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Research article

Combined Vs. Single Supplementation of L-Citrulline and Sodium Bicarbonate During Sprint Interval Training in Basketball Players: Effects on Physical Performance and Hormonal Adaptations

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Abstract
This study examined the effects of L-citrulline (L-CIT) and sodium bicarbonate (Sb) supplementation during short sprint interval training (SSIT), both individually and combined, over a 28-day period, to assess the impact on the physical performance and hormonal adaptations of basketball players. Forty young (age = 21.5 ± 1.7 years) male basketball players were randomly assigned into five groups of eight subjects including either L-CIT (6 g daily), Sb (0.3 g·kg^{-1} of Sb daily), L-CIT+Sb, placebo (PL), and or an active control group (CON). The training groups engaged in SSIT sessions, consisting of three sets of ten repetitions of five-second all-out sprints, three times per week over four weeks. A series of physical performance tests including countermovement vertical jump, a 20-m linear sprint, Illinois change of direction speed, Wingate anaerobic power, and an incremental exercise test were conducted before and after the training period. In addition, blood samples were obtained to analyze resting testosterone and cortisol levels before and after the training period. Significant improvements in physical performance were observed across all training groups after the 4-week intervention ($p < 0.05$). Notably, the groups receiving supplements exhibited more pronounced improvements in the physical performance tests ($p < 0.01$) in comparison to the PL group, indicating superior adaptations. In addition, no significant ($p > 0.05$) changes were seen in testosterone, but the supplement groups showed lower cortisol levels than other groups following the 4-week intervention. There were no significant differences in physical performance adaptations among the supplement groups. The study reveals that short-term supplementation of L-citrulline and sodium bicarbonate in the capsule form effectively enhance physical performance of basketball players in comparison to a placebo.

Key words: Ergogenic aid, athletic, interval training, physical performance.

Introduction

Basketball combines anaerobic glycolytic and aerobic oxidative energy demands, requiring frequent directional changes that place considerable stress on the neuromuscular system (Balčiūnas et al., 2006). The sport also demands repeated accelerations, sprints, frequent jumping, physical contests for positioning and possession, and the execution of specialized skills (Figueira et al., 2022). Optimizing physical fitness is crucial for enhancing sport-specific performance and ensuring the success of basketball players during competition (Fang and Jiang, 2024). Therefore, achieving high performance in basketball requires the involvement of both anaerobic and aerobic energy systems (Delextrat and Martinez, 2014), and implementing a standardized training program to enhance these qualities would be critical in enhancing athletes' physical abilities (Balčiūnas et al., 2006).

In addition to physical performance parameters, the regulation of catabolic and anabolic hormone responses to exercise training is recognized essential for enhancing the physical fitness characteristics of basketball players (Schelling et al., 2015; Miguel-Ortega et al., 2024). In fact, previous research indicated that changes in cortisol and testosterone levels during training and throughout the basketball season are associated with changes in physical performance (Miguel-Ortega et al., 2024). Additionally, the ratio of testosterone to cortisol may provide insights into the processes of muscle tissue, indicating whether it is undergoing catabolism or anabolism (Cofré-Bolados et al., 2019). Importantly, variations in cortisol and testosterone levels, whether they increase or decrease, can result from various training protocols implemented for athletes (Meckel et al., 2011).

Numerous training methods have been demonstrated to enhance physical performance and hormonal adaptations in basketball players (Ambroży et al., 2021; Arslan et al., 2022; Fang and Jiang, 2024; Song and Deng, 2023). Among these interventions, high-intensity interval training (HIIT) has proven particularly effective in improving both aerobic and anaerobic fitness, making it a valuable tool for basketball players seeking to elevate their performance (Laursen and Buchheit, 2019; Kunz et al., 2019; Song and Deng, 2023). Previous studies have shown that incorporating short sprint interval training (SSIT) lasting 5 to 10 seconds can produce adaptive responses comparable to traditional HIIT models, while offering more efficient training time and improving enjoyment by reducing the rate of perceived exertion (Arazi et al., 2017; Belfry et al., 2020; Lee et al., 2020; Boullosa et al., 2022). Moreover, observational data indicate that the duration of sprint running during a basketball match typically ranges from 2 to 6 seconds, suggesting that SSIT is a particularly suitable intervention for this population (Figueira et al., 2022; Xu et al., 2024). Consequently, SSIT protocols can be considered a novel, time-efficient, and enjoyable method for enhancing both aerobic and anaerobic metabolic pathways, as well as hormonal adaptations, in basketball players (Boullosa et al., 2022; Song and Deng, 2023).

In addition to training interventions, many athletes and coaches have integrated sports supplements into their

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routines over the past decade to enhance physical performance (Amawi et al., 2024; Gharaat et al., 2020). Competitive athletes frequently use nutritional supplements to enhance performance and gain a competitive advantage (National Institutes of Health, 2017). However, few athletes have access to reliable information to guide their supplement choices and predict potential outcomes. A well-balanced nutritional diet and strategic supplementation may be essential for optimizing performance, especially in high-intensity sports like basketball (Amawi et al., 2024; Kristensen et al., 2024).

Moreover, engaging in various training forms, including sprint training and small-sided games during practice, has been found to correlate with elevated levels of blood lactate, H^+, and stress hormones such as cortisol for basketball players (Montgomery et al., 2008; Conte et al., 2023) which can adversely affect physical performance. As a result, the incorporation of sports supplements during the training phase could potentially counteract these effects and facilitate improvements in physical performance (National Institutes of Health, 2017).

