



STUDIES IN HUMANS



Beetroot juice or creatine: which yields greater short-term benefits for resistance training capacity, performance and key physiological responses?

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ABSTRACT

This randomized controlled crossover trial compared the short-term effects of creatine (CR) and beetroot juice (BJ) on resistance training performance and physiological responses across ~72 h supplementation period. Eleven novice resistance-trained men completed bench press (BP) and back squat (BS) sets at 60–80% 1RM under CR, BJ, and placebo (PLA) conditions. Performance outcomes, intramuscular-oxygen-saturation (SmO_2), peak heart rate (HR), and heart rate variability (HRV) were assessed. Individual modulation prevalence was also determined. CR significantly improved repetition performance at 80% 1RM in BP ($d = 1.33$) compared to PLA. Both CR and BJ produced moderate-to-very large effects on velocity with superior effect using BJ ($d = 1.40$ – 2.82 vs. PLA). Higher SmO_2 ($d = 1.74$ – 2.9), lower peak HR ($d = 0.83$ – 2.74), and more favourable autonomic recovery (e.g. RMSSD: $d = 0.91$ – 2.99) were observed with BJ compared to both PLA and CR. Modulation analysis indicated greater proportions of meaningful individual adaptations, following BJ compared to CR. Overall, CR appeared to preferentially enhance mechanical performance, whereas BJ seemed to provide broader cardiometabolic and autonomic benefits.

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Introduction

Resistance training (RT) is a central component of athletic preparation and general health promotion, leading to improvements in maximal strength, power, and muscular endurance, as well as favourable adaptations in bone mass, metabolic health, and cardiovascular and neuromuscular functions (Hagerman et al. 2000; Strasser and Schobersberger 2011; Martinez et al. 2021). To sustain long-term adaptations, training

programs typically apply progressive overload by systematically increasing mechanical load, volume, or neuromuscular demand across sessions (Seguin and Nelson 2003). However, as training intensity and cumulative stress increase, athletes and physically active individuals are exposed to substantial metabolic, neuromuscular and cardiovascular strain, which can transiently impair performance and compromise recovery if not adequately managed (Buchheit et al. 2007; 2010; Gobbo et al. 2024). This has led athletes

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and practitioners to adopt nutritional ergogenic aids to sustain resistance exercise performance during demanding training periods and to enhance post-exercise recovery. Among these, creatine (CR) and beetroot juice (BJ) are two of the most extensively studied supplements, yet they act through distinct physiological mechanisms.

CR is considered particularly effective in high-intensity, short-duration exercise, especially RT, due to its role in augmenting phosphocreatine (PCr) stores, which serve as an immediate substrate for ATP resynthesis *via* the creatine kinase reaction during brief, intense muscular contractions (Francaux et al. 2000; Kreider et al. 2017). Numerous trials have shown that CR can improve maximal strength, repetition volume, and power output in multi-joint RT exercises such as bench press and squat (Earnest et al. 1995; Rossiter et al. 1996; Volek et al. 1997; Rawson and Volek 2003). CR may also modulate recovery by attenuating metabolic acidosis, reducing blood lactate accumulation, and influencing inflammatory responses and muscle soreness after strenuous exercise (Santos et al. 2004; Sahlin 2014; Candow et al. 2019). Despite extensive research on chronic CR supplementation, fewer studies have examined short-term CR protocols using an integrated approach combining performance, autonomic, and oxygenation measures (Kreider et al. 2017; Candow et al. 2019; Ribeiro et al. 2021).

In parallel, BJ is a rich source of inorganic nitrate (NO_3^-), which is sequentially reduced to nitrite (NO_2^-) and nitric oxide (NO) *via* the nitrate–nitrite–NO pathway, thereby increasing NO bioavailability (Lundberg et al. 2008; Bailey et al. 2009; Domínguez et al. 2017; Mueller et al. 2024). NO promotes vasodilation and endothelial function, resulting in enhanced blood flow, oxygen delivery, and mitochondrial efficiency, while reducing the oxygen cost of muscle contractions (Bailey et al. 2010; Ferguson et al. 2013; Fulford et al. 2013; Gao et al. 2021; Olas 2024). Beyond nitrate, beetroot contains betalains and other bioactive compounds with antioxidant and anti-inflammatory properties, which may contribute to attenuating exercise-induced muscle damage, oxidative stress, and delayed recovery (Chen et al. 2021; Daab et al. 2021; Varshney and Mishra 2022; Martinez et al. 2024). Recent meta-analyses have reported that repeated BJ supplementation may reduce post-exercise soreness, improve recovery kinetics, and preserve neuromuscular function following strenuous training (Jones et al. 2022; Rojano-Ortega et al. 2022). In the RT context, several acute studies have indicated improvements in repetition volume, peak power, and movement velocity during bench press and squat exercises (Mosher et al.

2016; Ranchal-Sánchez et al. 2020; Williams et al. 2020; Rodríguez-Fernández et al. 2021; Tan et al. 2023). These outcomes have been mechanistically linked to enhanced oxygen utilisation, improved contractile efficiency, and support of type II muscle fibre function (Bailey et al. 2010; Flanagan et al. 2016; Garnacho-Castaño et al. 2022; Ferguson et al. 2013). However, most existing RT studies have mainly examined single acute BJ doses, whereas evidence on short-term (multi-day) supplementation protocols that reflect practical use during intensive training microcycles remains limited (Domínguez et al. 2017; Głowacz et al. 2025). Additionally, although BJ-related improvements in repetition performance and fatigue resistance have been reported, studies integrating internal physiological markers—such as heart rate variability (HRV), reflecting autonomic modulation and recovery status (Buchheit et al. 2007; Dong 2016; Lechner et al. 2023; Ammar et al. 2024b), and near-infrared spectroscopy (NIRS)-derived muscle oxygen saturation (SmO_2), reflecting local oxygen extraction and microvascular adjustments (Garnacho-Castaño et al. 2022; Fulford et al. 2013)—to assess autonomic recovery and local muscle oxygenation remain scarce (Jurado-Castro et al. 2022; Salem et al. 2025b).

Recent work from our group indicated that acute ingestion of BJ and CR may elicit distinct cardiovascular and oxygenation responses during RT (Salem et al. 2025a). In separate short-term supplementation protocols, BJ enhanced high-load repetition performance, SmO_2 , and neuromuscular recovery (Salem et al. 2025b), while CR mainly improved buffering and metabolic efficiency (Salem et al. 2025c).

Beyond group mean responses, athletes often display heterogeneous physiological and performance adaptations to supplementation, reflecting variability in metabolic flexibility, autonomic responsiveness, oxygenation kinetics, and neuromuscular fatigue-resistance profiles (Hecksteden et al. 2015). Such interindividual variation is particularly relevant in resistance training, where movement characteristics, muscle activation strategies, and physiological responses exhibit marked individual specificity (Ammar et al. 2024a, 2024b, 2025). Therefore, in addition to analysing average effects, it is valuable to determine whether supplementation meaningfully modulates individual physiological responses beyond natural variability thresholds. Examining modulation prevalence (i.e. the proportion of individuals showing positive, neutral, or negative changes relative to placebo) can provide deeper insight into supplement responsiveness, practical applicability, and ecological effectiveness.

Despite this evidence, direct comparisons of the short-term effects of BJ and CR within the same participants and using an integrated physiological and performance framework remain limited in resistance-training contexts. Existing comparisons are limited to acute single-session protocols (Salem et al. 2025a) or examine each supplement separately versus placebo (Tomcik et al. 2018; Jurado-Castro et al. 2022; Negro et al. 2022; Tan et al. 2023; Salem et al. 2025b, 2025c). Moreover, the vast majority of existing studies, including our own earlier work, have primarily relied on mean-based group-level analyses, with little attention given to responder prevalence and individual modulation patterns. Given that BJ primarily targets nitric oxide-mediated vascular and mitochondrial pathways, whereas CR predominantly enhances phosphagen-dependent ATP turnover and metabolic buffering, a direct comparison may reveal distinct short-term response patterns across performance, physiological, and autonomic domains, as well as individual responsiveness.

Accordingly, the present study aimed to compare the short-term effects of BJ and CR supplementation on resistance exercise performance, muscle oxygenation, cardiovascular strain, and autonomic regulation, while also examining individual response patterns beyond conventional group-level analyses. We hypothesised that both BJ and CR would enhance RT performance compared to PLA, while BJ would produce larger improvements in muscle oxygenation, and autonomic/cardiovascular indices.

Methods

Study design and experimental protocol

This study is a pre-planned secondary analysis of a randomised, double-blind, placebo-controlled, three-condition crossover trial originally designed to

examine the acute and short-term effects of BJ, CR, and a nitrate/creatine-free PLA on RT performance, autonomic regulation, and muscle oxygenation (Figure 1).

