occurring, quaternary amine found in all mammalian species. In a human body, LC is stored mainly in skeletal muscles and a heart, while much lower concentrations are found in a liver, kidneys, and plasma [4]. LC can be both endogenously synthesized in a liver, kidneys, and a brain from the methylation of essential amino acid lysine, and also obtained from dietary sources, mainly from animal products including red meat, fish, poultry, and dairy products [15]. However, endogenous LC biosynthesis accounts for only 25% of an adult's daily requirement [40]. Thus, exogenous LC, either from dietary sources or supplemented, is necessary, especially in athletes who rely on fatty acids utilization as dietary fuel for skeletal and cardiac muscles [12, 15].

LC is crucial for facilitating acyl-coenzyme A (CoA) mitochondrial membrane transport and therefore plays a vital role in fatty acids oxidation required for generating adenosine triphosphate (ATP) during exercises [2]. Therefore, a primary hypothesis is that an elevated carnitine concentration in skeletal muscles would enhance fatty acids transport and oxidation, thereby improving maximal oxygen consumption ($\dot{V}O_2$ max) and thus exercise performance [22]. Additionally, LC is able to mitigate a blood lactate accumulation, possibly by reacting with excess acetyl-CoA to form acetyl-L-carnitine and CoA [31]. Given these potential effects on various physiological and metabolic pathways, LC supplementation demonstrates promise in enhancing athletic performance in both moderate- and high-intensity exercises [27].

Aim of Study

Considering LC presence in skeletal muscles and cardiac tissues, its potential performance-enhancing properties and essential role in energy metabolism, LC supplementation is suggested to have beneficial effects on exercise capacity and recovery. Nonetheless, recent studies have reported conflicting results regarding beneficial effects of LC in healthy subjects [34, 41, 43, 44]. Therefore, this meta-analysis aimed to review available data to determine an effect of LC supplementation on aerobic capacity ($\dot{V}O_2$ max) and post-exercise blood lactate levels, specifically in athletes or physically trained individuals. Additionally, the present study also provides evidence regarding an effective method of LC supplementation, whether administered acutely or chronically.

Methods

Search strategy

The current study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The authors searched PubMed, Google Scholar, and ProQuest from database inception to November 2023. The literature search was conducted using the undermentioned combination of terms and keywords based on the Medical Subject Headings (MeSH) system. For example, the search strategy used for PubMed was as follows:

#1 carnitine OR “L-carnitine”,
#2 VO2max OR “aerobic capacity” OR lactate OR “lactic acid”,
#3 athlete OR athletic OR sports OR exercise.

Additionally, a manual search was conducted on references cited in selected articles and published reviews.

Study selection and eligibility

The articles were selected according to inclusion criteria using the PICO model: Population (healthy professional or amateur athletes or trained people or physically active people whose $\dot{V}O_2$ max is considered good or higher, based on the ACSM criteria), Intervention (L-carnitine or L-carnitine L-tartrate or propionyl-L-carnitine oral supplementation), Comparison (a matched control group or placebo), Outcome (post-exercise blood lactate and/or $\dot{V}O_2$ max), which was performed in a study design of Randomized Controlled Trials (RCTs). Exclusion criteria were: 1) consuming LC in a multi-ingredients supplement; 2) animal studies; 3) trials without control groups; 4) review studies, case reports, editorial articles or letters to an editor; 4) currently on medication for a health problem.

Data extraction and quality assessment

Four investigators independently reviewed each eligible full-text manuscript and extracted data from the included studies. Details on authors, year, country, study design, sample characteristics, comparison groups, type of LC supplementation, and intervention strategies were collected. The Jadad scale was used to assess methodological quality of the included studies [18]. Scoring was performed independently by three investigators (EF, HP, and DS), and a median of final scores was considered to increase reliability. Out of a total of five points, studies with a score below three were considered to be of low quality, while scores of ≥3 were considered to be of high quality.

Statistical analysis

All statistical analyses were performed using the Review Manager software, version 5.4 (the Cochrane Collaboration, London, UK). Continuous variables were analyzed using Weighted Mean Differences (WMD) with Confidence Intervals (CI) of 95%. Existence of heterogeneity across the trials was evaluated using the I^2 test. An I^2 value of <25% indicated a low risk of heterogeneity. Consequently, a pooled effect was calculated using a fixed effects model. Conversely, a random effects model was performed if significant heterogeneity was observed across the studies (I^2 > 50%). Subgroup analyses were performed to determine whether duration of interventions might be a possible source of heterogeneity within the studies. The studies were divided into acute (within hours of exercises) and chronic supplementation (minimum one week of duration). Both random and fixed effects models were utilized to derive pooled estimates of the effects of LC supplementation on blood lactate and $\dot{V}O_2$ max. The overall effects were presented on forest plots and a possible publication bias was evaluated using a funnel plot. An asymmetric funnel plot suggests presence of a publication bias. A p value <0.05 was considered statistically significant.

Results

Search results

The initial search strategy identified 876 potential articles. In order to exclude irrelevant papers, the manuscripts were screened in sequential order based on titles, abstracts, and full texts. After removing duplicates, the remaining 795 studies were screened by titles and abstracts, of which 748 were excluded based on the titles and abstracts screening. The reviewers then analyzed 47 full texts to assess eligibility for study inclusion. Further 33 articles were excluded for the following reasons: studies were not conducted in athletes, or were conducted in untrained or unhealthy individuals (n = 19), an outcome of interest was unavailable (n = 7), multi-ingredients supplements were administered (n = 1), and articles were not written in English (n = 3). Ultimately, 14 studies met the inclusion criteria and were included in the systematic review and meta-analysis. The study selection process is presented in Figure 1.