L-citrulline (L-CIT) is a naturally occurring amino acid found in watermelon with potential as a sports supplement to enhance athletic performance (Gonzalez and Trexler, 2020). Its effectiveness is attributed to its ability to stimulate nitric oxide synthesis, which enhances blood flow and oxygen delivery to active muscles, while also facilitating the clearance of metabolic byproducts (Breuillard et al., 2015). Additionally, sodium bicarbonate (Sb) is recognized as an ergogenic aid that may help delay the onset of fatigue and enhance performance, particularly during high-intensity exercise (Barber et al., 2013). The fatigue encountered during short-duration, high-intensity training, such as SSIT, can be attributed to several factors, including the production of muscle energy, a decrease in adenosine triphosphate (ATP) levels, or disruptions in the electrochemical processes that regulate muscle contraction and relaxation (Buckinx et al., 2018). Prior research suggests that the intake of L-CIT and Sb may provide benefits for athletes looking to enhance their physical performance following various training modalities including resistance training (Kang et al., 2022; Varovic et al., 2023) and sprint training (Ducker et al., 2013; Stanelle et al., 2020). However, the specific advantages of each supplement, as well as their potential synergistic effects on athletic performance and hormonal changes when used together, remain unclear for athletes aiming to optimize their performance.

Furthermore, the impact of L-CIT and Sb supplementation on the hormonal alterations in athletes after training interventions is still not well understood. Previous studies have indicated that acute supplementation of L-CIT and Sb may significantly mitigate physiological stress responses during sprint and concurrent training (Peart et al., 2013; Caballero-García et al., 2021). However, the long-term effects of these supplements on resting cortisol and testosterone levels in basketball players following the SSIT have not been investigated, suggesting a significant area for future research, as it has not received sufficient focus. Additionally, existing evidence on L-CIT and Sb does not clarify whether their combined use would offer additional benefits for exercise performance and hormonal changes following SSIT. Understanding the combined effects of these supplements is crucial for coaches and athletes, as it could help in selecting the most effective supplementation strategy -whether using L-CIT, Sb, or a combination of both- to optimize physical performance and hormonal adaptations in basketball players undergoing SSIT. Therefore, this study aims to evaluate the impact of L-CIT, Sb, and their combination on physical performance and hormonal adaptations in young male basketball players following a 4-week SSIT program.

Methods

Participants

Forty trained young (age = 21.5 ± 1.7 years) male basketball players (Category III, McKay et al., 2022) from the local basketball academy with the same training levels and weekly training loads volunteered to participate in the study. To identify the suitable sample size for this study, a preliminary power analysis was carried out using the G*Power software (version 3.1.9, which is freely accessible from the University of Düsseldorf, Germany). The calculation of effect size was derived from a recent study that examined the effects of different supplements for enhancing the physical performance of basketball players (Afman et al., 2014). The analysis concluded that an optimal sample size of eight participants is required, with the type 1 error probability set at an alpha of 0.05, achieving a power of 0.80 for an effect size of 0.8. Participants were matched based on their playing position (i.e., guard, forward and center) and then were randomly assigned to five groups including L-CIT (age = 21.6 ± 1.5 years, height = 182.6 ± 7.5 cm, weight = 78.5 ± 4.1 kg, and basketball training experience = 4.1 ± 1.7 years), Sb (age = 21.2 ± 1.8 years, height = 181.2 ± 6.7 cm, weight = 79.8 ± 5.9 kg, and basketball training experience = 4.6 ± 1.1 years), L-CIT+Sb (age = 22.1 ± 1.1 years, height = 183.2 ± 7.1 cm, weight = 79.3 ± 4.8 kg, and basketball training experience = 4.6 ± 1.3 years), placebo (PL; age = 20.8 ± 1.9 years, height = 18.6 ± 6.6 cm, weight = 79.9 ± 3.8 kg, and basketball training experience = 4.9 ± 1.5 years) and an active control group (CON; age = 22.1 ± 2.2 years, height = 181.1 ± 4.3 cm, weight = 77.8 ± 4.7 kg, and basketball training experience = 4.3 ± 1.1 years). The randomization was made through a random number generator on a computer, ensuring unpredictability for authors and participants. A prerequisite for participation was the absence of any physical injuries and a supplementation period. Their eligibility for training was evaluated through screenings for potential musculoskeletal, neurological, or orthopedic conditions that could have affected their ability to engage in such training (Gharaat et al., 2025). Subjects were not allowed to use any nutritional supplements or medications throughout the study and at least 6 months before their inclusion in the study. To ensure adherence, a health-history questionnaire was conducted as part of the participant recruitment process to screen for the utilization of nutritional, drug, and hormonal supplements. Participants were fully informed about the potential risks and discomforts associated with the investigation, and they provided written consent to participate. The study was approved by the Ethics Committee of the University of Shenyang Normal University.

Study design

The present research is a longitudinal study utilizing a randomized, double-blind, placebo-controlled design. The study spanned a total of seven weeks, including one week of familiarization process, one week of pre-testing, four weeks of training and supplementing intervention, and one week of post-testing. Before and after the training period, participants underwent a series of physical performance tests on two days including assessments of countermovement vertical jump (CMVJ), 20-m sprint, and Illinois change of direction [COD] speed on day 1, and also Wingate anaerobic power test and incremental exercise test on day 2, with a 48-hour rest interval in between. In addition, resting blood samples were collected 48 hours before and after the completion of the training period to assess testosterone and cortisol hormones. One week before the start of the training period, all participants went through a familiarization session with the testing and training procedures, as well as the supplementation process. In this session, the subjects' anthropometric variables were measured, which included body mass (evaluated with participants wearing light clothing and barefoot using a digital scale, Seca, Hamburg, Germany, ± 0.1) and height (Stadiometer 208, Seca, UK, ± 0.5). All training groups (i.e., L-CIT, Sb, L-CIT+Sb, and PL) engaged in three non-consecutive days of basketball training on Monday, Wednesday, and Friday and also performed the SSIT program on Tuesday, Thursday and Saturday. All testing and training sessions were conducted in the afternoon (from 4:00 to 6:00 P.M.) to minimize the impact of circadian variations on the results. After the pre-test measurements were completed, the participants commenced their supplementation regimen in the capsule form as follows: L-CIT with a daily dosage of 6 g, Sb with 0.3 g per kg of body weight daily, L-CIT+Sb with a combination of L-CIT and Sb, and PL with 6 g of maltodextrin, all administered over a period of 28 days.