Each supplementation condition spanned four days and incorporated two identical resistance-training (RT) sessions, designed to reflect a typical real-world recovery interval between training sessions. The short-term loading phase corresponded to the ~72 h period between RT-session 1 and RT-session 2, both conducted at the same time of day. On Day 1, participants ingested the assigned supplement 2 h before RT-session 1. During the subsequent ~72 h interval (Days 2–3), supplementation was continued according to the protocol detailed below. On Day 4, participants returned approximately 72 h after RT-session 1 and again consumed the assigned supplement 2 h before RT-session 2. Acute responses observed during RT-session 1 following BJ and CR ingestion have been reported previously (Salem et al. 2025a) and are not the primary focus of the present manuscript. The present work focuses on the short-term effects, operationalised as the physiological and performance responses recorded during RT-session 2, following ~72 h of supplementation between sessions. In summary, RT-session 1 was used previously to examine acute effects, whereas the present analyses focus on RT-session 2, reflecting responses after ~72 h of supplementation (short-term loading phase). As argued by Salem et al. (2025b, 2025c), a 7-day washout period was implemented between conditions. A familiarisation session was conducted one week before the first experimental day. During this visit, body composition was assessed using bioelectrical impedance analysis (Tanita MC-780MA, Japan), and participants completed a standardised familiarisation protocol to ensure correct lifting technique for the back squat (BS) and bench press (BP). One-repetition maximum (1RM) for both exercises was determined during this session

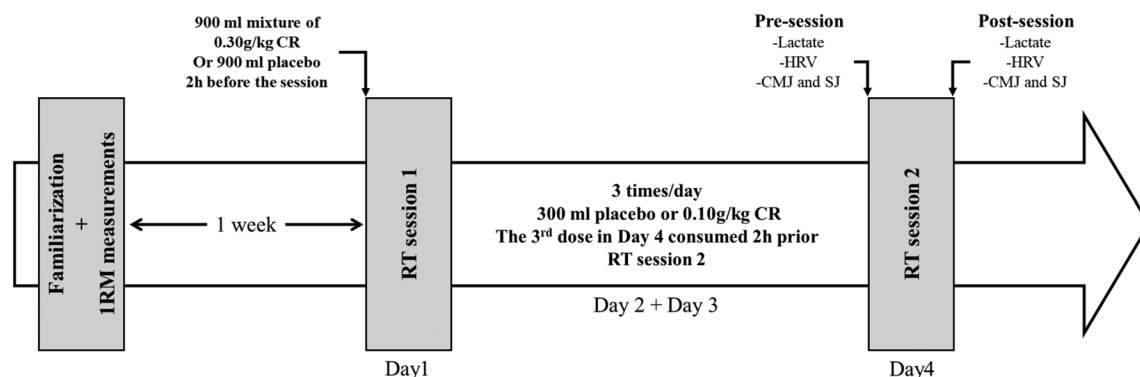


Figure 1. Study design highlighting the analysed outcomes in the present study.

while adhering to the American Society of Exercise Physiologists (ASEP) guidelines for muscular strength assessment (Brown and Weir 2001), and using the following procedure: five repetitions at 50% of the estimated 1RM, three repetitions at 70%, followed by up to five incremental 1RM attempts, with 3-minute rest intervals between attempts (Salem et al. 2025a, 2025b, 2025c). Movement velocity was monitored throughout (Conceição et al. 2016; González-Badillo and Sánchez-Medina 2010) using a linear position tracking system (Salem et al. 2025a, 2025b, 2025c) to confirm maximal effort and ensure that final 1RM loads aligned with expected velocity thresholds. These 1RM values were subsequently used to calibrate the relative intensities (60%, 70%, and 80% of 1RM) for experimental testing.

Familiarisation and testing took place in the afternoon (± 0.5 h), under controlled environmental conditions ($24 \pm 1^\circ\text{C}$), to minimise circadian-related variability (Ammar et al. 2015). Afternoon testing was selected based on evidence showing more favourable neuromuscular performance, lower perceived exertion, and more stable physiological responses during this time of day (Ammar et al. 2015, 2017, 2018).

Performance outcomes included countermovement jump (CMJ), squat jump (SJ), and BS and BP repetition volume at 60%, 70%, and 80% of 1RM. Peak Heart rate was determined during each repetition set and muscle oxygen saturation (SmO_2) was continuously recorded using near-infrared spectroscopy. Heart rate variability (HRV) indices and blood lactate concentrations were collected immediately before and after testing sessions.

Participants

A total of 11 healthy novice resistance-trained men (age = 21.36 ± 1.8 years; BMI = $21.29 \pm 2.29 \text{ kg/m}^2$) were recruited if they had at least 6 weeks (median 12 weeks, range 6–24 weeks) of structured RT experience (≥ 3 sessions/week), and reported stable dietary, and sleep habits during the preceding three months. Based on previous BJ and CR supplementation trials (Salem et al. 2025a, 2025b, 2025c), a minimum of nine participants was estimated to provide $\geq 90\%$ statistical power to detect within-subject differences in performance variables. To account for potential attrition, eleven participants were recruited, completed all supplementation conditions and were included in the final analyses.

Exclusion criteria included smoking; medication or supplement use affecting muscle biology (e.g. creatine, nitrate, NSAIDs ≥ 60 days prior); current

cardiovascular, metabolic, renal, or neurological disorders; and musculoskeletal injury preventing safe exercise performance. Female participants were excluded due to potential confounding effects of menstrual-related hormonal fluctuations on HRV, neuromuscular performance, and supplementation responsiveness, combined with the logistical challenges of controlling menstrual cycle phases in a cross-over design.

To enhance standardisation and control for external influences, participants were instructed to abstain from strenuous physical activity for 48h before each testing session, maintain habitual diet and hydration, and avoid consumption of additional supplements. They were also advised to abstain from foods rich in nitrate (e.g. beetroot, celery, spinach), creatine-rich foods, alcohol, caffeine, stimulants, and products altering oral microbiota (e.g. antiseptic mouthwash, gum, sweets) for at least three days before testing. To preserve nitrate–nitrite conversion efficiency, participants avoided brushing their teeth on test mornings and refrained from antiseptic mouth rinses throughout the study. To reduce confounding metabolic influences, they fasted (except water) for two hours before each experimental session and maintained a minimum of eight hours of sleep the night before testing.

Dietary consistency was monitored through 24-hour dietary recalls verbally administered and recorded by a trained researcher before each session, with special attention to nitrate- and creatine-containing products. Compliance with all pre-testing guidelines was recorded using a structured checklist, verbally confirmed on arrival, and monitored across conditions.

All participants provided written informed consent prior to participation. The study adhered to the Declaration of Helsinki and was approved by the local Research Ethics Committee of High Institute of Sport and Physical Education of El Kef, El Kef, Tunisia (ISSEPK-0033/2024). The study was registered at the Pan African Clinical Trials Registry database on 15 May 2025 (PACTR202505827886996).

Supplementation protocols

Supplements were administered in three separate conditions: BJ, CR, PLA. Supplement kits were prepared by two independent researchers not involved in data collection. Each kit contained the assigned supplement, measuring scoops, preparation instructions, a shaker bottle with fluid gradations, and a compliance log. Researchers and participants remained blinded to supplement identity until all data were collected. Blinding efficacy was assessed at the final visit, where

participants guessed the supplement received in each condition and rated their confidence.

Beetroot juice (BJ) protocol

Participants consumed Bio beetroot powder (Beta vulgaris; GymBeam GmbH, Berlin, Germany) dissolved in a nitrate-free flavoured juice. The juice matched beetroot supplementation in colour, texture, and caloric profile, except for the absence of nitrate. The beetroot powder provided ~ 450 mg of nitrate (≈ 7.26 mmol NO_3^-) per 15 g serving, with content and purity verified by external laboratory analysis (CBS, University of Sfax, Tunisia) and complete nutrition facts provided elsewhere (Salem et al. 2025b). On Day 1 and Day 4, participants ingested the full 15 g dose mixed in 900 mL of juice 120 min before the RT sessions, consistent with peak nitrate-to-nitrite conversion kinetics (Govoni et al. 2008; Gallardo and Coggan 2019). On Days 2 and 3, participants consumed three evenly spaced servings of 5 g (each in 300 mL of juice). This dosing strategy has been shown to optimise plasma nitrate accumulation, enhance NO availability, and induce meaningful ergogenic effects over multi-day supplementation (Govoni et al. 2008; Domínguez et al. 2017; Gallardo and Coggan 2019). The overall dosing structure was designed to reflect a short-term loading strategy across the ~ 72 h interval between RT sessions, combining distributed supplementation on Days 2–3 with a standardised pre-exercise dose on the testing day.

Creatine (CR) protocol

Creatine monohydrate (GymBeam GmbH, Berlin, Germany) was provided in powdered form and mixed with the same nitrate-free placebo juice to ensure identical taste, colour, and appearance for blinding. Participants followed a short-term loading regimen of $0.3 \text{ g} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}$ for three days (total ≈ 20 – 25 g/day), a strategy validated to rapidly increase intramuscular phosphocreatine stores (Greenhaff et al. 1994; Buford et al. 2007). Using a loading approach comparable to that applied for BJ supplementation, creatine was administered according to a short-term dosing strategy spanning the ~ 72 h interval between RT sessions. On the first supplementation day, participants consumed the full daily dose in a single serving two hours before the RT session, consistent with established creatine absorption kinetics (Greenhaff et al. 1994). During the subsequent loading period (Days 2 and 3), the daily dosage was divided into three equal servings ($\sim 0.1 \text{ g} \cdot \text{kg}^{-1}$ per serving) administered at breakfast, lunch, and late afternoon to maintain creatine availability. On Day 4,

participants again ingested the full daily creatine dose 120 min before RT-session 2, thereby reflecting the combined effects of short-term loading and standardised pre-exercise supplementation under ecologically valid between-session condition. All doses were dissolved in shaker bottles with marked volumes to standardise preparation. This protocol aligns with established methods shown to enhance phosphocreatine resynthesis, reduce metabolic stress, and sustain repeated high-intensity resistance exercise performance (Rossiter et al. 1996; Rawson and Volek 2003).

Placebo (PLA) condition

The placebo consisted of nitrate-free flavoured juice identical to the BJ and CR supplements in taste, colour, caloric content, and carbohydrate composition, but without nitrate or creatine. Supplementation timing and dosing frequency matched those of the BJ and CR protocols to ensure equal expectancy and control for timing effects. Participants maintained a compliance log to track supplement intake, which was reviewed and confirmed verbally upon arrival at each testing session, with results indicated guess accuracy near chance (Salem et al. 2025b).