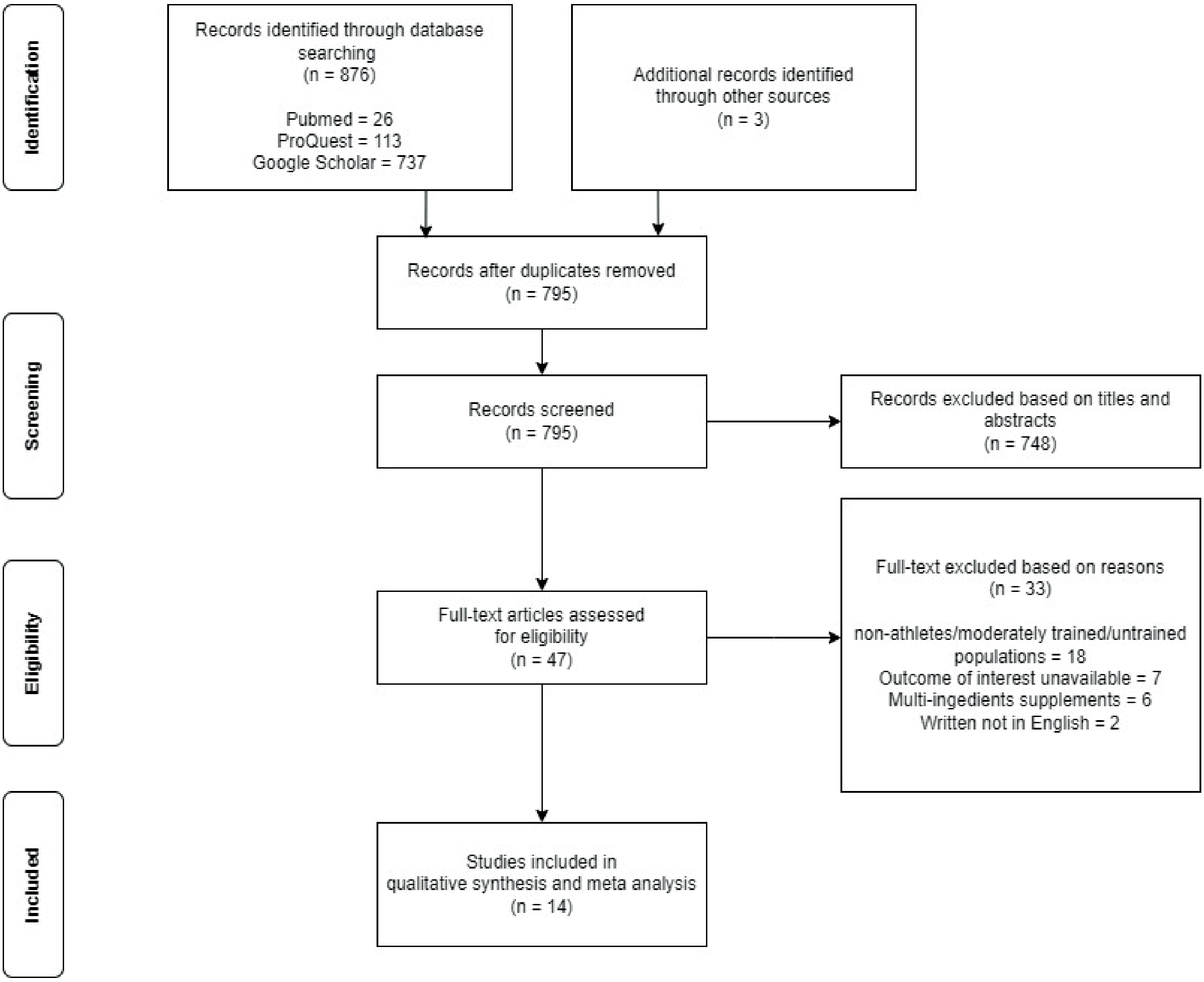

Figure 1. PRISMA Flow chart

Table 1. Summary of the included clinical studies

Study	Country	Study design	Population	Gender	Age (years, Mean ± SD)	Exercise program	Formulation	Dosage and duration	Outcome	Jadad score
AbuMoh'd et al. [1]	Jordan	RCT, parallel	20 endurance athletes	M	21.88 ± 2.44	aerobic exercise: 5000-m race	LC	3 g/d, 3 weeks	blood lactate	2
Arazi and Mehrtash [3]	Iran	RCT, parallel	18 gymnast athletes	M	21 ± 2.12	aerobic exercise: 20-m shuttle run anaerobic exercise: Running-Based Anaerobic Sprint Test (RAST)	LC	3 g, acute supplementation	blood lactate $\dot{V}O_2$ max	3
Broad et al. [5]	Australia	RCT, parallel	15 endurance athletes	M	32.5 ± 9	aerobic exercise: 80 minutes of continuous cycling at each 20%, 40%, 60%, and 80% of $\dot{V}O_2$ max	LCLT	2 g/d, 15 days	blood lactate	3
Chun et al. [7]	South Korea	RCT, parallel	36 soccer athletes	n/a	20.67 ± 1.21	aerobic exercise	LC	2 g, 3 g, 4 g, 5 g, and 6 g/d, 4 weeks	blood lactate $\dot{V}O_2$ max	2
Colombani et al. [8]	Switzerland	RCT, crossover	7 endurance athletes	M	36 ± 3	aerobic exercise: marathon run	LC	4 g, acute supplementation	blood lactate	3
Dehghani et al. [9]	Iran	RCT, parallel	20 elite wrestlers	M	21.8 ± 2.4	aerobic exercise: Conconi test on treadmill	LCLT	3 g, acute supplementation	$\dot{V}O_2$ max	1
Eroğlu et al. [10]	Turkey	CT, crossover	16 badminton athletes	8 M, 8 F	M: 25.38 ± 3.20 F: 20.38 ± 2.50	aerobic exercise: treadmill run at a speed of 9,7 km/h, 2% increments every 2 min until exhaustion	LC	2 g, acute supplementation	blood lactate $\dot{V}O_2$ max	1
Gorostiaga et al. [14]	France	RCT, crossover	10 endurance athletes	9 M, 1 F	25.8 ± 2.2	aerobic exercise: 45 min of cycling at 66% of individual $\dot{V}O_2$ max	LC	2 g/d, 4 weeks	blood lactate	2
Jacobs et al. [17]	USA	RCT, crossover	24 resistance athletes	M	25.2 ± 3.6	anaerobic exercise: Wingate test (5 10-sec. sprints on ergocycle)	GPLC	4.5 g, acute supplementation	blood lactate	3
Koozehchian et al. [20]	Iran	RCT, parallel	23 resistance athletes	M	25 ± 1.5	resistance training: 9 weeks, twice a week	LC	2 g/d, 9 weeks	blood lactate	4
Kraemer et al. [21]	USA	RCT, crossover	10 resistance athletes	M	22 ± 1	resistance exercise: whole-body plyometrics	LCLT	2 g/d, 3 weeks	blood lactate	3

Marconi et al. [25]	Italy	RCT, crossover	6 competitive walkers	M	25.3	aerobic exercise: 120 min of treadmill walk at ~65% of individual VO_2 max	LC	4 g/d, 2 weeks	blood lactate	2
Orer and Guzel [28]	Turkey	RCT, crossover	26 soccer athletes	M	18.4 ± 0.5	aerobic exercise: treadmill run at a speed of 8 km/h, 1 km/h increments every 3 min until exhaustion anerobic exercise: series of 10, 15, and 20 standardized jumps off both feet	LC	3-4 g/d, acute supplementation	blood lactate	4