Testing Procedures

Countermovement vertical jump

Participants' jumping ability was measured using maximal countermovement vertical jump (CMVJ). The VERTEC (Wall-mounted version, Power System, USA) device fixed on the basketball court, was used for evaluation. Before testing, the players performed three submaximal jumps as a warm-up and then performed three maximal vertical jumps to reach the highest possible height, with a 1-minute rest period between each attempt. The players were instructed to flex their knees until they achieved a 90° angle and then jump as high as possible. The CMVJ score was determined by measuring the initial and maximal finger contact distance. The highest value out of the three measurements was chosen for further analysis (Xu et al., 2024).

20-m linear sprint

Following the two warm-up trials, participants ran between two electronic timing gates (Brower Timing Systems, Draper, UT, USA) positioned at 0 m and 20 m to assess linear sprint performance. The time taken to complete the sprint was recorded with a precision of 0.01 s. The fastest sprint time out of the three attempts, with a 1-minute rest interval, was chosen for further analysis (Rimmer and Sleveret, 2000).

Illinois COD speed

To evaluate the ability of basketball players to accelerate, decelerate, change directions, and run at different angles, the Illinois COD speed test was employed after two trials for warm-up. This assessment method was previously described in detail by Miller et al. (2006). The fastest time (Brower Timing Systems, Draper, UT, USA) achieved in two trials, with a five-minute rest period in between, was recorded for further analysis.

Wingate anaerobic power test

The 30-second maximal Wingate test was used to evaluate the lower-body peak power output and mean power output (Fereshtian et al., 2017). After the 5-minute cycling for warm-up, the participants pedaled on a mechanically braked cycle ergometer (model 894E, Monark, Sweden) against a resistance equivalent to 0.075 $kg.kg^{-1}$ of their body mass. They started pedaling at maximum speed against the device's inertial resistance and then a personalized load was applied. Verbal encouragement was given to motivate them to pedal at their maximum effort for the entire 30 seconds. The highest power achieved at the 5-second mark represented peak power, while the average power throughout the test was recorded as mean power.

Incremental exercise test

In order to determine maximum oxygen consumption (VO_{2max}) in basketball plays, the incremental exercise test on a treadmill (T676, Sport Art Fitness, UK) was conducted after 5 minutes of jogging and stretching exercise for warm-up. The test started at an intensity of 8 km/h and was gradually increased 1 km/h every 3 minutes. Throughout the test, gas exchange was measured using a breath-by-breath gas collection device (2700 series; Hans Rudolph Inc., Shawnee, KS, USA). To determine the VO_{2max} the highest value in the 30-sec test with these criteria were used: a) reach maximum heart rate (220-age), b) the ratio of > 1.10 in respiratory exchange, and c) voluntary exhaustion (Eston and Reilly, 2009; Song and Sheykhlouvand, 2024; Tao et al., 2024).

Blood sampling and analysis

Blood samples were taken from the antecubital vein and collected in plain evacuated test tubes with a volume of 10 mL to evaluate the resting levels of testosterone and cortisol. Samples were allowed to clot at room temperature for 30 minutes and then centrifuged at 1500× g for 10 minutes. The resulting serum was separated and stored at -80°C for further analysis. To ensure control of the circadian hormonal range, these samples were collected after a 10-hour fast and 8 hours of sleep. The timing of blood collection was based on previous studies that used these procedures to regulate circadian hormonal fluctuations (Song and Deng, 2023). All analyses were conducted using the ELISA method with standardized procedures and commercially available kits (Monobind, Inc. Lake Forest, CA, USA). The intra-assay coefficient of variation (CV) was less than 6%.

Supplement intervention

The L-CIT supplement was composed of 6 g of L-citrulline powder (NOW Foods, Bloomingdale, IL) (Gonzalez and

Trexler, 2020). The Sb supplement consisted of 0.3 g per kg of body weight of sodium bicarbonate (Nutricost, UT, USA) (Grgic et al., 2021). The L-CIT+Sb supplement consisted of 6 g of L-citrulline combined with an additional 0.3 g per kg of body weight of sodium bicarbonate. The PL was composed of 6 g of maltodextrin. The participants were instructed to consume either the supplement or placebo in equal dosage four times daily including 09:00 AM, 01:00 PM, 05:00 PM, and 09:00 PM in a 330 cc of water to minimize potential gastrointestinal side effects. The PL was visually and taste-wise identical to the supplement, and it was provided in the same form. All the supplements were unidentifiable in appearance and taste, which was determined after a pilot study taste test and were produced in the capsule. The participants were instructed to return all packets at the end of each week, whether used or unused.

Diet control

Participants were instructed to report their dietary consumption for the three days leading up to the start of the study and also before post-testing. The information collected was then analyzed through the Nutritionist IV diet analysis software to clarify the total consumption of calories, protein, carbohydrates, and fats (Table 1).

Training intervention

The basketball players engaged in a comprehensive training program that focused on technical and tactical skills, small-sided games and comparative basketball practice 3 days a week for a duration of 90 to 120 minutes. In addition, the players in training groups performed SSIT which consisted of 3 sets of 10 repetitions of 5-second all-out running-based sprints with a 15-second active recovery period (1:3 ratio) between trials, and a 3-minute rest interval between sets (Laursen and Buchheit, 2019; Xu et al., 2024) on Tuesday, Thursday and Saturday. Before the initiation of training sessions, the participants completed a 15-minute standard warm-up including 5 minutes of running, 5 minutes of stretching and ballistic movements and also 5 minutes of short sprint trials. Additionally, after completing each training session, a 10-minute cool-down including light running and stretching movements was employed. All training sessions were conducted under the careful supervision of a Specialized Strength and Conditioning Coach and a researcher, ensuring that the execution was performed correctly while maintaining a coach-to-player ratio of 1:5.