Resistance training sessions and conducted measurements

The RT protocol was identical across all supplementation conditions. Neuromuscular performance was first assessed using CMJ and SJ *via* the My Jump 2 app, following validated procedures used in previous BJ and CR investigations (Coswig et al. 2019). For SJ, participants maintained a 90° knee angle with hands on hips before executing a maximal vertical jump, while CMJ began from a standing position, also without arm swing. Three trials were allowed for each test, and the best performance was retained for analysis (Salem et al. 2025a, 2025b, 2025c). Participants then completed a standardised warm-up consisting of 10 min of low-intensity cycling followed by two familiarisation sets at 30% 1RM. Next, they performed an incremental RT protocol in both BS and BP, consisting of one set to concentric failure at 60%, 70%, and 80% of 1RM, with 3–5 min of rest between sets (Salem et al. 2025a, 2025b, 2025c). The BS was always completed prior to BP. Lifting tempo was standardised with a 2-second eccentric phase and a self-selected concentric phase.

BS and BP performance-related variables included the maximum number of repetitions completed at each relative intensity, along with mean and peak

concentric velocity (MV) and power (MP). These were recorded using the validated Vmax Pro® accelerometer-based linear position transducer, which demonstrates strong agreement with gold-standard motion capture systems ($R^2 = 0.935$ vs. Vicon; $R^2 = 0.968$ vs. T-Force) (Feuerbacher et al. 2023).

Muscle oxygenation was continuously monitored throughout each RT session using near-infrared spectroscopy (NIRS), a validated, non-invasive method to assess local oxygen delivery and utilisation (Boushel and Piantadosi 2000; Crum et al. 2017). A Moxy 3-Sensor Bundle (Fortiori Design LLC, USA) was placed over the right vastus lateralis following standardised anatomical landmarking procedures. Data were sampled at 1 Hz and analysed to derive mean muscle oxygen saturation (SmO_2) and total haemoglobin (tHb), reflecting microvascular oxygen availability and blood volume changes in real time.

HRV was assessed according to current guidelines (Vondrasek et al. 2023). Participants remained seated quietly for 5 min immediately before and after RT session, breathing spontaneously (no paced breathing), while HRV was continuously monitored using a Polar H10 sensor and Elite HRV software (Vondrasek et al. 2023). Time-domain measures included mean RR interval (MeanRR), root mean square of successive differences (RMSSD), and standard deviation of RR intervals (SDNN), while frequency-domain analysis quantified low-frequency (LF) and high-frequency (HF) components and LF/HF ratio. Peak heart rate (HR) during exercise was also recorded.

In addition to traditional group-level analyses, an individual response modulation approach was also incorporated to examine whether supplementation meaningfully altered key physiological responses (SmO_2 , peak HR, and RMSSD) compared to placebo, thereby providing insight into inter-individual variability in responsiveness.

Capillary blood lactate was sampled from the ear-lobe, after sterilisation with 70% ethanol, immediately pre-exercise, post-exercise, and 3 min after testing (Forsyth and Farrally 2000; Goodwin et al. 2007). The Lactate Pro 2 device (AKRAY Europe B.V., Netherlands) was used for analysis, following validated protocols demonstrating accuracy and reliability in RT research settings.

Statistical analysis

Descriptive statistics were presented as Mean $\pm$ standard deviation (SD). The normality of the data was checked using the Shapiro-Wilk test.

The primary statistical analyses were designed to examine the effects of supplementation condition (BJ, CR, PLA) and exercise intensity or time on performance and physiological outcomes. Specifically, differences between supplementation conditions (BJ vs. CR vs. PLA) and intensity (60% vs. 70% vs. 80%) for strength test performance, as well as differences between supplementation conditions and time (pre- vs. post-session) for heart rate variability (HRV) indices, lower-limb strength, and blood lactate, were analysed using two-way analyses of variance (ANOVA) when parametric assumptions were met.

When parametric assumptions were violated, non-parametric longitudinal analyses were conducted using the LD-F2 model, which provides ANOVA-type statistics for main effects (condition and intensity or time) and their interaction. Significant main or interaction effects were followed by post-hoc pairwise comparisons using t-tests or Wilcoxon tests, as appropriate, with Bonferroni adjustment applied to control for multiple comparisons.

Effect sizes were reported as partial eta-squared (η^2) for ANOVA and LD-F2 models and interpreted as small (0.01), moderate (0.06), or large (0.14) (Cohen 2013). Standardised mean differences (Cohen's d) were calculated for pairwise comparisons and interpreted using Hopkins' thresholds: trivial ($d \leq 0.20$), small ($0.20 < d \leq 0.60$), moderate ($0.60 < d \leq 1.20$), large ($1.20 < d \leq 2.0$), very large ($2.0 < d \leq 4.0$), and extremely large ($d > 4.0$). Statistical significance was set a priori at $p < 0.05$.

In addition to these primary, mean-based analyses, an exploratory modulation prevalence approach was applied to provide insight into individual physiological responses to supplementation. This analysis evaluated whether supplementation-induced changes relative to placebo exceeded normal measurement variability for selected key variables (muscle oxygen saturation [SmO_2], peak heart rate [HR], and RMSSD). For each participant, the absolute difference between BJ or CR and PLA was calculated, and changes exceeding $\pm 2 \times$ the standard measurement error (SME) were classified as positive, negative, or neutral modulation. SME values were derived from previously published reliability studies (SmO_2 : 1.89%, threshold $\pm 3.79\%$ (Crum et al. 2017); peak HR: 1.18 bpm, threshold ± 2.01 bpm (Coswig et al. 2020); RMSSD: 0.65 ms, threshold ± 1.3 ms (Shaffer and Ginsberg 2017)). This approach aligns with recommendations for identifying true individual responses beyond normal measurement error (Hopkins 2000; Atkinson and Batterham 2015; Ammar et al. 2021). The prevalence of positive modulators was compared between BJ and CR using chi-square (χ^2) tests.

All analyses were performed using R (R Core Team 2020). Parametric ANOVA models were conducted using the afex package (Singmann 2016), non-parametric LD-F2 analyses using the nparLD package (Noguchi et al. 2011), and Friedman tests and post-hoc comparisons using t-tests or Wilcoxon tests with the rstatix package (Kassambara 2019).

Results

Strength performance

Figure 2 presents the mean $\pm$ SD values and post-hoc comparisons for repetition volume, peak velocity, and peak power across supplementation conditions (BJ, CR, PLA) at incremental intensities (60%, 70%, 80%

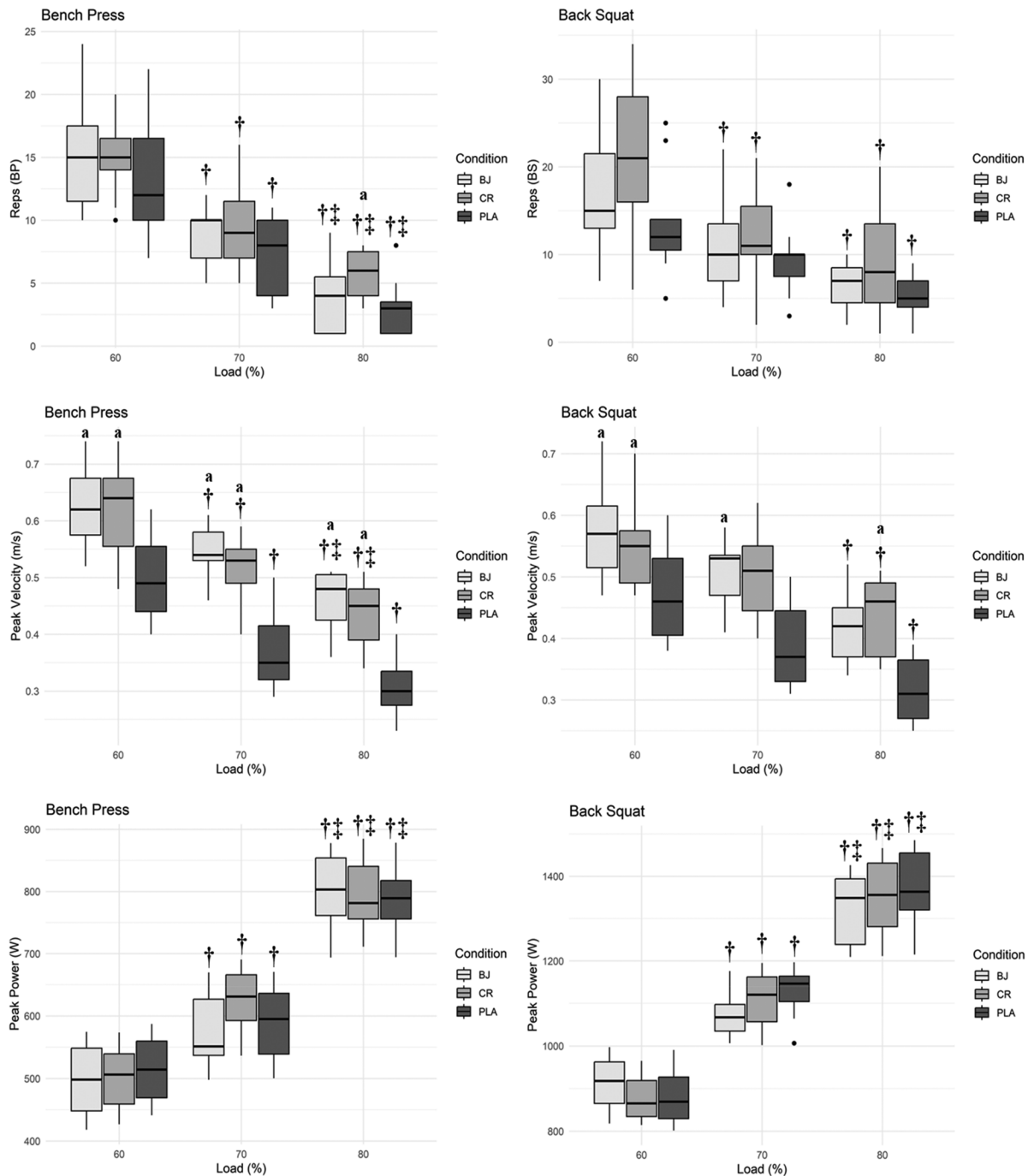


Figure 2. Mean $\pm$ SD values and post-hoc comparisons for repetition volume, peak velocity and power in bench press and back squat at incremental intensities.

