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Beetroot juice modulates physiological responses and accelerates recovery during the special judo performance: a randomized trial

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Abstract

The ability of nitrate (NO_3^-)-rich beetroot juice (BJ) to improve exercise depends on training status. However, the mechanisms are understudied. The

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aim of this study was to investigate the impact of acute BJ supplementation on the Special Judo Fitness Test (SJFT) outcomes in elite and recreational judokas.
Forty judo athletes (17 elite and 23 recreational) completed two SJFT sessions after drinking either BJ or a placebo in a randomized, double-blind, placebo-controlled crossover design. Plasma NO_3^- and lactate, tissue saturation index (TSI) and SJFT outcomes were measured.
Plasma NO_3^- increased after BJ intake in both groups ($p < 0.001$). Elite athletes achieved more total throws (TT) ($p < 0.05$) and exhibited lower TSI during SJFT, 1-minute post-SJFT heart rate (HR_1), and SJFT index ($p < 0.05$), but higher post-SJFT lactate and TSI than recreational athletes ($p < 0.05$). TT did not improve following supplementation ($p > 0.05$). BJ increased post-SJFT TSI (elite: 2.6 ± 3% vs. recreational: 4.55 ± 2.6%) and reduced HR_1 (elite: -5.6 ± 3.3% vs. recreational: -9.8 ± 4.7%) and SJFT index (elite: -2.7 ± 5.6% vs. recreational: -6 ± 5.8%) overall ($p < 0.001$ compared to placebo), with greater effects in recreational athletes ($p < 0.05$). BJ also decreased post-SJFT lactate only in recreational athletes ($p < 0.01$). Higher maximal oxygen uptake correlated with smaller BJ-induced improvements in lactate ($r = - 0.57$, $p < 0.001$), HR_1 ($r = - 0.50$, $p < 0.001$), SJFT index ($r = - 0.43$, $p < 0.01$), and TSI during the third period of SJFT effort ($r = - 0.5$, $p < 0.001$) and during 1-minute recovery ($r = - 0.35$, $p < 0.05$).
BJ primarily attenuates the physiological cost and enhances recovery-related markers during the judo performance, rather than directly increasing the performance, with responsiveness modulated by training status.

Keywords: nitrate supplementation; judo performance; heart rate recovery; tissue oxygenation; training status

Highlights

- Acute BJ (140 ml, ~12.8 mmol nitrate) supplementation improved the SJFT index in both elite and recreational judo athletes.
- BJ-induced Improvement in the SJFT index primarily resulted from the reduced physiological cost and accelerated recovery.
- BJ-induced improvements in the SJFT index were more pronounced in athletes with lower training status.

1. Introduction

Judo is a combat sport where athletes score points by throwing an opponent to the ground or achieving a hold/submission [1]. Matches can be very short (a single point or “Ippon” ends the bout) or last over 4 minutes plus potential overtime [1]. Thus, judokas must develop both advanced technical-tactical skills

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and a high level of physical fitness. The physiological demands are high, as repeated explosive and complex movements in the standing and ground phases place athletes under significant stress [2]. Energy system analysis indicated that judo engages all metabolic pathways: anaerobic systems fuel the rapid throws, locks, and holds (with and without lactate), while aerobic capacity is crucial for sustaining repeated attacks, maintaining alertness, and supporting muscular strength during prolonged efforts [3].

Choosing the appropriate dietary supplements can help optimize athletes' performance. Natural foods like vegetables and fruits are rich in bioactive compounds and can serve as alternatives to synthetic supplements for enhancing physiological function [4]. Beetroot juice (BJ) is particularly high in inorganic nitrate (NO_3^-) and improves various aspects of exercise performance. For example, BJ supplementation prolongs time to exhaustion in aerobic and muscular endurance activities, enhances performance in high-intensity interval exercise, improves cognitive function, reduces the phosphocreatine (PCr) cost of force production, alleviates perceived muscle soreness after exercise, and accelerates recovery following exercise-induced muscle damage [5-11]. These performance benefits are attributed to increased nitric oxide (NO) availability after BJ intake [12]. NO is a signaling molecule that enhances blood flow distribution, mitochondrial respiration, endothelial function, and skeletal muscle metabolism and contraction [13-16].