Ransone and Lefavi [32]	USA	RCT, crossover	26 endurance athletes	M	20.9 ± 2.4	anerobic exercise: 600-m sprint	LC	2 g/d, 3 weeks	blood lactate	3

Note: RCT – Randomized Controlled Trial, CT – non-randomized Controlled Trial, M – male, F – female, LC – L-carnitine, LCLT – L-carnitine L-tartrate, GPLC – glycine propionyl-L-carnitine, n/a – data not available, g/d – gram/day

Study characteristics

The characteristics of the 14 included studies are summarized in Table 1. A total of 257 athletes or trained individuals were included in the review, of whom 248 were men and 9 were women. Regarding their training types, 84 individuals were endurance-trained, 78 were team-based sports athletes (soccer and badminton), 57 were resistance-trained, 20 were wrestlers, and 18 were gymnasts. The age of the participants ranged from 17 to 44 years. The articles were published from 1985 to 2021, of which 13 were randomized controlled trials, 8 were crossover studies, and the rest were parallel studies. Five studies were conducted in Asian countries, five in Europe, three in North America, and one in Australia. These studies mainly prescribed LC at doses ranging from 2 to 6 grams per day. Durations of the interventions varied, with the shortest being acute (pre-exercise) and the longest lasting 9 weeks. Several studies reported more than one study design, which varied in terms of LC dosage, duration of supplementation, type of exercises, and gender of participants [3, 7, 10, 20, 28]. Therefore, some studies were included more than once in the meta-analysis. Trial quality of the included studies was assessed using the Jadad score. The quality of these studies ranged from 1 to 4 points; eight studies were classified as high-quality [3, 5, 8, 17, 20, 22, 28, 32], while six studies were categorized as low-quality [1, 7, 9, 10, 14, 25].

Effect of L-carnitine supplementation on blood lactate

Post-exercise blood lactate/lactic acid levels were reported in 13 publications. The heterogeneity among these studies was moderate (I^2 = 64%), therefore, the random effect model was performed to estimate the pooled effect size. The pooled analysis demonstrated that LC supplementation significantly decreased blood lactate/lactic acid levels compared with placebo (SMD = –0.52 mmol/L, 95% CI: –0.85 to –0.19, p = 0.002) (Figure 2A). The funnel plot analysis showing the asymmetrical funnel plot for the blood lactate levels suggested the presence of the publication bias (Figure 2B).