†: significantly different compared to 60% of 1RM; ‡: significantly different compared to 70% of 1RM; a: significantly different compared to PLA.

Table 1. Effect size for repetition volume, peak velocity and power in bench press and back squat at incremental intensities.

Performance		BP			BS		
		ES ₁	ES ₂	ES ₃	ES ₁	ES ₂	ES ₃
Repetition Volume	60%	0.44	0.43	0.07	0.99	0.62	0.51
	70%	0.69	0.43	0.38	0.56	0.34	0.21
	80%	1.33	0.41	0.78	0.82	0.56	0.5
Peak Velocity (m · s ⁻¹)	60%	1.54	1.75	0.1	1.04	1.25	0.26
	70%	2.17	2.92	0.61	1.59	1.91	0.1
	80%	2.35	2.88	0.36	2.07	1.79	0.32
Peak Power (W)	60%	0.22	0.33	0.13	0.02	0.54	0.6
	70%	0.68	0.13	0.84	0.29	1.07	0.65
	80%	0.06	0.21	0.14	0.24	0.57	0.31

ES₁: effect size of the post hoc comparison CR vs. PLA; ES₂: effect size of the post hoc comparison BJ vs. PLA; ES₃: effect size of the post hoc comparison CR vs. BJ.

of 1RM) in BP and BS. Effect sizes values are presented in Table 1.

Repetitions volume

The analysis for BP data revealed a significant main effect of condition ($F=13.09$, $p<0.001$, $\eta_p^2=0.567$) and load ($F=184.9$, $p<0.001$, $\eta_p^2=0.949$). In contrast, the Condition $\times$ Load interaction was not significant ($F=0.85$, $p=0.45$, $\eta_p^2=0.079$). Post hoc comparisons showed that the number of repetitions was significantly higher in CR compared to PLA in 80% of 1RM ($p=0.023$, $d=1.33$). In all condition (BJ, CR, and PLA), the number of repetitions decreased significantly at 70% and 80% compared to 60% of 1RM ($p<0.012$, $d=1.64$ – 3.07), and at 80% compared to 70% of 1RM ($p<0.015$, $d=1.55$).

The analysis for BS data revealed a significant main effect of condition ($F=6.64$, $p=0.015$, $\eta_p^2=0.399$) and load ($F=73.37$, $p<0.001$, $\eta_p^2=0.880$). In contrast, the Condition $\times$ Load interaction was not significant ($F=3$, $p=0.051$, $\eta_p^2=0.231$). Post hoc comparisons showed that, in all three conditions (BJ, CR, and PLA), the number of repetitions significantly decreased at 80% compared to 60% of 1RM ($p<0.002$, $d=1.6$). In addition, in the CR and BJ conditions, repetitions decreased significantly at 70% compared to 60% ($p=0.025$, $d=0.99$).

Peak velocity

The analysis for BP peak velocity revealed a significant main effect of condition ($F=30.82$, $p<0.001$, $\eta_p^2=0.755$) and load ($F(1.65)=85.11$, $p<0.001$, $\eta_p^2=0.895$). In contrast, the Condition $\times$ Load interaction was not significant ($F=0.43$, $p=0.676$, $\eta_p^2=0.04$). Post hoc comparisons showed that, at all three loads, peak velocity was significantly higher in the BJ and CR condition than in PLA ($p<0.015$, $d=1.54$ – 2.92). In both BJ and CR conditions, peak velocity decreased significantly at 70% and 80% compared to 60% of 1 RM ($p<0.011$, $d=1.38$ – 2.08), and at 80%

compared to 70% of 1RM ($p<0.037$, $d=0.84$). In PLA condition, peak velocity decreased significantly only at 80% and 70% compared 60% of 1 RM ($p<0.001$, $d=1.07$ – 1.98).

The analysis for BS peak velocity data revealed a significant main effect of condition ($F=26.26$, $p<0.001$, $\eta_p^2=0.72$) and load ($F=36.99$, $p<0.001$, $\eta_p^2=0.79$). In contrast, the Condition $\times$ Load interaction was not significant ($F=0.53$, $p=0.684$, $\eta_p^2=0.05$). Post hoc comparisons showed that peak velocity was significantly higher in the CR condition at 80% of 1RM ($p=0.051$, $d=2.07$) and in the BJ condition at 60% and 70% of 1RM ($p<0.043$, $d=1.79$ – 1.91) compared to PLA. In all conditions, 60% were higher than 80% of 1RM ($p<0.012$, $d=1.71$).

Peak power

The analysis for BP peak power revealed no significant main effect of condition ($F=0.73$, $p=0.457$, $\eta_p^2=0.068$), whereas a significant main effect of load was observed ($F=140.69$, $p<0.001$, $\eta_p^2=0.934$). The Condition $\times$ Load interaction was not significant ($F=1.32$, $p=0.286$, $\eta_p^2=0.116$). Post hoc comparisons indicated that, across all three conditions (BJ, CR, and PLA), peak power was higher at 70% than at 60% 1RM, and higher at 80% than at both 60% and 70% 1RM ($p<0.015$, $d=1.64$ – 5.39).

The analysis for back squat peak power revealed no significant main effect of condition ($F=1.58$, $p=0.208$, $\eta_p^2=0.14$), whereas a very large main effect of load was observed ($F=536.64$, $p<0.001$, $\eta_p^2=0.98$). The Condition $\times$ Load interaction did not reach significance ($F=2.09$, $p=0.097$, $\eta_p^2=0.17$). In all conditions, peak power was significantly higher at 70% compared with 60% 1RM, and higher at 80% compared with both 60% and 70% 1RM (all $p=0.001$, $d=3.26$ – 6.03).

CMJ and SJ

The analysis of jump height outcomes (Figure 3) showed no significant main effect of condition for

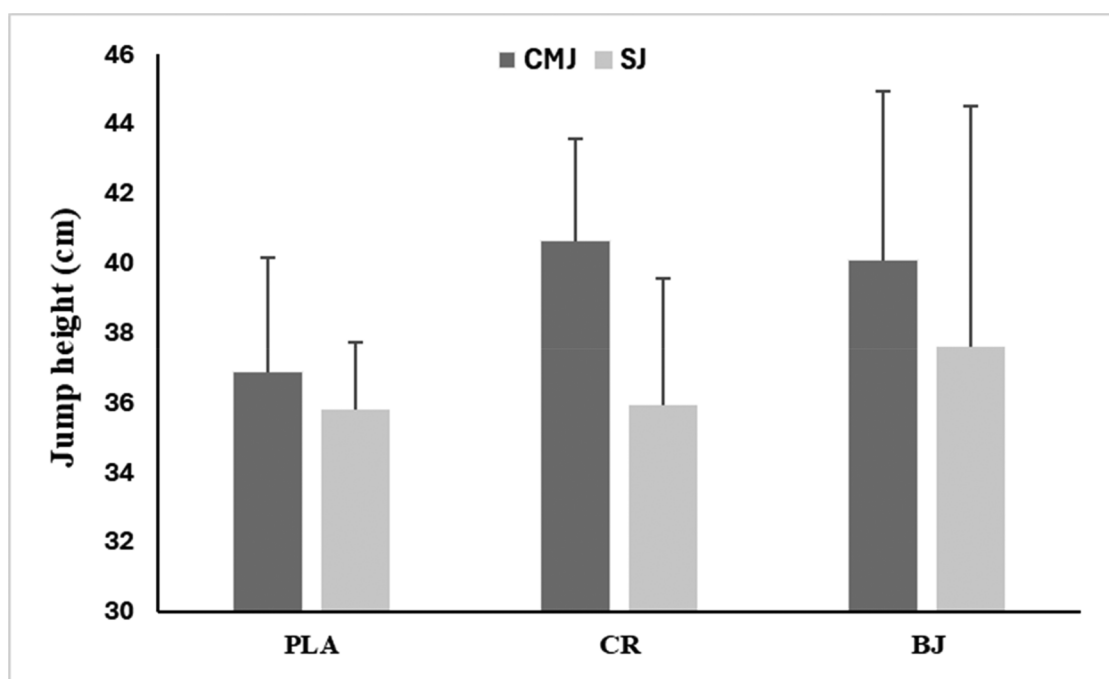


Figure 3. CMJ and SJ recorded pre- and post-session. PLA: Placebo; CR: Creatine; BJ: Beetroot juice.

either CMJ ($F(1.21, 12.07) = 0.29, p = 0.642, \eta_p^2 = 0.028$) or SJ ($F(1.45, 14.54) = 0.30, p = 0.675, \eta_p^2 = 0.029$).

Muscle oxygenation, total hemoglobin, and peak heart rate

Table 2 presents the physiological responses during BP and BS sets across incremental intensities (60%, 70%, and 80% of 1RM), including SmO_2 , tHb, and peak HR under PLA, CR, and BJ supplementation conditions, along with their corresponding effect sizes.

SmO_2

The analysis for BP SmO_2 data revealed a significant main effect of condition ($F = 68.28, p < 0.001, \eta_p^2 = 0.872$), whereas neither the main effect of load ($F = 1.69, p = 0.213, \eta_p^2 = 0.145$) nor the Condition $\times$ Load interaction ($F = 0.62, p = 0.615, \eta_p^2 = 0.059$) reached statistical significance. Post hoc comparisons showed that, at all three loads (60–80% 1RM), SmO_2 was significantly higher in the BJ condition compared with both CR and PLA ($p < 0.001, d = 2.23$ – 2.98).