Despite its promising effects, research on the acute effects of BJ supplementation in combat sports remains limited with mixed results. For example, de Oliveira et al. [17] reported that acute beetroot gel (12.2 ± 0.2 mmol of NO_3^-) improved handgrip strength recovery without altering muscle oxygenation in recreational combat athletes. Study by Miraftabi et al. [18] indicated that acute BJ (400–800 mg of NO_3^-) increased aerobic and anaerobic capacity in taekwondo athletes but failed to translate this into improved sport-specific performance. Antonieto et al. [19], however, demonstrated that a single dose of beetroot extract (1 g) enhanced aerobic capacity and improved sport-specific test results in taekwondo athletes. These inconsistent findings highlight the complexity of BJ's acute impact and likely reflect a combination of factors, including the specific nature of the tests employed (e.g., non-specific *vs.* sport-specific), the differing populations studied (recreational *vs.* elite), and potentially varying baseline fitness levels, encompassing not only aerobic capacity but also anaerobic power, strength-endurance, and overall conditioning status crucial for combat sports performance.

Dietary inorganic NO_3^- is reduced sequentially to nitrite (NO_2^-) and NO via enterosalivary and tissue pathways. NO exerts multiple effects that are plausibly relevant for judo: (i) vasodilation and microvascular recruitment; (ii)

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modulation of mitochondrial respiration and reduced oxygen cost of ATP production; and (iii) potential influences on autonomic regulation (parasympathetic reactivation) [14,20]. Given the intermittent, high-intensity nature of judo that alternates maximal explosive efforts and short recovery periods, increased NO availability could therefore improve the efficiency of recovery between efforts and possibly lower metabolic cost for a given output. Based on these mechanisms, we hypothesized that acute BJ would (a) increase systemic NO_3^-, (b) enhance muscle oxygenation recovery and autonomic recovery, (c) improve judo performance efficiency, and (d) reduce metabolic cost, with larger effects in athletes with lower baseline aerobic fitness. To our knowledge, no prior study has directly tested the acute effects of BJ on judo-specific performance or examined how athlete training status influences these effects. In addition, the mechanisms by which acute BJ ingestion causes probable alterations in the special judo performance are not fully understood. Therefore, the aim of this study was to investigate the impact of acute BJ supplementation on the Special Judo Fitness Test (SJFT) outcomes in both elite and recreational judokas.

2. Methods

2.1. Participants

An a priori power analysis (G*Power v. 3.1.9.4) determined that 34 participants were required to detect a difference between conditions, given an estimated effect size of 0.5, a statistical power of 80%, and an alpha error of < 0.05. To account for potential dropouts, we enrolled 40 adult judokas, including 17 elite (national-level; 11 males, 6 females) and 23 recreational (15 males, 8 females) athletes. All participants provided written informed consent after being fully informed about the research procedures, including any risks and benefits. The elite judokas were defined as black belts (1st to 4th Dan) with a minimum of 5 years of experience in judo, averaging ~24 hours of exercise training per week over the preceding 6 months. Crucially, these elite athletes were also active competitors at the national level, possessing at least 3 years of competitive experience at this level, and had achieved a top 3 national ranking within the last year. Conversely, the recreational group comprised individuals holding purple (n=7) or brown (n=16) belts, with ≤3 years of judo experience and ~7 hours of training per week. These athletes primarily participated in club-level training for fitness and personal development and did not have a history of participating in provincial or national championships prior to the study (see **Table 1**). All participants were healthy, free from neuromuscular or musculoskeletal disorders, non-smokers, non-alcohol drinkers, and not

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taking any medications regularly. The study was conducted during the 4-week transition (off-season) phase. During this period, elite athletes continued training 5 times per week (3 judo-specific and 2 general conditioning sessions, including strength training), while recreational athletes trained 3 times per week (judo-specific sessions). Testing in female athletes occurred during the late follicular menstrual phase. Participants were excluded if they experienced any pain or discomfort, failed to complete all trials, or did not follow study instructions. All 40 participants completed the study without any dropouts or adverse events (**Fig. 1:** CONSORT flow diagram).