The data was further analyzed based on the duration of supplementation (acute vs. chronic supplementation). The chronic supplementation group comprised of the studies which prescribed the LC supplementation for at least a week. The subgroup analysis showed that chronic LC supplementation resulted in the significantly lower post-exercise blood lactate levels than placebo (SMD = –0.69 mmol/L, 95% CI: –1.16 to –0.21, p = 0.004). Moreover, the acute supplementation group also demonstrated the lower blood lactate

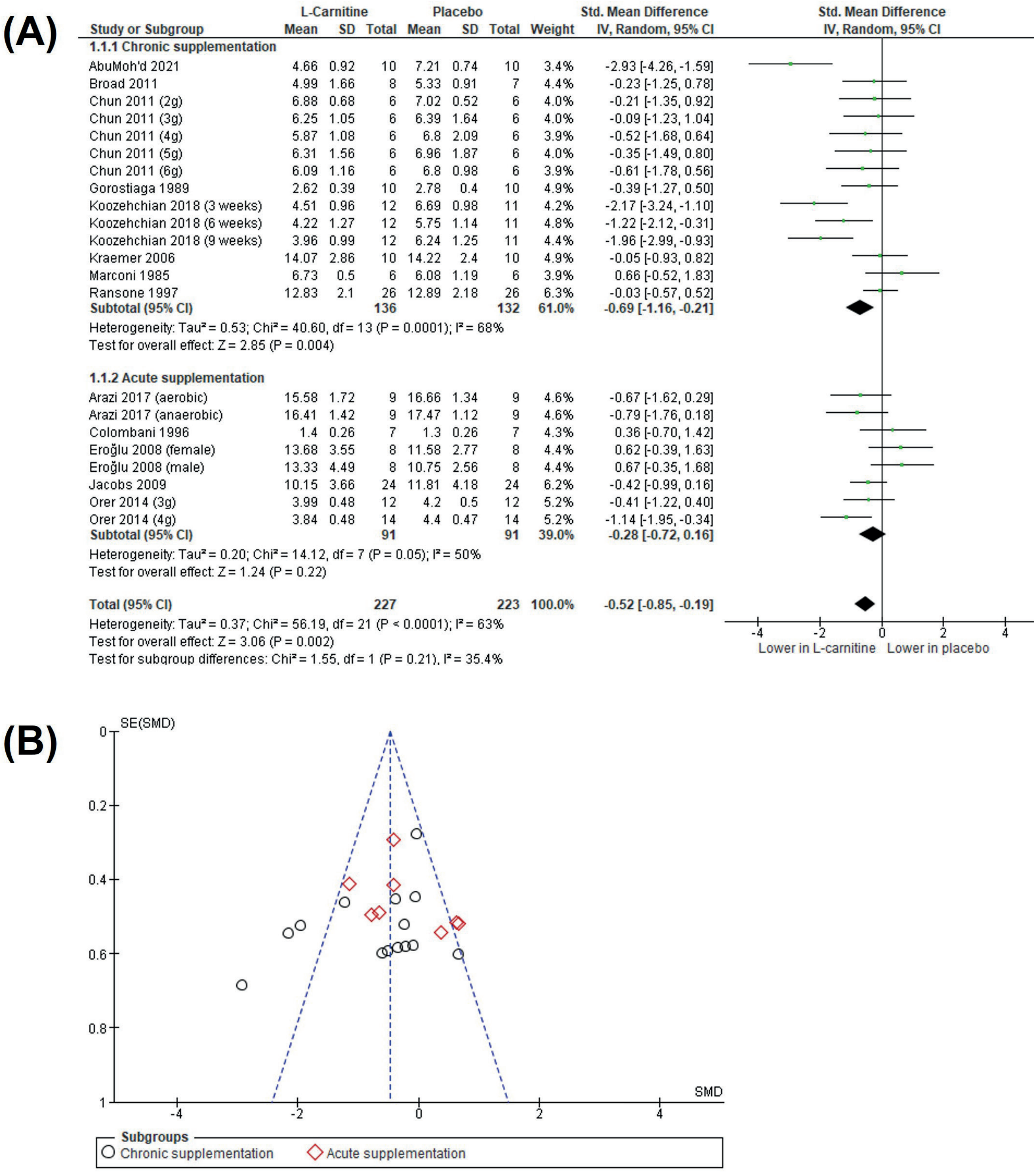

Figure 2. Forest plot and funnel plot of lactate level

levels than the placebo group, although statistically insignificant (SMD = –0.28 mmol/L, 95% CI: –0.72 to 0.16, p = 0.22). Therefore, the results of the subgroup analyses suggested that the beneficial effect of LC supplementation might be more pronounced in athletes receiving chronic supplementation.