The analysis for BS SmO_2 data revealed a large main effect of condition ($F = 60.75, p < 0.001, \eta_p^2 = 0.859$), whereas neither the main effect of load ($F = 1.34, p = 0.283, \eta_p^2 = 0.118$) nor the Condition $\times$ Load interaction ($F = 0.18, p = 0.874, \eta_p^2 =$

0.018) reached statistical significance. Post hoc comparisons indicated that SmO_2 was significantly higher in BJ compared with both CR and PLA at all three loads (60–80% 1RM; $p < 0.001, d = 1.98$ – 3.86).

tHb

The analysis for tHb during BP revealed that neither the main effect of condition ($F = 2.84, p = 0.085, \eta_p^2 = 0.221$) nor the main effect of load ($F = 0.58, p = 0.561, \eta_p^2 = 0.055$) reached statistical significance. The Condition $\times$ Load interaction was also non-significant ($F = 1.67, p = 0.191, \eta_p^2 = 0.143$). Post hoc comparisons showed a single significant difference at 80% of 1RM, where tHb was lower in CR compared with PLA ($p = 0.047, d = 0.48$).

The analysis for tHb during the BS revealed no significant main effect of condition ($F = 0.31, p = 0.662, \eta_p^2 = 0.030$) or time/load ($F = 1.53, p = 0.246, \eta_p^2 = 0.132$). The Condition $\times$ Time interaction was also not significant ($F = 0.30, p = 0.822, \eta_p^2 = 0.029$).

Peak HR

The analysis for BP's peak HR data revealed a significant main effect of condition ($F = 30.06, p < 0.001, \eta_p^2 = 0.75$) and load ($F = 136.02, p < 0.001, \eta_p^2 = 0.93$), also, a significant Condition $\times$ Load interaction ($F = 3.73, p = 0.013, \eta_p^2 = 0.27$). Post hoc comparisons between conditions showed that, at 60% and 70% of 1RM, peak HR was significantly lower in the BJ

Table 2. Results for peak HR, muscle oxygen saturation (SmO₂), and total haemoglobin (tHb) in bench press and back squat at incremental intensities.

		BP						BS					
		PLA			CR			PLA			CR		
		Mean	ES ₁	ES ₂	Mean	ES ₁	ES ₂	Mean	ES ₁	ES ₂	Mean	ES ₁	ES ₂
SmO ₂ (g/dl)	60%	79.52 ± 1.92	0.06	0.06	79.42 ± 1.4	0.06	0.06	81.04 ± 1.95	0.56	0.56	80.11 ± 1.35	0.56	0.56
	70%	80.3 ± 2.9	0.3	0.3	79.64 ± 1.15	0.3	0.3	79.84 ± 2.12	0.11	0.11	79.63 ± 1.64	0.11	0.11
	80%	80.26 ± 1.27	0.07	0.07	79.75 ± 1.82	0.07	0.07	80.45 ± 1.74	0.42	0.42	79.46 ± 2.83	0.42	0.42
tHb (%)	60%	12.52 ± 0.22	0.07	0.07	12.51 ± 0.15	0.07	0.07	12.63 ± 0.22	0.77	0.77	12.44 ± 0.28	0.77	0.77
	70%	12.47 ± 0.28	0.19	0.19	12.52 ± 0.28	0.19	0.19	12.42 ± 0.17	0.55	0.55	12.52 ± 0.18	0.55	0.55
	80%	12.58 ± 0.18	0.17	0.17	12.54 ± 0.22 ^a	0.17	0.17	12.42 ± 0.19	0.48	0.48	12.52 ± 0.22	0.48	0.48
Peak HR (bpm)	60%	141.18 ± 3.84	0.1	0.1	141.73 ± 6.47	0.1	0.1	172.09 ± 5.39	0.24	0.24	170.55 ± 7.46	0.24	0.24
	70%	152.91 ± 6.51 [†]	0.59	0.59	148.55 ± 8.26	0.59	0.59	180.82 ± 3.89	0.07	0.07	180.55 ± 4.31 [†]	0.07	0.07
	80%	165.27 ± 2.61 ^{††}	0.38	0.38	164.18 ± 3.16 ^{††}	0.38	0.38	186.27 ± 4.76 [†]	0.52	0.52	188.18 ± 2.18 ^{††a}	0.52	0.52

ES₁: effect size of the post hoc comparison CR vs. PLA; ES₂: effect size of the post hoc comparison BJ vs. PLA; ES₃: effect size of the post hoc comparison CR vs. BJ; HR: heart rate.[†]Significantly different compared to 60% of 1RM.^{††}Significantly different compared to 70% of 1RM.^aSignificantly different compared to PLA.^bSignificantly different compared to CR.

PLA: Placebo; CR: Creatine; BJ: Beetroot juice.

condition compared to both CR and PLA ($p < 0.02$, $d = 0.88$ – 0.92). In all conditions (BJ, CR, and PLA), peak HR was significantly higher at 80% compared with both 60% and 70% 1RM ($p < 0.018$, $d = 2.22$ – 4.03), while only in the PLA condition was peak HR at 70% 1RM significantly higher than at 60% 1RM ($p = 0.011$, $d = 0.93$).

The analysis for BS peak HR data revealed a strong main effect of time ($F = 22.21$, $p < 0.001$, $\eta_p^2 = 0.690$), whereas the main effect of condition only approached significance ($F = 4.04$, $p = 0.060$, $\eta_p^2 = 0.288$). The Condition $\times$ Time interaction was not significant ($F = 2.08$, $p = 0.134$, $\eta_p^2 = 0.172$). Post hoc comparisons showed that, in both BJ and CR conditions, peak HR was significantly higher at 70% and 80% compared with 60% 1RM, and higher at 80% than at 70% 1RM (all $p < 0.041$, $d = 0.99$ – 1.87), whereas in PLA, peak HR was significantly higher at 80% compared with 60% 1RM only ($p = 0.003$, $d = 1.87$).

HRV and blood lactate

Figure 4 illustrates the pre- and post-session heart rate variability (HRV) indices (MeanRR, RMSSD, SDNN, LF, HF) and blood lactate concentrations across the three supplementation conditions (PLA, CR, BJ). The standardised effect sizes (Cohen's d) for post-session comparisons, along with their respective 95% confidence intervals, are presented in Figure 5.

MeanRR

The analysis for mean RR revealed a significant main effect of condition ($F = 4.01$, $p = 0.035$, $\eta_p^2 = 0.286$) and time ($F = 246.30$, $p < 0.001$, $\eta_p^2 = 0.961$). In contrast, the Condition $\times$ Time interaction was not significant ($F = 0.01$, $p = 0.984$, $\eta_p^2 < 0.001$). Post hoc comparisons showed that, in all condition (BJ, CR, PLA), mean RR was significantly lower post-session compared with pre-session (all $p \leq 0.001$, Cohen's $d = 1.83$ – 2.66).

RMSSD

The analysis for RMSSD revealed significant main effects of condition ($F = 59.41$, $p < 0.001$, $\eta_p^2 = 0.856$) and time ($F = 61.16$, $p < 0.001$, $\eta_p^2 = 0.859$). The Condition $\times$ Time interaction did not reach statistical significance ($F = 3.29$, $p = 0.066$, $\eta_p^2 = 0.248$). Post hoc comparisons showed that RMSSD was higher at pre-session in BJ than in CR and PLA ($p = 0.014$ and < 0.001 , respectively; $d = 0.48$ – 2.92), and higher in CR than in PLA ($p = 0.007$, $d = 1.94$). A similar pattern was observed post-session, with RMSSD remaining

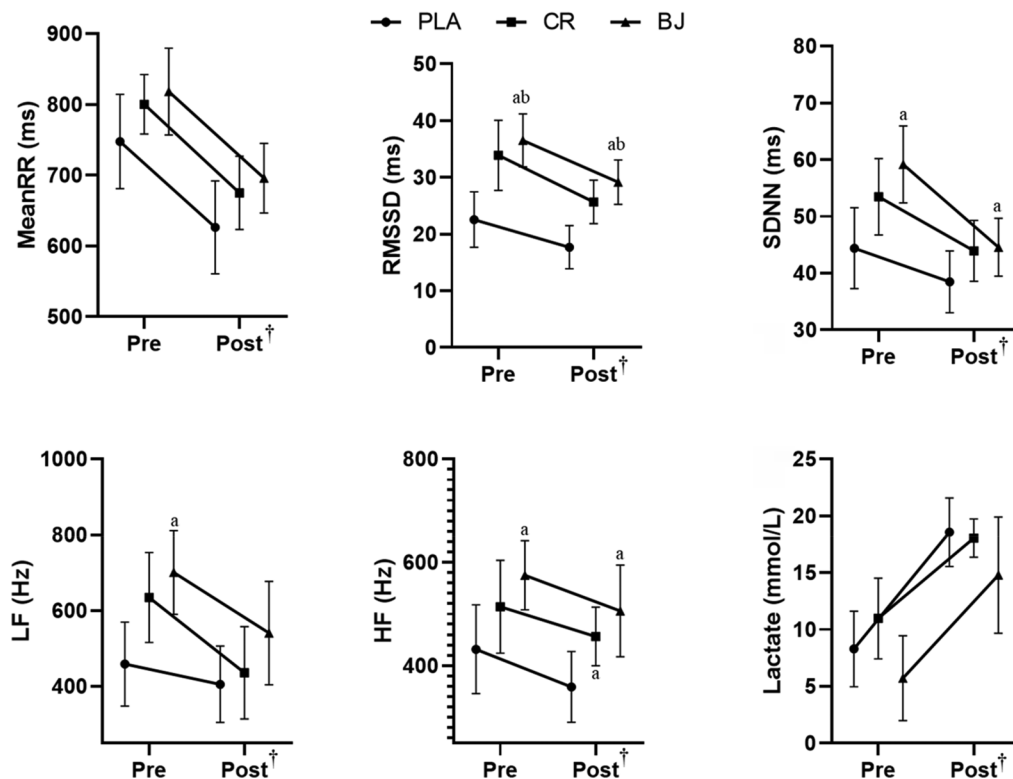


Figure 4. HRV indices and blood lactate recorded at pre- and post-session. PLA: Placebo; CR: Creatine; BJ: Beetroot juice; †: compared to pre-session; a: compared to PLA; b: compared to CR.

higher in BJ and CR compared with PLA ($p < 0.001$, $d = 2.1$ – 2.99). In all condition, RMSSD decreased significantly from pre- to post-session (all $p < 0.001$, $d = 1.11$ – 1.71).