2.2. Experimental Design

This study used a randomized, double-blind, placebo-controlled crossover design with four sessions for each participant. The familiarization session allowed athletes to practice one set of the SJFT, and they were trained to use the Borg rate of perceived exertion (RPE) scale (6–20). Subsequently, anthropometric and maximal oxygen consumption ($\dot{V}O_2$max) measurements were obtained in the second session, which was carried out three days after the familiarization. Each participant then completed two experimental sessions separated by at least 5 days, allowing for recovery. In each experimental session, participants ingested 140 ml of either BJ (Beet It Sport®, James White Drinks Ltd., UK; ~12.8 mmol NO_3^-, energy ~140 kcal) or placebo (NO_3^--depleted BJ, Beet It Sport®, James White Drinks Ltd., UK; < 0.05 mmol NO_3^-, energy ~140 kcal), which had exactly the same color and taste and were packaged in bottles with the same appearance. The order of supplement administration was randomized and counterbalanced. The RAND function of Excel software was used for randomization, and a researcher who was not involved in data collection and analysis coordinated the randomization. Both participants and investigators were blinded to the treatment. Participants remained seated after consuming BJ or placebo and relaxed in the gym for 120 minutes. Volunteers completed the SJFT under the supervision of a qualified coach. To control for dietary sources of nitrites, participants were instructed to avoid NO_3^--rich foods (e.g., beets, celery, spinach, lettuce, etc.) for 48 hours before each trial. Participants were also instructed to maintain a high-carbohydrate diet for 24 hours prior to the experiments. They recorded all foods and beverages consumed during this 24-hour period, continuing the diet before the second session. A nutritionist provided individualized consultations and monitored dietary adherence throughout the study. Volunteers also refrained from strenuous exercise for 72 hours prior to each test and maintained consistent sleep schedules. All testing sessions were conducted between 07:00 and 10:00 following an

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overnight fast to minimize circadian and dietary influences, allowing for a more precise evaluation of the direct effects of BJ on performance metrics. Verbal encouragement was standardized and given throughout each SJFT trial.

The protocol of this study was in accordance with the Declaration of Helsinki (2013) and was approved by the Ethics Committee for Human Research at International Science and Technology University (202505-03). Informed consent was obtained from all participants. This study was carried out in Turkey and was registered with the Iranian Registry of Clinical Trials (IRCT20231004059615N3) from 2025-05-22.

2.3. Anthropometric and $\dot{V}O_2$max measurements

We first measured body mass and body fat percentage during the second session using a bioelectrical impedance analyzer (InBody 970; Biospace, South Korea). Participants then performed an incremental cycling test to determine $\dot{V}O_2$max. After a 5-minute warm-up at 150 W, the workload increased by 30 W every 3 minutes until volitional exhaustion. Respiratory data ($\dot{V}O_2$, $\dot{V}CO_2$, and ventilation) were collected breath-by-breath using an online metabolic cart (PowerCube-Ergo, Ganshorn, Germany), which was calibrated before each test. The highest 10-second average $\dot{V}O_2$ was recorded as $\dot{V}O_2$max. We confirmed attainment of $\dot{V}O_2$max when at least three of the following criteria were met: (a) a plateau in $\dot{V}O_2$ despite increased workload, (b) respiratory exchange ratio (RER) > 1.20, (c) peak Heart rate (HR) ≥ 90% of age-predicted maximum, and/or (d) observable exhaustion [21].

2.4. SJFT protocol

A standardized warm-up consisting of 5 minutes of jogging was performed, which was followed by 5 minutes of supervised dynamic exercises (such as walking lunges, heel flicks, high knees, big arm circles, leg swings, and jumping jacks) [22], and ending with 5 minutes of the ippon-seoi-nage technique uchikomi (repetition training). Participants then completed the SJFT. The SJFT is a specific evaluation test divided into three periods of effort after 5 minutes of passive rest: (A = 15 seconds, B and C = 30 seconds each), with 10 seconds of intervals between them. Two ukes (thrown colleagues) were positioned 6 meters away, and the tori (participant) ran towards each uke and threw them as many times as possible using the ippon-seoi-nage technique. All athletes involved had similar heights (± 3 cm) and body masses (± 2 kg). HR was measured (Polar RS800CX, Finland) immediately at the end (HR_0) and 1 minute after the test (HR_1). The SJFT index (Index = HR_0 + HR_1 / TT) was calculated from the total number of throws (TT), HR_0, and HR_1; a lower index value indicates better performance in the test [23,24]. Immediately following

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effort C, the participants indicated their perceived exertion levels on the Borg RPE scale. The session ended with a 5-minute cool-down.

2.5. Muscle oxygenation measurements

Muscle oxygenation was recorded continuously during the entire SJFT using a near-infrared spectroscopy system (NIRS). A portable NIRS device (Portamon, Artinis Medical Systems, Netherlands) was placed unilaterally on the vastus lateralis muscle on each subject's dominant side. The NIRS device uses three light source transmitters (each with two wavelengths between 750 and 850 nm) at 30, 35, and 40 mm distance to the receiver to monitor three separate regions of the tissue simultaneously. A sample rate of 10 Hz was used to record the data. The tissue saturation index (TSI, %) was calculated using the manufacturer's software, based on variations in the concentrations of oxygenated hemoglobin, deoxygenated hemoglobin, and total hemoglobin. Baseline TSI was assessed from the resting values recorded over the last 30 s of a 5-minute resting period preceding the start of the SJFT. The averaged TSI was analyzed separately for each part of the SJFT (effort A, rest 1, effort B, rest 2, effort C, 1-minutes post-SJFT recovery). To ensure that all participants had skinfold thicknesses less than 15 mm [25], a skinfold measurement was taken on the dominant side vastus lateralis muscle using a Harpenden skinfold caliper.