Statistical analysis

The mean ± SD was used to present the data. The Shapiro-Wilk Normality test was conducted to analyze the normality of distribution. A 5 [group] × 2 [time] repeated-measures ANOVA was performed to determine significant differences between the groups for each variable tested. When a significant F value was achieved, a Bonferroni post hoc procedure was employed to identify the pairwise differences between the means with aiming to control Type 1 error. Hedges' g was used to calculate effect sizes (ES), which were categorized as trivial (< 0.20), small (0.20 - 0.60), moderate (0.60 - 1.20), large (1.20 - 2.0), or very large (> 2.0). The 95% confidence interval (CI) was reported as well (Hopkins et al., 2009). The significance level was set at 0.05.

Results

All participants exhibited full compliance during the entire study period, leading to an exceptional accomplishment of achieving a 100% success rate. Additionally, there were no documented cases of injuries related to the training and testing interventions, nor were there any gastrointestinal issues following the supplementation phase. The CON group showed trivial changes in all variables, while all training groups demonstrated statistically significant differences in comparison to the CON group after the intervention ($p < 0.05$).

All training groups (L-CIT, Sb, L-CIT+Sb, and PL) demonstrated significant improvements in the CMVJ (Figure 1, A), 20-m linear sprint (Figure 1, B) and Illinois COD speed (Figure 1, C) following the 4-week intervention, with ES ranging from small to large. There was a significant group by time interaction in the CMVJ ($F = 30.1$, $p = 0.001$, Moderate ES [L-CIT = 0.94, Sb = 0.72, L-CIT+Sb = 0.95] vs. Small ES [PL = 0.51]), 20-m linear sprint ($F = 11.9$, $p = 0.001$, Moderate ES [L-CIT = -0.75, Sb = -1.02, L-CIT+Sb = -0.99] vs. Small ES [PL = -0.48]) and Illinois COD speed ($F = 18.5$, $p = 0.001$, Large ES [L-CIT = -1.49, Sb = -1.32, L-CIT+Sb = -1.21] vs. Small ES [PL = -0.49]), indicating more adaptations for the supplement groups than the PL group.

Table 1. Dietary intake (mean ± SD).

Groups		Variables			
		Energy intake (kcal.d^{-1})	Carbohydrate (g.d^{-1}, 60%)	Fat (g.d^{-1}, 25%)	Protein (g.d^{-1}, 15%)
L-CIT	Pre	2770 ± 175	415 ± 32	77 ± 17	103 ± 14
	Post	2815 ± 182	422 ± 28	78 ± 20	105 ± 18
Sb	Pre	2820 ± 166	423 ± 35	78 ± 21	106 ± 17
	Post	2845 ± 201	427 ± 42	79 ± 22	107 ± 19
L-CIT+Sb	Pre	2795 ± 182	419 ± 29	77 ± 22	105 ± 16
	Post	2850 ± 196	427 ± 33	79 ± 23	107 ± 20
PL	Pre	2805 ± 179	421 ± 36	78 ± 25	105 ± 13
	Post	2850 ± 205	428 ± 39	79 ± 24	108 ± 17
CON	Pre	2745 ± 166	411 ± 23	76 ± 19	103 ± 15
	Post	2758 ± 172	413 ± 26	77 ± 21	103 ± 16

L-CIT: L-Citrulline, Sb: sodium bicarbonate, L-CIT+Sb: combined, PL: plasebo, CON: control.