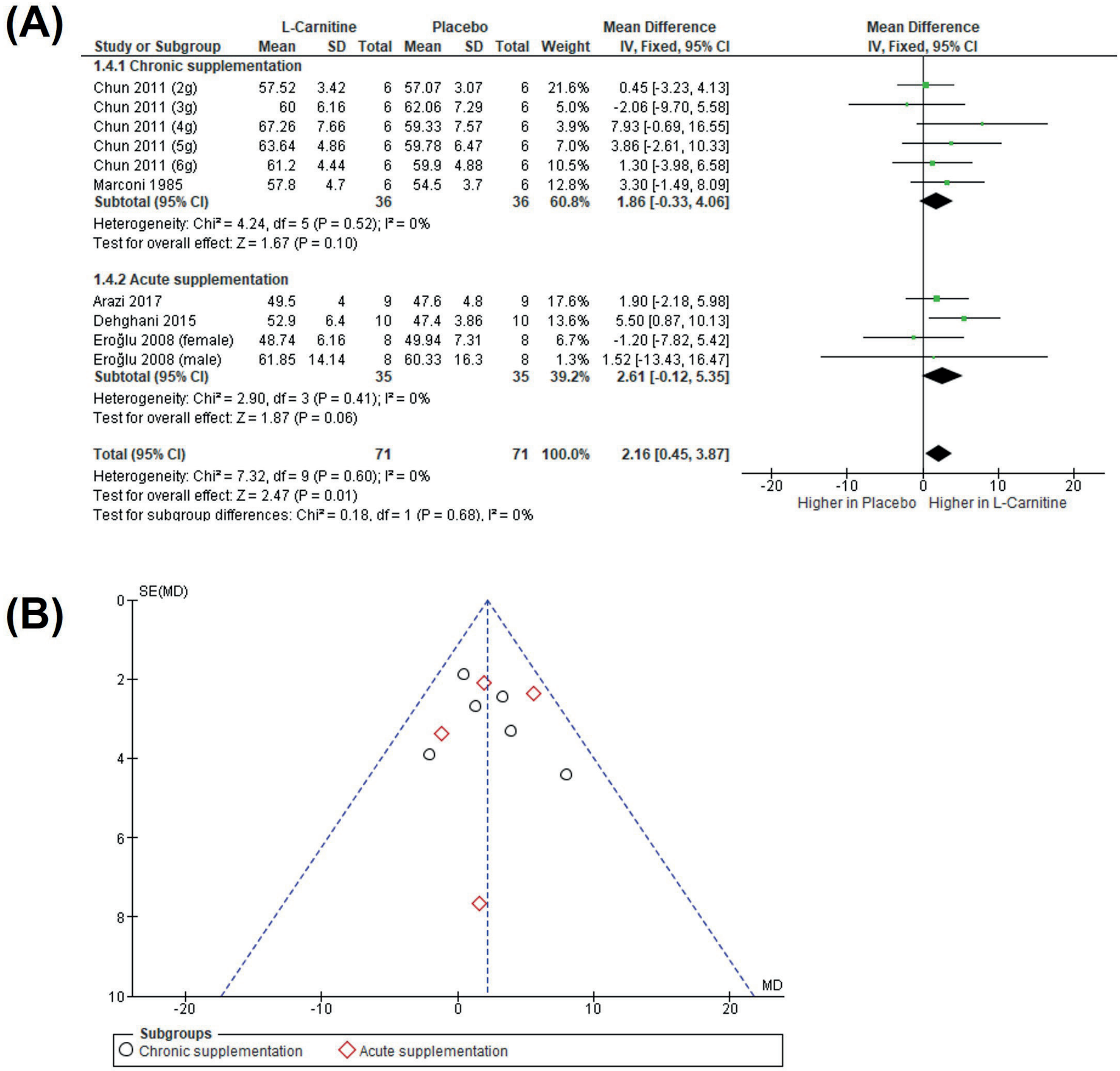

Figure 3. Forest plot and funnel plot of $\dot{V}O_2$ max

Effect of L-carnitine supplementation on $\dot{V}O_2$ max

Four publications reported $\dot{V}O_2$ max after either LC or placebo supplementation. The heterogeneity among these studies was very low ($I^2 = 0.00\%$), thus the fixed effect model was used in the analysis. The pooled analysis showed that the LC supplementation group had significantly higher $\dot{V}O_2$ max compared to the placebo group (MD = 2.16 ml/kg/min, 95% CI: 0.45 to 3.87, $p = 0.01$). Moreover, the subgroup analyses showed that both acute and chronic LC supplementation effects on $\dot{V}O_2$ max were similar (Figure 3A). The funnel plot analysis showing the symmetrical funnel plot for $\dot{V}O_2$ max indicated that the presence of the publication bias was unlikely (Figure 3B).

Discussion

The main aim of this meta-analysis was to determine the effects of LC supplementation on exercise performance, specifically on aerobic capacity ($\dot{V}O_2$ max) and post-exercise blood lactate levels. Additionally, it provided the evidence of the effective duration of LC supplementation. The main results indicated that oral

LC supplementation could result in lower plasma lactate after exercises and higher $\dot{V}O_2$ max in athletes and/or physically trained individuals. Furthermore, the subgroup analyses revealed that only chronic LC supplementation resulted in significantly lower post-exercise blood lactate levels than placebo, while both acute and chronic LC supplementation caused higher $\dot{V}O_2$ max.