2.6. Plasma measurements

Venous blood was drawn from the antecubital vein with participants seated, immediately before the supplementation at baseline, before the onset of exercise, and 5 minutes after exercise into tubes containing ethylenediamine tetra-acetic acid (EDTA). Samples were centrifuged at 3,500 rpm for 10 minutes at 4°C, after which plasma was aliquoted into microcentrifuge tubes and stored at −80°C until analysis. Lactate was measured using a human lactate ELISA kit (ab287808, Abcam). To measure NO_3^- and NO_2^- levels, plasma was deproteinized 1:1 (v/v) with ice-cold methanol, centrifuged at 12,000 g for 10 minutes, and the supernatant diluted with the ENO-20 system’s running buffer (10 mM phosphate, pH 3.0). NO_3^- and NO_2^- were separated on a sulfonated polystyrene-divinylbenzene column maintained at 40 °C and quantified by ion-exclusion high-performance liquid chromatography with post-column Griess derivatization (ENO-20; EiCom, Kyoto, Japan). In this method, NO_2^- reacts directly with Griess reagent to form an azo dye, while NO_3^- is first reduced to NO_2^- in a cadmium reduction column before dye formation; both are detected photometrically at 540 nm. Concentrations were calculated against external calibration curves (0.1–100

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µM), yielding intra- and inter-assay coefficients of variation < 5% [26]. Plasma NO_2^- concentrations were below the assay quantification limit (1 µM) in all participants; therefore, only plasma NO_3^- is reported.

2.7. Blinding efficacy

Participants were asked which supplement they believed they had consumed ("BJ", "placebo", or "I do not know") at the conclusion of each experimental session to evaluate the success of blinding [27].

2.8. Statistical analyses

Data are presented as mean ± standard deviation (SD). Statistical analyses were performed using SPSS version 27. Normality was tested with the Shapiro–Wilk test and homogeneity of variance with Levene's test. The blinding efficacy was assessed by Chi-Square (χ^2) test. Baseline differences between groups (elite vs. recreational) were assessed by independent t-tests. Plasma parameters and NIRS scores were examined with a three-way repeated-measures Analysis of Variance (ANOVA) (time (3) × condition (2) × group (2) for NO_3^- and lactate, and time (7) × condition (2) × group (2) for TSI). Performance outcomes (HR_0, HR_1, TT, and SJFT index) were examined using a two-way repeated-measures ANOVA with condition (2) and group (2) as factors. A two-way repeated-measures ANOVA (time (7) × group (2)) was also carried out on the absolute changes (BJ - placebo) of TSI scores. Bonferroni correction was used to post hoc comparisons if the significant F ratio was detected. Pearson's correlation coefficients were calculated between training status ($\dot{V}O_2max$) and the absolute change in each outcome (BJ - placebo). Effect size for ANOVA was calculated using partial eta squared (ηp^2) (< 0.01, 0.01-0.059, 0.06-0.139, and ≥ 0.14 for trivial, small, moderate, and large effects, respectively). For pairwise comparisons, Hedge's g (g) was calculated to provide a standardized mean difference that accounts for unequal sample sizes, with values of < 0.20, 0.20–0.49, 0.50–0.79, and ≥ 0.80 interpreted as trivial, small, moderate, and large effects, respectively. The 95% confidence intervals (CIs) were also calculated. A p-value < 0.05 was considered statistically significant.

3. Results

All participants completed the study and were included in the statistical analysis. Baseline characteristics are shown in **Table 1**. Elite judokas had a significantly higher $\dot{V}O_2max$ ($p < 0.001$, $g = 2.7$, 95% CI [55.1, 61.2] vs. [43.9, 46.8]), judo experience ($p < 0.001$, $g = 3.1$, 95% CI [6.3, 9] vs. [1.6, 2.2]), and

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training hours per week over the last 6 months ($p < 0.001$, $g = 4$, 95% CI [21.2, 27.6] vs. [6.5, 7.9]) compared with recreational athletes.

The blinding assessment showed that there was no significant difference between the correct responses to recognize BJ and placebo supplementation (χ^2 (1) = 3.340, $p = 0.314$). The blinding answers for the 2 experimental sessions were as follows: mean values (%) for BJ: elite, true =20%, false = 30%, unable = 50%, and recreational, true = 33.3%, false = 25%, unable = 41.6%; for placebo: elite, true = 30%, false = 30%, unable = 40%, and recreational, true = 25%, false = 41.6%, unable = 33.3%.