SDNN

The analysis for SDNN revealed significant main effects of condition ($F = 14.69$, $p < 0.001$, $\eta_p^2 = 0.595$) and time ($F = 89.07$, $p < 0.001$, $\eta_p^2 = 0.899$), whereas the Condition $\times$ Time interaction was not significant ($F = 0.74$, $p = 0.486$, $\eta_p^2 = 0.068$). Post hoc comparisons showed that SDNN was higher in BJ than in PLA both at pre-session ($p < 0.002$, $d = 2.12$) and post-session ($p = 0.001$, $d = 1.16$). In all condition (BJ, CR, PLA), SDNN decreased significantly from pre- to post-session (all $p < 0.001$, $d = 0.93$ – 2.43).

LF

The analysis for LF power revealed significant main effects of condition ($F = 4.52$, $p = 0.036$, $\eta_p^2 = 0.311$) and time ($F = 40.58$, $p < 0.001$, $\eta_p^2 = 0.802$). In contrast, the Condition $\times$ Time interaction was not significant ($F = 1.39$, $p = 0.273$, $\eta_p^2 = 0.122$). Post hoc comparisons showed that, at pre-session, LF power was significantly higher in BJ than in PLA ($p = 0.015$, $d = 2.18$). In all

condition (BJ, CR, PLA), LF power decreased significantly from pre- to post-session (all $p < 0.015$, $d = 0.5$ – 1.65).

HF

The analysis for HF power revealed significant main effects of condition ($F = 8.02$, $p = 0.006$, $\eta_p^2 = 0.445$) and time ($F = 235.28$, $p < 0.001$, $\eta_p^2 = 0.959$), whereas the Condition $\times$ Time interaction was not significant ($F = 0.62$, $p = 0.492$, $\eta_p^2 = 0.058$). Post hoc comparisons showed that HF power was higher in BJ than in PLA both at rest (pre-exercise; $p = 0.017$, $d = 1.86$) and post-exercise ($p < 0.001$, $d = 1.86$). After exercise, HF was also higher in CR than in PLA ($p = 0.018$, $d = 1.55$). In all condition (BJ, CR, PLA), HF power decreased markedly from pre- to post-exercise (all $p < 0.001$, $d = 0.77$ – 0.94).

Blood lactate

The analysis for blood lactate revealed no significant main effect of condition ($F = 1.42$, $p = 0.266$, $\eta_p^2 = 0.124$) and no Condition $\times$ Time interaction ($F = 1.06$, $p = 0.366$, $\eta_p^2 = 0.095$). In contrast, there was significant main effect of time ($F = 324.22$, $p < 0.001$, $\eta_p^2 = 0.970$). Post hoc comparisons showed that, in all three conditions (BJ, CR, PLA), blood lactate was

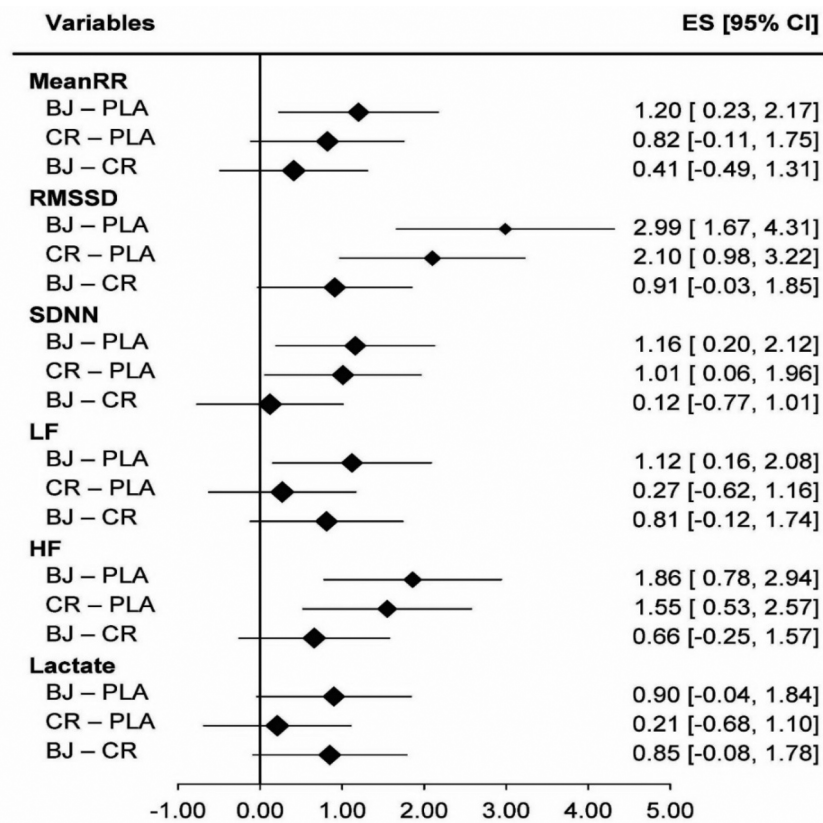


Figure 5. Standardised effect sizes [Cohen's *d*] and 95% confidence intervals for post-session HRV indices and blood lactate after CR and BJ supplementation compared with PLA. Positive ES values indicate effects favouring the first-listed condition in each comparison (i.e. BJ vs. PLA, CR vs. PLA, and BJ vs. CR). Modulation of main physiological responses to RT.

significantly higher post-session compared with pre-session (all $p \leq 0.001$, $d = 2.03$ – 3.24).

Overall, [Figure 5](#) shows generally positive standardised effects for BJ (and to a lesser extent CR) relative to PLA across post-session HRV indices (e.g. MeanRR, RMSSD, SDNN, and HF), whereas lactate effect estimates are comparatively small and all corresponding 95% confidence intervals cross zero, suggesting limited evidence for a condition-specific effect on post-session blood lactate.

Responder analysis ([Table 3](#)) revealed that BJ elicited a substantially higher prevalence of positive modulation in SmO_2 across all intensities (55–64%) compared to CR (0–18%), with χ^2 tests confirming significant differences at all loads and across both exercises ($p < 0.022$). Similarly, BJ induced significantly higher positive modulation than CR in peak HR reduction at 60% BP (82% vs. 36%, $p = 0.030$), although differences narrowed at higher intensities. For RMSSD, BJ produced a higher prevalence of positive post-session autonomic modulation compared to CR (82% vs. 64%), though the difference was not statistically significant ($p = 0.338$).

Discussion

This study investigated the short-term effects of BJ and CR supplementation on resistance exercise performance, physiological regulation, and autonomic recovery following a 3-day loading protocol. Both supplements demonstrated ergogenic benefits compared to placebo, although through distinct physiological mechanisms in this sample. CR predominantly enhanced phosphagen-driven performance, showing large to very large effect sizes for total work, particularly in upper-body exercises where ATP-PCr reliance is highest. Both supplements markedly improved movement velocity compared to PLA, with BJ demonstrating a small-to-moderate advantage over CR under high-intensity (80% 1RM) loading, suggesting better preservation of neuromuscular efficiency under fatigue. Furthermore, BJ produced substantial improvements in SmO_2 across all intensities and exercise modalities, along with significantly lower peak heart rate and superior maintenance of autonomic function. Direct comparisons suggested divergent response patterns, with CR showing greater effects on anaerobic work capacity, whereas BJ was associated with more

Table 3. Prevalence of individual physiological modulation in peak HR, SmO₂, and RMSSD during bench press (BP) and back squat (BS) across incremental intensities (60%, 70%, 80%) following short-term CR and BJ supplementation.

	Peak HR						SmO ₂						RMSSD					
	BP			BS			BP			BS			CR			BJ		
	60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%
CR	4	7	4	5	5	2	0	1	0	1	0	1	0	1	1	0	0	1
Positive modulation	5	3	2	4	4	7	0	1	1	1	0	1	0	2	2	0	0	2
Negative modulation	2	1	5	2	2	2	11	9	10	9	11	8	9	8	8	11	11	8
Neutral	36	64	36	45	45	18	0	9	0	9	0	9	0	9	9	0	0	9
% positive modulation																		
BJ	9	9	7	4	7	3	7	6	5	7	7	7	7	7	7	7	7	7
Positive modulation	0	1	2	6	1	3	0	0	0	0	0	0	0	0	0	0	0	0
Negative modulation	2	1	2	1	3	5	4	5	6	4	4	4	4	4	4	4	4	4
Neutral	82	82	64	36	64	27	64	55	45	64	64	64	64	64	64	64	64	64
% positive modulation																		
X ²	4.70	0.92	1.64	0.19	0.73	0.26	10.27	5.24	6.47	7.07	10.27	7.07	X ² (1)	X ² (1)	X ² (1)	X ² (1)	X ² (1)	X ² (1)
p	0.030	0.338	0.201	0.665	0.392	0.611	0.001	0.022	0.011	0.008	0.001	0.008	p	p	p	p	p	p
Post																		

pronounced changes in vascular regulation, muscle oxygen saturation, and parasympathetic indices, reflecting potentially distinct mechanistic pathways under the present experimental conditions. Importantly, the magnitude of these effects suggests that short-term supplementation may extend physiological responses previously observed under acute conditions (Salem et al. 2025a), particularly for BJ, where cumulative nitrate contribute to changes in muscle oxygenation and autonomic regulation. However, this interpretation should be considered within the limits of the short intervention period and the present sample characteristics. Overall, these findings support the concept of supplement-specific response profiles and suggest that the selection of ergogenic aids may be informed by the targeted physiological domain and contextual training demands.