Exercise-induced fatigue, resulting from prolonged and intense physical effort, may negatively affect athletic performance [29]. Previous evidence indicated an association between increased blood lactate levels and an incidence of exercise-induced muscle fatigue [16, 39]. Lactate is a by-product of glycolysis, an anaerobic pathway that rapidly produces ATP during periods of dysoxia [33]. Consequently, to enhance sports performance, it is essential to explore strategies for either delaying onset of exercise-induced fatigue or accelerating a recovery process. LC supplementation has been claimed to improve recovery after exercises through different mechanisms, for example by reducing intramuscular metabolic stress associated with an increased lactate accumulation [1, 44]. In a crossover study on six untrained individuals, Giamberardino et al. reported that 3 weeks of LC supplementation alleviated muscle pain and tenderness, as well as reduced creatine kinase (a marker of muscle damage) levels after eccentric effort [13]. Moreover, a series of studies conducted by Kraemer et al. revealed a positive impact of LC on alleviating exercise-induced hypoxia, muscle damage, and delayed onset muscle soreness (DOMS) [21, 22, 37]. Arazi et al. observed that acute LC supplementation resulted in lower lactate levels compared to placebo after both aerobic and anaerobic exercises in gymnast athletes [3]. Another study also reported that acute oral supplementation of glycine propionyl-L-carnitine (GPLC) can reduce lactate production in resistance-trained men after high-intensity exercises [17]. This effect was probably due to a role of LC supplementation in regulating energy metabolism by maintaining the acetyl-CoA/CoA ratio, thereby allowing continuous pyruvate dehydrogenase activity and thus preventing lactate formation [36]. Another study also reported that a two-week daily oral supplementation of LC decreased serum LDH levels after an intense bout of exercise in active healthy young men, which may further prevent lactate formation [30]. In addition, LC enhances esterified fatty acids transport across an inner mitochondrial membrane for β-oxidation, thereby reducing utilization of muscle and liver glycogen as an energy source, resulting in reduced lactic acid production [35]. Furthermore, LC increases blood flow and oxygen delivery to muscle tissues by enhancing endothelial function. This, in turn, may decrease cellular and biochemical disturbances induced by hypoxia, ultimately contributing to a reduced lactate accumulation and improved muscle recovery [11]. However, other studies reported contradictory results that do not support a beneficial effect of acute LC supplementation on blood lactate response after exercising [8, 10, 25, 38]. Meanwhile, a recent meta-analysis result indicated that chronic LC supplementation alleviated DOMS and reduced levels of muscle damage biomarkers, including CK, myoglobin (Mb), and LDH, in both untrained [43] and physically active healthy young men [30]. A possible rationale is that acute LC supplementation is insufficient to increase muscle LC content [11].

$\dot{V}O_2$ max represents the maximum capacity of the pulmonary, cardiovascular, and muscular systems to uptake, transport, and utilize oxygen throughout prolonged and intense physical activity. Therefore, $\dot{V}O_2$ max is frequently used as a parameter of athletes' aerobic capacity and their fitness level [23]. $\dot{V}O_2$ max can be increased by means of endurance physical training with specific frequency and duration [6, 24]. However, increasing $\dot{V}O_2$ max through diet or consumption of certain supplements, remains a subject to debate. LC supplementation has been reported to increase $\dot{V}O_2$ max, although a physiological mechanism is still unclear [3, 7, 9, 25]. The present meta-analysis revealed that the LC supplementation group had significantly higher $\dot{V}O_2$ max compared to the placebo group. The increase in $\dot{V}O_2$ max from LC supplementation may be related to its effect on enhancing fat oxidation. Because fat oxidation requires more oxygen compared to carbohydrates, the cardiovascular system must deliver more oxygen to muscles [26]. Therefore, an increase in an oxygen demand to facilitate an entry of pyruvate into the beta-oxidation pathway may result in elevated oxygen consumption as a physiological response. Moreover, the effect of LC on an increasing blood flow and oxygen delivery to muscle tissues also contributes to an improvement of $\dot{V}O_2$ max [11]. Furthermore, it seems that a decrease in blood lactate levels after LC supplementation can also explain the improvement of $\dot{V}O_2$ max. Lower lactate production during exercises may have allowed the LC group to achieve higher levels of $\dot{V}O_2$ max before fatigue occurred, suggesting a potential improvement in endurance capacity.

Conclusions

To the best of our knowledge, this is the first systematic review and meta-analysis to evaluate the effects of both acute and chronic LC supplementation on aerobic capacity ($\dot{V}O_2$ max) and post-exercise blood lactate levels in athletes or physically trained individuals. The current study demonstrated that chronic LC supplementation may be beneficial for enhancing athletic performance by reducing post-exercise blood lactate levels and improving $\dot{V}O_2$ max in athletes. Further research is required to quantify the efficacy of LC in a homogeneous supplementation strategy with regard to dosage and timing, and a similar exercise protocol over a longer timeframe and with a larger number of participants.

Conflict of Interest

The authors declare no conflict of interest.