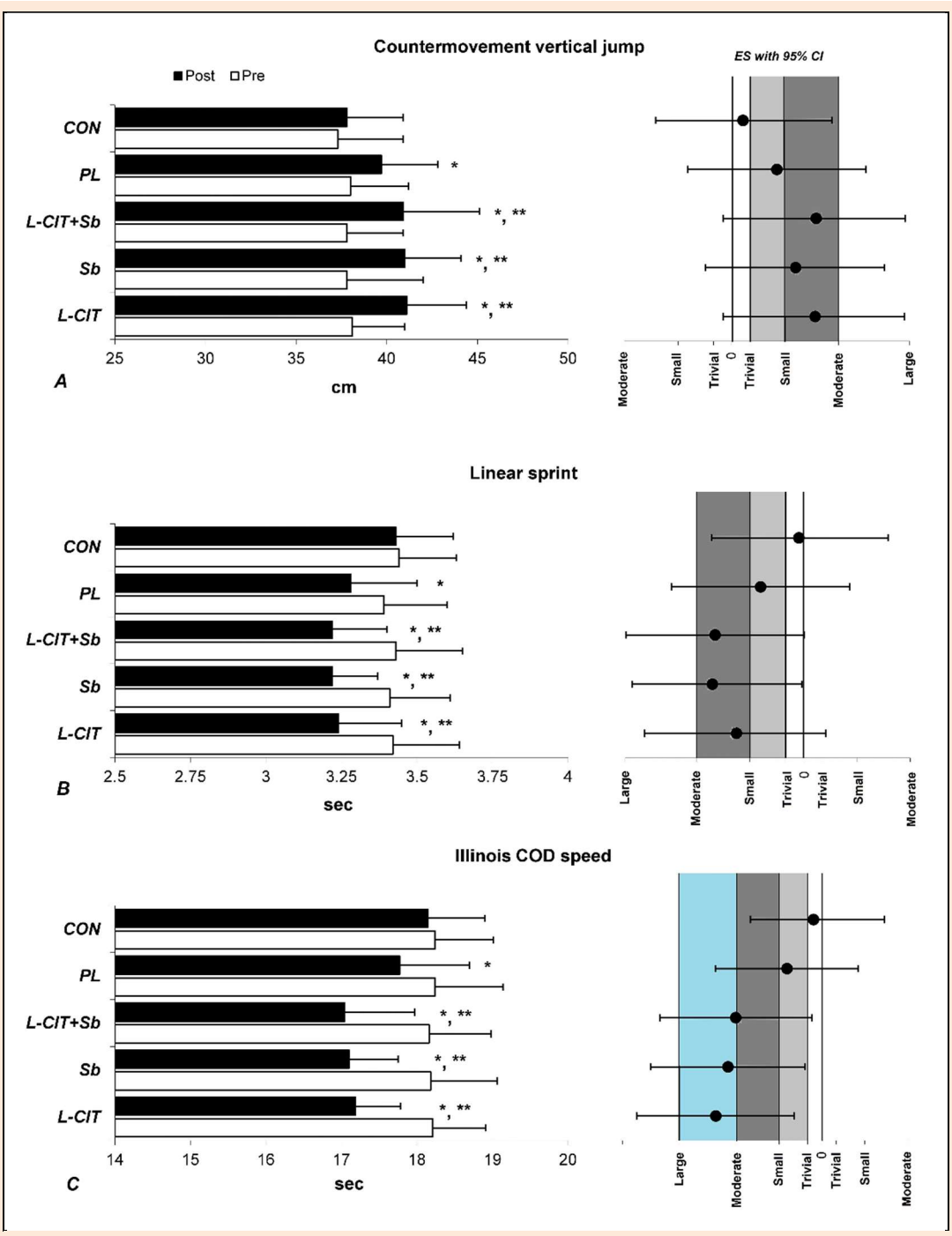

Figure 1. Changes in countermovement vertical jump (A), sprint (B) and Illinois COD speed (C) from pre- to post-intervention (mean ± SD) and ES with 95% of CI for the L-Citrulline (L-CIT), sodium bicarbonate (Sb), combined (L-CIT+Sb), placebo (PL) and control (CON) groups. *Significant differences compared with pre and CON ($p < 0.05$), **significant differences compared with PL ($p < 0.05$).

All training groups (L-CIT, Sb, L-CIT + Sb, and PL) demonstrated significant improvements in the peak power (Figure 2, A), mean power (Figure 2, B) and VO_{2max} (Figure 2, C) following the 4-week intervention, with ES ranging from small to large. There was a significant group by time interaction in the peak power ($F = 30.5$, $p = 0.001$, Large ES [L-CIT = 1.64, Sb = 1.39, L-CIT+Sb = 1.91] vs. Moderate ES [PL = 1.17]), and mean power ($F = 36.2$, $p = 0.001$, Moderate ES [L-CIT = 0.77, Sb = 0.75, L-CIT+Sb = 0.93] vs. Small ES [PL = 0.54]), indicating more adaptations for the supplement groups than the PL group, while in the VO_{2max} all groups indicated similar training effects (Moderate ES [L-CIT = 0.71, Sb = 0.81, L-CIT+Sb = 0.97, PL = 0.65]).

The finding revealed no significant ($p > 0.05$) main effect of time, group, or group by time interaction in testosterone levels, which suggests that neither SSIT nor L-CIT and Sb supplementation had any impact on the changes in resting testosterone levels (Figure 3, A). All supplement groups showed significant reductions in the cortisol levels (Figure 3, B), while the PL group indicated increases in the serum cortisol level after the training

period. There was a significant group by time interaction (F = 18.4, p = 0.001, Small decrease vs. Small increase), indicating lower cortisol levels for the supplement groups than the PL group after the 4-week intervention [ES: L-CIT = -0.27, Sb = -0.24, L-CIT+Sb = -0.33, vs. PL = 0.21].