Performance responses: CMJ, SJ, repetitions, velocity, and power

Although between-condition differences in repetition number reached statistical significance versus PLA only at 80% 1RM, effect size analysis revealed large to very large benefits of CR at higher intensities ($d=0.44-1.33$), particularly in upper-body exercises. This highlights meaningful improvements in anaerobic work capacity and phosphagen availability, consistent with its role in enhancing ATP-PCr turnover and inter-set recovery (Greenhaff et al. 1993, 1994; Rawson and Volek 2003). BJ showed small effects, more pronounced in lower-limb exercises ($d=0.41-0.43$), suggesting improved fatigue resistance through enhanced perfusion and oxygen utilisation (Salem et al. 2025b), rather than large increases in total repetition output.

It should be noted that the number of repetitions achieved across intensities, especially in the BP, was lower than the estimated mean repetition ranges recently reported for resistance exercise at comparable %1RM loads (Nuzzo et al. 2024). In that meta-regression, training status (trained vs. untrained) and exercise modality (e.g. bench press vs. squat) were highlighted as potential moderators, with trained individuals and lower-body exercises typically completing more repetitions per set at a given relative load.

In the present study, participants had relatively modest RT experience and were largely within the anatomical adaptation and technical learning phases for both BP and BS; stages characterised by high motor-learning demands, reduced neuromuscular efficiency, and lower strength-endurance capacity (Kraemer and Ratamess 2004; Haff and Triplett 2016). These developmental factors likely contributed to the

comparatively lower repetition volumes observed here, particularly for the upper-body exercise. Therefore, although the relative effects of supplementation remain interpretable, the absolute repetition counts should be interpreted cautiously and not generalised to more advanced or highly trained strength athletes.

For peak velocity, statistical significance was observed between CR and PLA at all loads in BP and at 80% 1RM for CR in BS, whereas BJ outperformed PLA at all loads during BS and both 70% and 80% 1RM during BS. These differences were supported by very large effect sizes, confirming that movement velocity is a highly sensitive indicator of supplementation effects during resistance training (BP: $d \approx 1.38$ – 2.92 ; BS: $d \approx 1.79$ – 2.07). Direct comparisons between BJ and CR showed small-to-moderate advantages for BJ ($d \approx 0.1$ – 0.61), particularly at 80% 1RM, indicating more stable velocity maintenance under cumulative fatigue. This likely reflects mechanisms previously described namely NO-related improvements in neuromuscular efficiency and oxygen delivery, without needing to restate full pathways.

CR also produced velocity benefits compared to PLA, particularly in bench press, where effect sizes were higher than in back squat (BP: $d \approx 1.54$ – 2.35 vs. BS: $d \approx 1.04$ – 2.07). This pattern may reflect greater reliance on phosphagen-driven energy systems in smaller upper-body muscle groups, whereas larger muscles under squat conditions may depend more on cardiovascular and metabolic regulation. The observed exercise-specific responsiveness aligns with previous findings, where creatine was shown to yield greater performance benefits in movements with higher ATP-PCr dependency (Wax et al. 2021; Wang et al. 2024; Salem et al. 2025b).

In contrast, peak power showed overall smaller effects compared to velocity ($d < 0.60$), with only CR at 70% BP and BJ at 60% BS showing moderate effects ($d = 0.68$ and 1.07 , respectively). This reinforces the notion that peak velocity may be a more sensitive early performance indicator under short-term supplementation (Ranchal-Sánchez et al. 2020), particularly in high-intensity loading where movement efficiency, repetition sustainability, and contractile quality become more functionally relevant than instantaneous maximal power.

Jump performance was better preserved under both supplementation conditions compared to PLA, particularly for CMJ, where moderate (BJ vs PLA, $d \approx 0.77$) to large (CR vs PLA, $d \approx 1.20$) effects were observed. These findings support a protective effect on neuromuscular function during explosive stretch–shortening cycle actions. In SJ, BJ showed a small improvement

compared to PLA ($d \approx 0.36$), whereas CR demonstrated only a trivial effect ($d \approx 0.04$), suggesting that BJ may support controlled concentric actions slightly more effectively. Direct comparisons revealed small effects favouring BJ for SJ ($d \approx 0.31$) and trivial differences for CMJ ($d \approx -0.14$), indicating no clear superiority but differing physiological contributions.

In synthesising these patterns, CR appears more effective in enhancing total work capacity and power-related outcomes, particularly in upper-body and higher-intensity efforts, where phosphagen demand is dominant (Lanhers et al. 2017). In contrast, BJ consistently favoured movement velocity preservation and resistance to fatigue, particularly in lower-limb and high-intensity conditions where oxygen-dependent metabolic flexibility plays a larger role (Salem et al. 2025b). These findings extend observations from acute trials (Salem et al. 2025a) by indicating that short-term loading may accentuate supplement-specific response patterns, with CR more closely related to phosphagen-driven performance outcomes and BJ more closely related to neuromuscular efficiency and fatigue-related indices.

Physiological responses: Muscle oxygenation, total hemoglobin, and heart rate

The SmO_2 findings provide strong and consistent evidence for the microvascular and oxygenation-related benefits of BJ supplementation. Across all intensities (60–80% 1RM) and both exercises (BP and BS), BJ elicited very large increases in muscle oxygen saturation, with Cohen's d ranging from 2.03 to 2.48 vs. PLA, and 2.34 to 3.86 vs. CR, demonstrating a substantial enhancement in oxygen availability during resistance exercise. Importantly, BJ was significantly superior to both PLA and CR at all loads (60%, 70%, 80%) in both BP and BS, confirming a load-independent and exercise-modality-independent oxygenation benefit. These results are consistent with enhanced intramuscular oxygen availability, more efficient perfusion distribution, and greater resistance to exercise-induced desaturation, particularly under metabolically stressful conditions (Fulford et al. 2013; Rojano-Ortega et al. 2022; Salem et al. 2025b).

These improvements are consistent with mechanisms proposed within the nitrate–nitrite–NO pathway, where dietary nitrate enhances vasodilation, improves endothelial function, increases local muscle perfusion, and optimises oxygen delivery during high-demand contractions (Bailey et al. 2010; Ferguson et al. 2013). Additionally, enhanced mitochondrial efficiency and reduced oxygen cost of ATP resynthesis may contribute

to greater oxygen saturation retention during loading (Domínguez et al. 2017; Salem et al. 2025b). The absence of any condition $\times$ load interaction further confirms that BJ's effects are robust across varying intensities, highlighting its role in preserving oxygenation under fatigue-sensitive resistance exercise conditions.

In contrast, CR produced no meaningful changes in SmO_2 at any load or exercise mode, with trivial effect sizes ($d \approx 0.06$ to 0.32), consistent with its mechanism that primarily supports phosphagen replenishment rather than vascular or oxygen-transport adaptations (Salem et al. 2025c, Greenhaff et al. 1994; de Araujo Bonetti de Poli et al. 2019). Together, these findings support the mechanistic distinction between BJ (oxygenation/perfusion-focused) and CR (phosphagen/energy-focused), reinforcing their differential roles in resistance exercise physiology.

Total haemoglobin (tHb) values did not differ meaningfully across conditions, as indicated by trivial-to-small effect sizes ($d < 0.60$), suggesting that BJ's oxygenation improvements are not due to changes in blood volume, but rather to more efficient oxygen extraction and microvascular regulation, rather than increased muscle blood pooling. This is consistent with NO-mediated improvements in vascular conductance and perfusion efficiency rather than total blood displacement (de Oliveira et al. 2018; Volino-Souza et al. 2020).

Regarding peak HR, BJ produced significantly lower peak HR values than both PLA and CR at 60% and 70% in BP, and at 80% in BS, indicating reduced cardiovascular strain during resistance loading. These reductions were accompanied by small-to-large effect sizes vs. PLA ($d \approx 0.31$ – 2.65) and vs. CR ($d \approx 0.46$ – 1.79), particularly at higher intensities, suggesting improvements in cardiac efficiency, endothelial responsiveness, and autonomic modulation (Ferguson et al. 2013; Jurado-Castro et al. 2022). In contrast, CR showed only trivial-to-small effects on peak HR ($d < 0.6$), reinforcing its limited impact on cardiovascular strain despite its metabolic support role (Salem et al. 2025b).

Together, these findings indicate that mainly BJ improves intramuscular oxygen saturation and reduces cardiovascular strain under resistance exercise, without significantly altering blood volume. Conversely, CR seems to contribute to performance enhancement through enhancing metabolic energy availability rather than influencing oxygen delivery or cardiac load regulation, confirming a clear mechanistic divergence between both supplements.

In direct comparison, BJ demonstrated superior effects on SmO_2 and peak HR regulation across loads and exercise types, while CR showed no meaningful

impact on oxygenation or cardiovascular responses, highlighting its primarily metabolic support role. These findings reinforce the concept of supplement-specific physiological signatures, whereby BJ enhances vascular, metabolic efficiency, and autonomic regulation (Jurado-Castro et al. 2022; Poon et al. 2025; Celik et al. 2026), while CR preferentially supports phosphagen-driven anaerobic work and energy buffering (Kreider et al. 2017; de Araujo Bonetti de Poli et al. 2019), as discussed in Section 4.1.

Heart rate variability (HRV) and autonomic recovery

The HRV results highlight a distinct autonomic recovery profile between BJ and CR during short-term supplementation. BJ demonstrated the most robust parasympathetic support, significantly improving both pre- and post-session RMSSD, SDNN, and HF compared to PLA, with large to very large effect sizes (RMSSD: $d = 2.99$; SDNN: $d = 1.16$; HF: $d = 1.86$), and outperforming CR for RMSSD ($d = 0.91$). These improvements suggest that nitrate supplementation not only limits exercise-induced parasympathetic withdrawal but also enhances post-exercise reactivation, likely through NO-mediated improvements in microvascular perfusion, oxygen delivery, endothelial function, and baroreflex sensitivity (Jurado-Castro et al. 2022; Salem et al. 2025b; Raimundo et al. 2025). CR also improved but not significantly RMSSD and HF compared to PLA (RMSSD: $d = 2.10$; HF: $d = 1.55$); however, these effects were consistently smaller than those observed with BJ, indicating a less pronounced enhancement of parasympathetic reactivation. These slight enhancements suggest that CR's autonomic benefits may be attributed more to reduced metabolic strain rather than direct enhancement of cardiovascular or parasympathetic modulation. (Salem et al. 2025c; Mert et al. 2017).