References

1. AbuMoh'd MF, Obeidat G, Alsababha W. Effect of oral supplementation with L-carnitine on performance time in a 5000 m race and responses of free fatty acid and carnitine concentrations in trained-endurance athletes. Monten J Sports Sci Med. 2021;10(2):5-11. https://doi.org/10.26773/mjssm.210901
2. Adeva-Andany MM, Calvo-Castro I, Fernández-Fernández C, Donapetry-García C, Pedre-Piñeiro AM. Significance of L-carnitine for human health. IUBMB Life. 2017;69(8):578-594. https://doi.org/10.1002/iub.1646
3. Arazi H, Mehrtash M. Effect of acute L-carnitine supplementation on blood lactate, glucose, aerobic and anaerobic performance in elite male artistic gymnasts. Balt J Sport Health Sci. 2017;1:2-7. https://doi.org/10.33607/bjshs.v1i104.9
4. Brass EP. Pharmacokinetic considerations for the therapeutic use of carnitine in hemodialysis patients. Clin Ther. 1995;17(2):176-185. https://doi.org/10.1016/0149-2918(95)80017-4
5. Broad EM, Maughan RJ, Galloway SDR. Effects of exercise intensity and altered substrate availability on cardiovascular and metabolic responses to exercise after oral carnitine supplementation in athletes. Int J Sport Nutr Exerc Metab. 2011;21(5):385-397. https://doi.org/10.1123/ijsnem.21.5.385
6. Chen B, Wu Z, Huang X, Li Z, Wu Q, Chen Z. Effect of altitude training on the aerobic capacity of athletes: a systematic review and meta-analysis. Heliyon. 2023;9(9):e20188. https://doi.org/10.1016/j.heliyon.2023.e20188
7. Chun YS, Lee KE, Kang SK, Lee NJ, Kim JK. Influence of L-Carnitine intake for maximal exercise performance and fatigue recovery exercise athletes: based on elite soccer players [Internet]. 2011. Available from: https://kiss.kstudy.com/Detail/Ar?key=2903902#
8. Colombani P, Wenk C, Kunz I, Krähenbühl S, Kuhnt M, Arnold M, et al. Effects of L-carnitine supplementation on physical performance and energy metabolism of endurance-trained athletes: a double-blind crossover field study. Eur J Appl Physiol. 1996;73(5):434-439. https://doi.org/10.1007/BF00334420
9. Dehghani M, Shakerian S, Nejad S, Naseri M. Effects of L-carnitine L-tartrate acute consumption on lipid metabolism, maximum oxygen consumption (VO2max), and distance run following aerobic exhaustive exercise on treadmill in elite athletes wrestling. Ayer. 2015;2:2015-2189.
10. Eroğlu H, Şenel Ö, Atalay Guzel N. Effects of acute L-Carnitine intake on metabolic and blood lactate levels of elite badminton players. Neuro Endocrinol Lett. 2008;29:261-266.
11. Fielding R, Riede L, Lugo JP, Bellamine A. L-carnitine supplementation in recovery after exercise. Nutrients. 2018;10(3):349. https://doi.org/10.3390/nu10030349
12. Flanagan JL, Simmons PA, Vehige J, Willcox MD, Garrett Q. Role of carnitine in disease. Nutr Metab. 2010;7(1):30. https://doi.org/10.1186/1743-7075-7-30
13. Giamberardino MA, Dragani L, Valente R, Di Lisa F, Saggini R, Vecchiet L. Effects of prolonged L-carnitine administration on delayed muscle pain and CK release after eccentric effort. Int J Sports Med. 1996;17(5):320-324. https://doi.org/10.1055/s-2007-972854
14. Gorostiaga EM, Maurer CA, Eclache JP. Decrease in respiratory quotient during exercise following L-carnitine supplementation. Int J Sports Med. 1989;10(3):169-174. https://doi.org/10.1055/s-2007-1024895
15. Gupta D, Rawat S, Gupta P. Clinical research and therapeutic importance of dietary supplement L-carnitine: review. Asian J Pharm Res. 2018;8(1):47-58. https://doi.org/10.5958/2231-5691.2018.00010.2
16. Hall M, Rajasekaran S, Thomsen T, Peterson A. Lactate: friend or foe. PM&R. 2016;8:S8-S15. https://doi.org/10.1016/j.pmrj.2015.10.018
17. Jacobs PL, Goldstein ER, Blackburn W, Orem I, Hughes JJ. Glycine propionyl-L-carnitine produces enhanced anaerobic work capacity with reduced lactate accumulation in resistance trained males. J Int Soc Sports Nutr. 2009;6(1):9. https://doi.org/10.1186/1550-2783-6-9
18. Jadad AR, Moore RA, Carroll D, Jenkinson C, Reynolds DJ, Gavaghan DJ, et al. Assessing the quality of reports of randomized clinical trials: is blinding necessary? Control Clin Trials. 1996;17(1):1-12. https://doi.org/10.1016/0197-2456(95)00134-4
19. Knapik JJ, Steelman RA, Hoedebecke SS, Austin KG, Farina EK, Lieberman HR. Prevalence of dietary supplement use by athletes: systematic review and meta-

analysis. Sports Med. 2016;46(1):103-123. https://doi.org/10.1007/s40279-015-0387-7