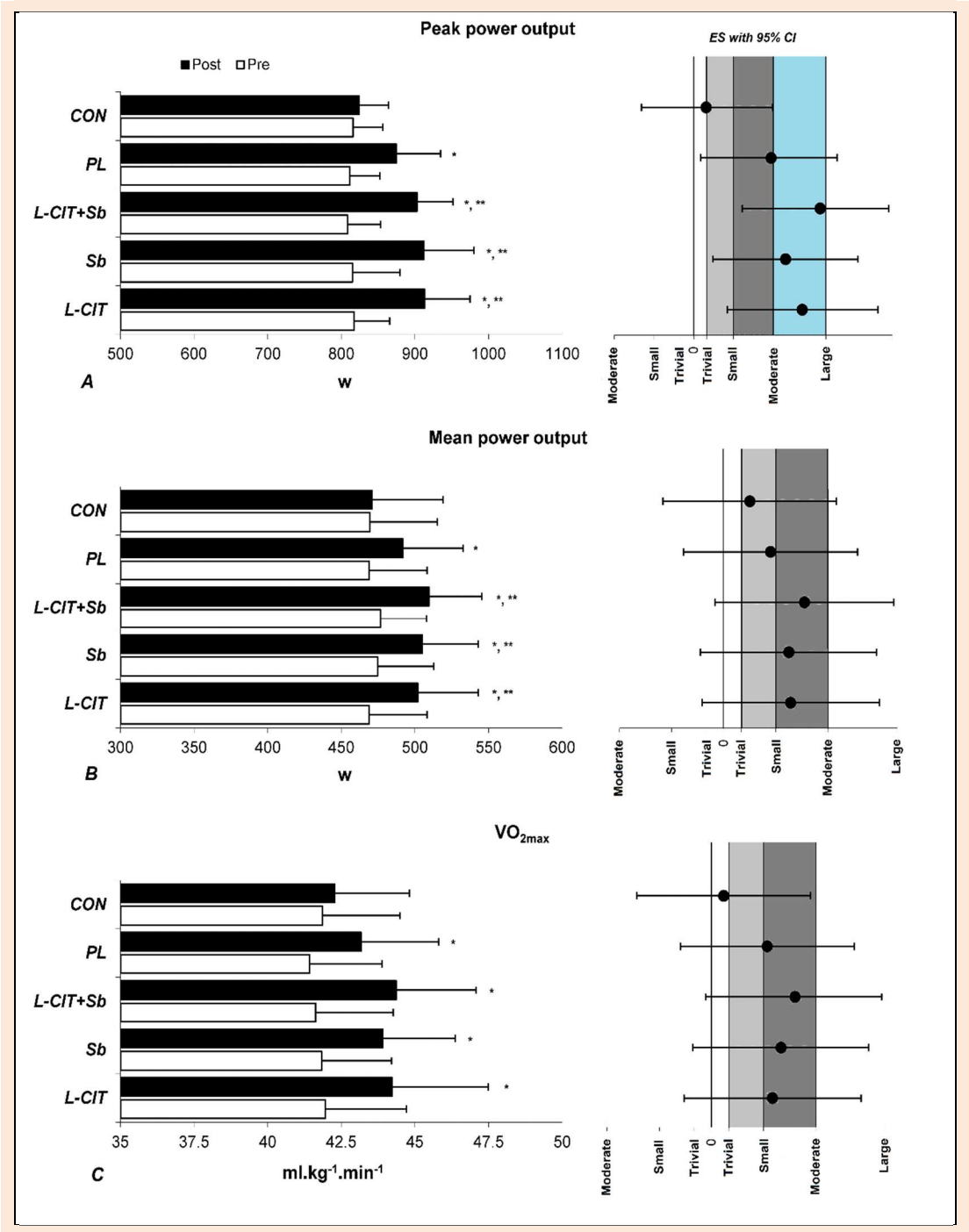

Figure 2. Changes in peak power output (A), mean power output (B) and VO_{2max} (C) from pre- to post-intervention (mean ± SD) and ES with 95% of CI for the L-Citrulline (L-CIT), sodium bicarbonate (Sb), combined (L-CIT+Sb), placebo (PL) and control (CON) groups. *Significant differences compared with pre and CON ($p < 0.05$), **significant differences compared with PL ($p < 0.05$).

Discussion

This investigation is the first to explore the effects of short-term supplementation with L-CIT and Sb alongside SSIT on the physical performance and hormonal responses of male basketball players. The results indicated that SSIT significantly improves physical performance of basketball players, and those who supplemented with L-CIT, Sb, or both showed greater improvements than those in the PL group. This finding highlights the effectiveness of L-CIT, Sb, or their combination in maximizing physical performance adaptations, with the exception of VO_{2max}, over a 4-week period. Importantly, the basketball players who took L-CIT, Sb, or both reported no gastrointestinal problems

during the supplementation phase, which underscores the effectiveness of the capsule forms of supplements on enhancing physical performance while avoiding gastrointestinal issues.

The findings of this study indicate that all training groups found significant improvements in the CMVJ, 20-m linear sprint, and Illinois COD speed after the 4-week SSIT intervention. These results are consistent with earlier research that highlighted the beneficial effects of SSIT on enhancing CMVJ, 20-m sprint, and COD abilities among basketball players (Arslan et al., 2022; Delextrat and Martinez, 2014; Fang and Jiang, 2024). In contrast, the CON group did not demonstrate any significant changes in these performance indicators, highlighting that conventional basketball training alone is inadequate for enhancing these parameters; therefore, involvement in a targeted training program is necessary. The observed improvements in these variables can be attributed to the superior mechanical properties of the muscle-tendon system, specifically the enhancement of muscle viscoelasticity that facilitates the storage of mechanical energy and the effective transmission of substantial muscular forces to the skeletal structure (Kubo et al., 2022). Additionally, better coordination among muscles, particularly the synchronization of agonist and antagonist muscles, along with a heightened firing rate of alpha motor neurons during interval training sessions, contribute to these enhancements (Laursen and Buchheit, 2019). Furthermore, the interval training approach employed in this research (i.e., SSIT) necessitated swift changes in muscle actions, particularly in muscles characterized by lower ground contact and fast-twitch fibers, resulting in adaptations within the neuromuscular systems (Kunz et al., 2019; Song and Deng, 2023) and subsequent improvements in CMVJ, 20-m linear sprint, and Illinois COD speed.

Our research findings revealed that a 4-week supplementation regimen involving L-CIT, Sb, or both led to significantly greater enhancements in the CMVJ, 20-m linear sprint, and Illinois COD speed than those observed in the PL group. This emphasizes the superior benefits of these supplements in conjunction with SSIT compared to SSIT alone during the short-term period. The results corroborate previous experimental and review studies that have shown the beneficial effects of L-CIT and Sb supplementation on the physical performance of both athletes and non-athletes (Ducker et al., 2013; Kang et al., 2022; Grgic et al., 2021; Papadia et al., 2018; Gonzalez and Trexler, 2020).

Engaging in sprint training with maximal intensity, known as SSIT, is associated with an increase in metabolites such as blood lactate and H^+ (Montgomery et al., 2008; Conte et al., 2023) and it seems that the supplementation of L-CIT and Sb appears to have significant effects in mitigating these responses and enhancing physical performance. On the other hand, the implementation of SSIT as a training modality for athletes requires a high degree of in arousal levels and a notable increase in the firing frequency of muscle fibers (Boullosa et al., 2022).