Although MeanRR differences did not reach statistical significance, BJ showed a large effect versus PLA ($d = 1.20$) and a small advantage over CR ($d = 0.41$), suggesting better preservation of vagally mediated heart rhythm stabilisation (Benjamim et al. 2021). The peak HR data further support this, as BJ elicited significantly lower cardiovascular strain across all intensities in both BP and BS, pointing to improved cardiovascular efficiency and autonomic-cardiovascular interaction. In contrast, CR produced only trivial reductions in HR and did not significantly impact microvascular or oxygen-related parameters, consistent with its role in metabolic buffering rather than autonomic modulation.

Blood lactate responses further reinforce this divergence, with BJ showing moderately lower values compared to PLA ($d=0.90$) and CR ($d=0.85$), indicating more efficient metabolic regulation and possibly greater oxidative recovery capacity (Ranchal-Sánchez et al. 2020), even though differences did not reach statistical significance. CR showed negligible blood lactate modulation compared to PLA ($d=0.21$), aligning with its primary role in ATP-PCr resynthesis rather than aerobic or vascular recovery (Wax et al. 2021).

Taken together, these findings suggest that BJ may be associated with broader short-term physiological responses across vascular, oxygenation, and autonomic domains, potentially contributing to reduced cardiovascular strain and enhanced post-exercise parasympathetic reactivation. In contrast, CR appears to influence autonomic recovery to a lesser extent under the present conditions, with observed effects likely related to metabolic unloading rather than direct modulation of cardiovascular-autonomic pathways. Therefore, while both supplements exhibit ergogenic potential, BJ may be more relevant in contexts characterised by elevated recovery demands, autonomic stress, or metabolic strain, whereas CR may be more closely associated with improvements in anaerobic work capacity and phosphagen-driven performance.

Individual modulation and practical responsiveness of main physiological outcomes

The modulation analysis strengthens the group-based findings by demonstrating that BJ was not only statistically more effective in increasing SmO_2 and reducing peak HR, but also more likely to induce meaningful physiological modulation at the individual level. In particular, BJ produced significantly higher rates of positive modulation in SmO_2 at all intensities (55–64%) compared to CR (0–18%), indicating superior support for oxygenation and perfusion under metabolic stress (Wong et al. 2025). This aligns with the large effect sizes observed in Section 4.2 and confirms that BJ's vascular benefits were not restricted to average group responses but were consistently observed across participants.

For peak HR, BJ produced the highest modulation prevalence at 60% BP (82% vs 36%), suggesting improved cardiovascular efficiency even under moderate intensities, consistent with its NO-dependent endothelial effects (Domínguez et al. 2017). Although CR supported modest improvements, these were more variable and not consistently above modulation thresholds, reflecting its indirect cardiovascular

modulation. In RMSSD, BJ also demonstrated a higher proportion of positive autonomic responders (82% vs. 64%), consistent with its effects on HF and SDNN, although the difference did not reach statistical significance. This suggests that autonomic reactivation may depend partly on metabolic or vascular recovery (supported more strongly by BJ) rather than pure phosphagen replenishment (CR). Consistent with this interpretation, the relatively wide 95% confidence intervals observed for post-session HRV and blood lactate outcomes indicate substantial inter-individual variability, which highlights inter-individual variability and underscores the importance of interpreting group-level effects alongside individual-response patterns.

Overall, these findings indicate that BJ was associated with more consistent group-level and individual-level modulation in selected physiological markers related to oxygenation and autonomic regulation, whereas CR responses appeared more variable and context-dependent. In contrast, CR seems to support performance primarily through metabolic buffering and ATP-PCr restoration (Gutiérrez-Hellín et al. 2024), with comparatively limited influence on cardiovascular or vascular-related parameters under the present experimental conditions.

Strengths, limitations, and future directions

This study benefits from a double-blind, within-subject crossover design, which reduces inter-individual variability and enables direct comparison of supplement-specific physiological and performance responses. The integration of external performance metrics (repetition volume, velocity, power) with internal physiological (SmO_2 , tHb, peak HR) and autonomic indicators (HRV) provided a comprehensive and multidimensional evaluation of each supplement's ergogenic profile. The use of real-time NIRS-based oxygenation monitoring offered novel insight into peripheral and more local physiological regulation during resistance exercise, while HRV analysis captured more holistic autonomic recovery dynamics. A further methodological strength is the incorporation of an individual response modulation analysis, adding practical relevance by moving beyond conventional mean-based statistics to assess responsiveness at the individual level, thereby enhancing sensitivity to physiological variability, ecological effectiveness, and real-world applicability of supplementation strategies. Moreover, the short-term supplementation framework improves ecological validity, reflecting realistic usage patterns frequently employed during intensified

training blocks, pre-competition phases, or recovery-oriented microcycles.

However, several limitations should be acknowledged. First, the relatively small and homogeneous sample of resistance-trained males limits the generalisability of the findings. Consequently, the results should be interpreted as exploratory and hypothesis-generating rather than confirmatory, and future studies should include more diverse populations (e.g. females, older adults, youth athletes, and elite athletes). Second, participants were classified as novice resistance-trained, which likely influenced both absolute performance levels and inter-individual variability. The relatively low repetition volumes observed in this cohort, particularly in BP, may reflect ongoing neuromuscular adaptation and technical learning processes. Because recent estimates of mean repetitions indicate higher repetition capacities at comparable relative loads, the present findings regarding repetition volume may underestimate absolute performance potential and should be interpreted with caution and not generalised to advanced trained subject. Future research should incorporate participants with broader training backgrounds. Third, the short supplementation period represents an important limitation, as it precludes conclusions regarding chronic adaptations or long-term training effects. Accordingly, the observed responses should be interpreted as short-term physiological and performance modulations rather than stable ergogenic adaptations.

Fourth, mechanistic inferences remain indirect, as no biochemical verification (e.g. plasma nitrate/nitrite, intramuscular PCr) was performed. Additionally, because SME values were derived from external reliability studies rather than condition-specific test–retest data in the present sample, modulation prevalence estimates should be interpreted cautiously as approximations of “true” individual responses.

Taken together, these limitations indicate that the present findings are context-specific and should not be interpreted as definitive evidence of supplement superiority across populations, training phases, or long-term performance outcomes. Future studies should integrate biochemical validation, longer intervention periods, and more heterogeneous samples, and should examine inter-individual responsiveness, potential co-supplementation effects, and adaptation dynamics across periodized training models.

Practical implications

Although the study design does not allow general statements about population-level effectiveness or the probability of benefit, the present findings provide

preliminary indications that may guide practitioners in applied settings, while requiring cautious interpretation. In applied sport and training contexts, creatine appears most useful during phases demanding high power output, repetition capacity, or sustained phosphagen-driven performance, such as hypertrophy blocks, maximal strength development, or high-intensity anaerobic protocols. Beetroot juice, by contrast, appears particularly suited to training phases characterised by elevated metabolic stress, reduced recovery windows, or high session frequency, where cardiovascular efficiency, oxygen transport, and autonomic stability are key performance-limiting factors (e.g. tapering, metabolic conditioning, return-to-training, or deload weeks).

The modulation prevalence analysis further highlights that supplementation effects are not uniform across individuals. Some participants exhibited more pronounced responses to BJ in physiological markers such as SmO_2 , RMSSD, and peak HR, while others responded preferentially to CR in performance outputs such as repetition preservation or velocity maintenance. This underscores the importance of monitoring individual responsiveness through objective markers (e.g. SmO_2 , HRV, peak HR, velocity profiles) rather than relying exclusively on mean group-based outcomes.

Therefore, practitioners are encouraged to combine physiological monitoring (mNIRS, HRV, peak HR) with performance-based tracking (velocity, repetition loss, fatigue index) not to categorise athletes rigidly as responders or non-responders, but to inform individualised and dynamic adjustments to supplementation and training plans according to each athlete's evolving response profile. CR may be prioritised when the goal is to enhance mechanical output, anaerobic work tolerance, and phosphagen dominance. Conversely, BJ may be favoured when the objective is to support autonomic resilience, cardiovascular efficiency, oxygenation-based fatigue management, or recovery stability.

Given the exploratory nature of these findings, further research is needed to better understand inter-individual responsiveness, possible interactions or combined effects of BJ and CR (e.g. additive or antagonistic mechanisms), and whether co-supplementation may yield distinct ergogenic profiles. Long-term studies are also warranted to examine sustained efficacy, adaptation over chronic training cycles, and any potential side effects associated with repeated or prolonged supplementation use. Thus, supplement selection in practice should be driven not only by immediate performance outcomes but also by

the targeted physiological adaptations and athletes' individual responsiveness profiles.

Conclusion

Short-term supplementation with creatine (CR) and beetroot juice (BJ) was associated with improvements in resistance exercise performance, but through distinct physiological mechanisms. CR appeared to be more closely related to changes in repetition volume and phosphagen-dependent power output, particularly at higher intensities, consistent with its role in phospho-creatine availability, ATP resynthesis, and metabolic buffering. In contrast, BJ was associated with more pronounced changes in intramuscular oxygen saturation, cardiovascular strain, and indices of parasympathetic regulation, suggesting a potential role in vascular and autonomic responses during resistance exercise.

Importantly, modulation prevalence analyses indicated that BJ more frequently elicited meaningful individual changes in SmO_2 , peak HR, and RMSSD compared with CR, whereas CR responses were more evident in performance-related outcomes. These divergent response profiles suggest that CR and BJ may influence different physiological domains under short-term supplementation conditions. Accordingly, supplement selection may be informed by targeted physiological outcomes and individual response patterns rather than performance measures alone.

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