20. Koozehchian MS, Daneshfar A, Fallah E, Agha-Alinejad H, Samadi M, Kaviani M, et al. Effects of nine weeks L-Carnitine supplementation on exercise performance, anaerobic power, and exercise-induced oxidative stress in resistance-trained males. J Exerc Nutr Biochem. 2018;22(4):7-19. https://doi.org/10.20463/jenb.2018.0026
21. Kraemer WJ, Spiering BA, Volek JS, Ratamess NA, Sharman MJ, Rubin MR, et al. Androgenic responses to resistance exercise: effects of feeding and L-carnitine. Med Sci Sports Exerc. 2006;38(7):1288-1296. https://doi.org/10.1249/01.mss.0000227314.85728.35
22. Kraemer WJ, Volek JS, Dunn-Lewis C. L-carnitine supplementation: influence upon physiological function. Curr Sports Med Rep. 2008;7(4):218-223. https://doi.org/10.1249/JSR.0b013e318180735c
23. Lee J, Zhang XL. Physiological determinants of VO2max and the methods to evaluate it: a critical review. Sci Sports. 2021;36(4):259-271. https://doi.org/10.1016/j.scispo.2020.11.006
24. Ma X, Cao Z, Zhu Z, Chen X, Wen D, Cao Z. VO2max (VO2peak) in elite athletes under high-intensity interval training: a meta-analysis. Heliyon. 2023;9(6):e16663. https://doi.org/10.1016/j.heliyon.2023.e16663
25. Marconi C, Sassi G, Carpinelli A, Cerretelli P. Effects ofl-carnitine loading on the aerobic and anaerobic performance of endurance athletes. Eur J Appl Physiol. 1985;54(2):131-135. https://doi.org/10.1007/BF02335919
26. Melzer K. Carbohydrate and fat utilization during rest and physical activity. e-SPEN Eur J Clin Nutr Metab. 2011;6(2):e45-e52. https://doi.org/10.1016/j.eclnm.2011.01.005
27. Mielgo-Ayuso J, Pietrantonio L, Viribay A, Calleja-González J, González-Bernal J, Fernández-Lázaro D. Effect of acute and chronic oral L-carnitine supplementation on exercise performance based on the exercise intensity: a systematic review. Nutrients. 2021;13(12):4359. https://doi.org/10.3390/nu13124359
28. Orer GE, Guzel NA. The effects of acute L-carnitine supplementation on endurance performance of athletes. J Strength Cond Res. 2014;28(2):514. https://doi.org/10.1519/JSC.0b013e3182a76790
29. Owens DJ, Twist C, Cobley JN, Howatson G, Close GL. Exercise-induced muscle damage: what is it, what causes it and what are the nutritional solutions? Eur J Sport Sci. 2019;19(1):71-85. https://doi.org/10.1080/17461391.2018.1505957
30. Parandak K, Arazi H, Khoshkhahesh F, Nakhostin-Roohi B. The effect of two-week L-carnitine supplementation on exercise-induced oxidative stress and muscle damage. Asian J Sports Med. 2014 Jun;5(2):123-128.
31. Pekala J, Patkowska-Sokola B, Bodkowski R, Jamroz D, Nowakowski P, Lochynski S, et al. L-carnitine – metabolic functions and meaning in humans life. Curr Drug Metab. 2011;12(7):667-678. https://doi.org/10.2174/138920011796504536
32. Ransone JW, Lefavi RG. The effects of dietary L-carnitine on anaerobic exercise lactate in elite male athletes. J Strength Cond Res. 1997;11(1):4.
33. Rogatzki MJ, Ferguson BS, Goodwin ML, Gladden LB. Lactate is always the end product of glycolysis. Front Neurosci. 2015;9:22. https://doi.org/ 10.3389/fnins.2015.00022
34. Samsudin N, Ahmad NS, Ooi FK, Abdul Kadir A, Kassim NK. Randomised clinical trial of combined L-carnitine supplement and exercise on biochemical markers and exercise performance: a systematic review. Malays J Med Health Sci. 2023;19(2):259-270. https://doi.org/10.47836/mjmhs.19.2.37
35. Siddiqui MK, Mughal SA, Siddiqui MS, Hayat AS. Effects of L-carnitine; on skeletal muscle of rabbit. Professional Med J. 2015;22(8):p1001. https://doi.org/10.29309/tpmj/2015.22.08.1145
36. Siliprandi N, Di Lisa F, Pieralisi G, Ripari P, Maccari F, Menabo R, et al. Metabolic changes induced by maximal exercise in human subjects following L-carnitine administration. Biochim Biophys Acta. 1990;1034(1):17-21. https://doi.org/10.1016/0304-4165(90)90147-O
37. Spiering BA, Kraemer WJ, Hatfield DL, Vingren JL, Fragala MS, Ho JY, et al. Effects of L-carnitine L-tartrate supplementation on muscle oxygenation responses to resistance exercise. J Strength Cond Res. 2008;22(4):1130-1135. https://doi.org/10.1519/JSC.0b013e31817d48d9
38. Stuessi C, Hofer P, Meier C, Boutellier U. L-carnitine and the recovery from exhaustive endurance exercise: a randomised, double-blind, placebo-controlled trial. Eur J Appl Physiol. 2005;95(5):431-435. https://doi.org/10.1007/s00421-005-0020-9
39. Theofilidis G, Bogdanis GC, Koutedakis Y, Karatzaferi C. Monitoring exercise-induced muscle fatigue and adaptations: making sense of popular or emerging indices and biomarkers. Sports. 2018;6(4):153. https://doi.org/10.3390/sports6040153
40. Vaz FM, Wanders RJA. Carnitine biosynthesis in mammals. Biochem J. 2002 Feb 1;361(Pt 3):417–29. https://doi.org/10.1042/0264-6021:3610417
41. Vecchio M, Chiaramonte R, Testa G, Pavone V. Clinical effects of L-carnitine supplementation on physical performance in healthy subjects, the key to success in

rehabilitation: a systematic review and meta-analysis from the rehabilitation point of view. J Funct Morphol Kinesiol. 2021;6(4):93. https://doi.org/10.3390/jfmk6040093

42. Wardenaar FC, Ceelen IJM, Dijk JWV, Hangelbroek RWJ, Roy LV, Pouw BV der, et al. Nutritional supplement use by Dutch elite and sub-elite athletes: does receiving dietary counseling make a difference? Int J Sport Nutr Exerc Metab. 2017;27(1):32-42. https://doi.org/10.1123/ijsnem.2016-0157
43. Yarizadh H, Shab-Bidar S, Zamani B, Vanani AN, Baharlooi H, Djafarian K. The effect of L-carnitine supplementation on exercise-induced muscle damage: a systematic review and meta-analysis of randomized clinical trials. J Am Coll Nutr. 2020;39(5):457-468. https://doi.org/10.1080/07315724.2019.1661804
44. Zhu Y, Wang Q, Rahimi M. Effect of L-carnitine supplementation during exercises on blood fatigue and energy metabolism factors: a systematic review and meta-analysis of randomized controlled trials. Prog Nutr. 2022;24:2022091. https://doi.org/10.23751/pn.v24i3.12436