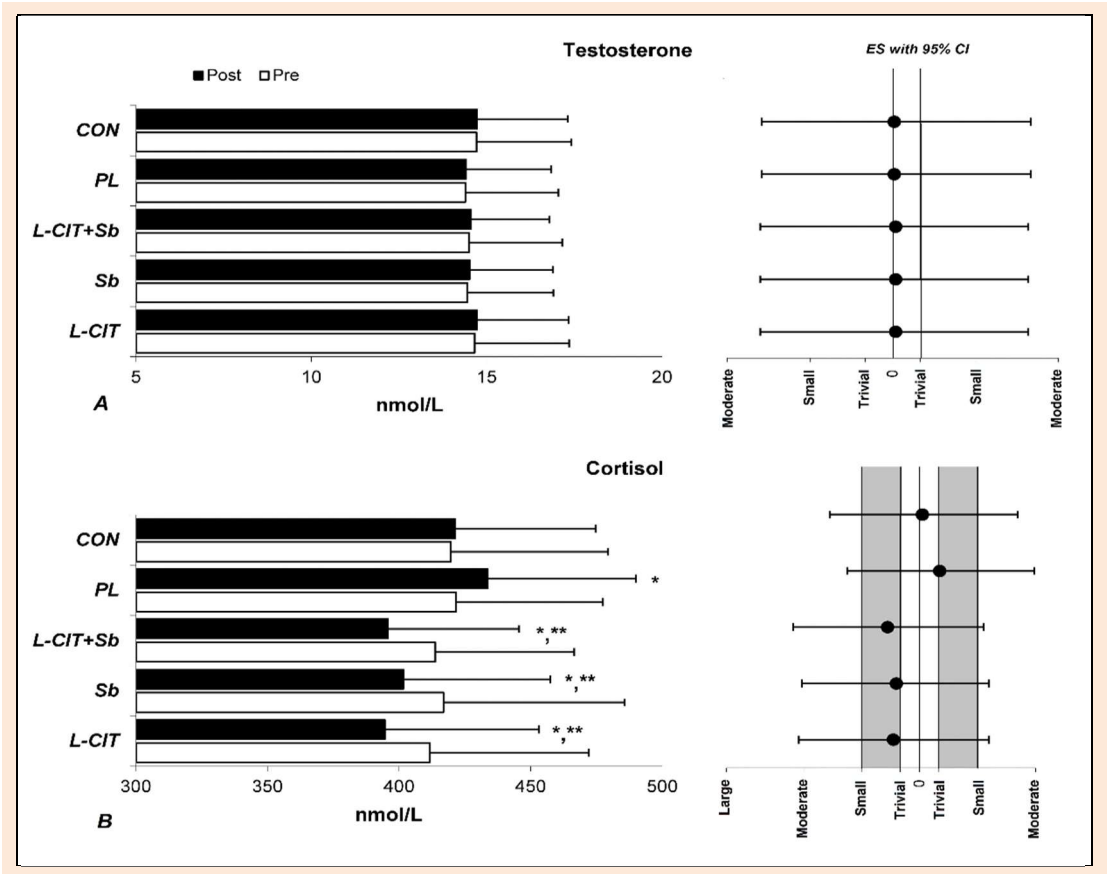

Figure 3. Changes in resting serum testosterone (A), and cortisol (B) levels from pre- to post-intervention (mean ± SD) and ES with 95% of CI for the L-Citrulline (L-CIT), sodium bicarbonate (Sb), combined (L-CIT+Sb), placebo (PL) and control (CON) groups. *Significant differences compared with pre and CON ($p < 0.05$), **significant differences compared with PL ($p < 0.05$).

Additionally, there should be enhanced activation of fast-twitch muscle fibers (Laursen and Buchheit, 2019). These fibers primarily utilize anaerobic glycolysis for energy, which results in a higher accumulation of lactic acid and a decrease in intracellular pH due to the release of H+, ultimately contributing to muscle peripheral fatigue (Usher-Smith et al., 2006). The supplementation with L-CIT, Sb, and their combination has demonstrated significant effects in managing these responses by enhancing the muscle oxygenation and speeds up VO_2 kinetics (i.e., deliver of oxygen to contracting muscles) (de Oliveira et al., 2022) and buffering capacity via an increase in bicarbonate concentration, leading to more work per cross-sectional area of the muscle fibers and enhanced rate of force development (Grgic et al., 2021; Gonzalez and Trexler, 2020), resulting in greater adaptive responses in the CMVJ, 20-m linear sprint, and COD performance in basketball players. Overall, the administration of 6 g of L-CIT per day and 0.3 g per kg of body weight of Sb, as well as their combined use in capsule form, demonstrates comparable ergogenic effects that facilitate physiological adaptations and improve performance in basketball players during a short-term period. Our findings suggest that these supplementation dosages effectively promote adaptations in basketball players; however, the mechanisms behind these changes remain ambiguous and speculative. Additional research is required to clarify the physiological adaptations induced by L-CIT and Sb that lead to greater improvements than a PL in CMVJ, 20-m sprint, and Illinois COD speed among young basketball athletes.

The results indicated that all training groups improved both peak and mean power output, as well as VO_{2max}, throughout the 4-week training duration. Furthermore, the groups receiving supplements (i.e., L-CIT, Sb, and L-CIT+Sb) exhibited greater improvements in peak and mean power compared to the PL group. However, all training groups demonstrated similar adaptations in VO_{2max} after the 4-week period. These results are in accordance with previous studies that have reported enhancements in the aerobic and anaerobic capacities of basketball players following interval training (Arslan et al., 2022; Buckinx et al., 2018; Song and Deng, 2023), especially SSIT (Fang and Jiang, 2024; Xu et al., 2024). This suggests that short-term SSIT may facilitate enhanced adaptations in anaerobic power performance through various mechanisms related to power, such as improved rate of force development and increased muscle fiber recruitment during SSIT (Laursen and Buchheit, 2019).

In this study, players who received supplementation with L-CIT, Sb, or a combination of L-CIT and Sb during short-term SSIT exhibited significantly large ES in peak power and moderate ES in mean power, surpassing those in the PL group, which demonstrated small ES. Additionally, the observed enhancements in anaerobic power (i.e., peak and mean power output) attributed to the supplementation of L-CIT and Sb, can be explained by an increase in bicarbonate levels and the effective clearance of lactic acid during SSIT (Gurton et al., 2024; Hadzic et al., 2019; Forbes and Sheykhlouvand, 2016; Ning and Sheykhlouvand, 2025). Participation in SSIT requires a higher recruitment of muscle fibers (Boullosa et al., 2022), and the subsequent rise in blood lactate can negatively influence the contractile capabilities of these fibers (Ducker et al., 2013; Laursen and Buchheit, 2019). The supplementation of L-CIT and Sb may counteract these adverse effects, allowing muscles to exert greater force during SSIT, which leads to improvements in both peak and mean power output. Additionally, alleviating acidosis in muscle fibers by L-CIT and Sb supplementation (Grgic et al., 2021; Gonzalez and Trexler, 2020) may enhance calcium sensitivity (i.e., concentration of free calcium ions available for muscle fibers to generate force), thereby improving contractile properties and enabling each muscle fiber to perform more work, ultimately resulting in increased power outputs (Smith et al., 2023).

In terms of cardiorespiratory fitness (VO_{2max}), no differences were detected among the training groups, and all of them indicated moderate ES. The observed increase in cardiorespiratory fitness following SSIT can be linked to improvements in both central (oxygen delivery) and peripheral (oxygen extraction and utilization by active muscles) components of aerobic fitness (Gharaat et al., 2024; Laursen and Buchheit, 2019). Moreover, previous research has indicated that the improvement in aerobic fitness following the implementation of SSIT may be attributed to various factors, including increases in oxygen pulse ($\dot{V}O_2$/HR), maximal ventilation, tidal volume, respiratory frequency, and cardiac output (Yang et al., 2024; Zhao and Lu, 2024). Additionally, participation in SSIT is linked to enhancements in mitochondrial biogenesis (i.e., increases the number of mitochondria) (MacInnis and Gibala, 2017), which may contribute to an increase in aerobic capacity. However, these assertions remain speculative in light of earlier studies that demonstrated a positive impact of SSIT on the aerobic fitness of athletes, necessitating further research to elucidate the specific adaptations resulting from SSIT. In the present investigation, supplementation did not facilitate further adaptations in VO_{2max}; therefore, a longer supplementation period may be necessary to elicit significant enhancements in aerobic capacity.

The findings of the current study revealed that neither SSIT nor L-CIT, Sb, nor the combination of L-CIT and Sb supplementation had any effect on resting testosterone levels. In contrast, the PL group exhibited an increase in cortisol levels, whereas the supplementation groups experienced notable reductions following the 4-week intervention. In fact, supplementation with L-CIT, Sb, or L-CIT+Sb not only maintained testosterone levels but also led to a reduction in cortisol levels over the 4-week period, thereby reinforcing the anti-catabolic properties of these supplements during training. The lack of change in testosterone levels may be attributed to various nutritional, physiological, psychological, environmental, and lifestyle factors that influence testosterone responses to training (Zurek et al., 2022). Our findings align with prior research indicating that neither SSIT nor supplementation with L-CIT and Sb has any effect on resting testosterone levels (Peart et al., 2013; Zurek et al., 2022; Caballero-García et al., 2021). Furthermore, it has been observed that engaging in SSIT is associated with an increase in cortisol levels (Hadzic et al., 2019), as this form of exercise necessitates maximal effort (Boullosa et al., 2022), potentially leading

to heightened inflammation and muscle damage (Leite et al., 2023). Conversely, the supplementation of L-CIT and Sb appears to play a significant role in exerting anti-catabolic effects, which may contribute to a decrease in inflammation and muscle damage (Gurton et al., 2024; Kang et al., 2022), as well as facilitate the clearance of metabolites, thereby resulting in lower resting cortisol levels in the supplemented groups (Abbaszadeh et al., 2021). Nevertheless, these assertions remain speculative based on prior studies, and further research is required to elucidate the physiological adaptations that occur when cortisol levels are reduced through L-CIT and Sb supplementation.

Limitation

The current study has several limitations that warrant acknowledgment. The primary limitation is the small sample size, which presents interesting possibilities for future research. However, the G*power was used to determine the study's optimal sample size. The findings of this study are particularly applicable to trained male basketball players, and additional research is needed to assess the generalizability of these results to female athletes across different age groups and fitness levels. Furthermore, the lack of laboratory measurements regarding changes in blood pH, lactate levels, and neuromuscular adaptations (such as EMG) restricts the study's capacity to evaluate the metabolic conditioning and muscular adaptations in basketball players' anaerobic and aerobic capabilities, as well as their physical performance. Consequently, the ergogenic effects of L-CIT and Sb supplementation on physical performance during SSIT is not completely clear and the discussion remains speculative, necessitating further investigation into this important issue. It is crucial to note that the L-CIT supplementation was administered in absolute dosages, as suggested by prior research to enhance performance. However, to address this perspective, future studies may consider incorporating relative L-CIT dosages. It is important to mention that this aspect was not previously established, and only Sb is currently recommended to be utilized in relative dosages for maximizing performance improvements in athletes.

Conclusion

The findings of our study suggest that a short-term (i.e., 4 weeks) application of SSIT is an effective training modality in improving the CMVJ, 20-m linear sprint, Illinois COD speed, peak and mean power output as well as VO_{2max} of basketball players. The results demonstrated that when players ingested L-CIT, Sb, or a combination of both, the adaptive response in the physical performance to SSIT was significantly enhanced compared to the PL group (except VO_{2max}) with significant reduction of resting cortisol level, throughout the 4-week training duration. Notably, the combination of L-CIT and Sb did not yield additional adaptations beyond those achieved with either supplement alone, indicating that for a short-term SSIT regimen, either L-CIT or Sb is sufficient. In light of these findings, it is suggested that basketball players can benefit from the incorporation of L-CIT, Sb, or both to enhance their CMVJ, 20-m sprint performance, and Illinois COD speed, as well as to increase anaerobic power output while effectively reducing cortisol levels during a 4-week training period compared with the PL condition.

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The experiments comply with the current laws of the country where they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who organized the study.

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Key points

- Engaging in SSIT is a suitable training approach in a short-duration period to enhance physical performance adaptive responses in basketball players.
- Supplementation with L-CIT, Sb, or a combination of both could induce meaningful effects in physical performance gains and reduction of cortisol levels compared to the PL group.
- No further effects were observed when L-CIT and Sb are combined together for adaptations in physical performance and hormonal levels.

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