The analysis of NO_3^- revealed significant main effects of time ($F = 316.509$, $p < 0.001$, $\eta p^2 = 0.89$) and condition ($F = 346.085$, $p < 0.001$, $\eta p^2 = 0.9$), as well as a time × condition interaction ($F = 328.672$, $p < 0.001$, $\eta p^2 = 0.89$). BJ increased NO_3^- concentration in both elite and recreational judokas at pre- (95% CI for elite [491, 670] and recreational [505, 669] judokas) and post-SJFT (95% CI for elite [497, 683] and recreational [619, 690] judokas) compared to baseline (95% CI for elite [32.2, 44.1] and recreational [32, 41.7] judokas) and placebo (95% CI for elite [34.4, 47] and recreational [31.4, 43.1] judokas at pre-SJFT and 95% CI for elite [32.4, 45.3] and recreational [32.7, 44.5] judokas at post-SJFT) ($p < 0.001$, large effects; **Figure 2**).

Three-way repeated-measures ANOVA indicated significant main effects of time ($F = 158.978$, $p < 0.001$, $\eta p^2 = 0.98$) and group ($F = 9.074$, $p < 0.01$, $\eta p^2 = 0.19$), as well as time × group ($F = 5.731$, $p < 0.01$, $\eta p^2 = 0.13$) and time × condition ($F = 16.651$, $p < 0.001$, $\eta p^2 = 0.3$) interactions for lactate. Compared to baseline, lactate concentration increased post-SJFT in both elite (placebo: $p < 0.001$, $g = 5.5$, 95% CI [1.1, 1.4] vs. [15.4, 17.1]; BJ: $p < 0.001$, $g = 6.7$, 95% CI [1.2, 1.6] vs. [15.3, 16.8]) and recreational (placebo: $p < 0.001$, $g = 4.2$, 95% CI [1.1, 1.4] vs. [14.2, 15.7]; BJ: $p < 0.001$, $g = 4$, 95% CI [1, 1.4] vs. [13.8, 15.3]) athletes. Elite athletes had a greater increase in lactate concentration than recreational judokas, regardless of supplementation (placebo: $p < 0.05$, $g = 0.72$; BJ: $p < 0.01$, $g = 0.95$). BJ decreased post-SJFT plasma lactate in recreational athletes ($p < 0.001$, $g = 1.2$) but not in elite athletes ($p = 0.1$, $g = 0.41$; **Figure 3**).

Three-way repeated-measures ANOVA on TSI values showed significant main effects of condition ($F = 22.322$, $p < 0.001$, $\eta p^2 = 0.37$) and time ($F = 107.313$, $p < 0.001$, $\eta p^2 = 0.74$), as well as interaction effects of time × group ($F = 9.058$, $p < 0.001$, $\eta p^2 = 0.19$), condition × time ($F = 7.531$, $p < 0.001$, $\eta p^2 = 0.16$), and condition × time × group ($F = 2.674$, $p < 0.05$, $\eta p^2 = 0.07$). There was not a significant main effect for group ($F = 1.249$, $p = 0.271$, $\eta p^2 = 0.03$) or condition × group ($F = 3.939$, $p = 0.054$, $\eta p^2 = 0.09$) interaction. The significant main effects of time ($F = 7.531$, $p < 0.001$, $\eta p^2 = 0.16$) and time ×

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group interaction ($F = 2.674$, $p < 0.05$, $\eta p^2 = 0.07$) were also observed by the two-way repeated-measures ANOVA on the absolute change of TSI scores. However, the main effect of group was not statistically significant ($F = 3.939$, $p = 0.054$, $\eta p^2 = 0.09$). Regardless of supplementation, TSI decreased during different periods of the SJFT compared to baseline values ($p < 0.01$, moderate to large effects), with greater reduction observed in elite athletes ($p < 0.05$, moderate to large effects). The tissue oxygen re-saturation during the 1-minute recovery period was also faster in elite athletes than in recreational athletes during both placebo ($p < 0.01$, $g = 0.89$, 95% CI [8.3, 13.4] vs. [3.4, 8.5]) and BJ conditions ($p < 0.001$, $g = 1.4$, 95% CI [11.2, 15.2] vs. [5.8, 9.3]). During the second ($p < 0.001$, $g = 0.74$, 95% CI [58.1, 63.7] vs. [55, 61.9]) and third ($p < 0.001$, $g = 0.95$, 95% CI [55.5, 60.9] vs. [51.5, 58.7]) periods of effort (efforts B and C), as well as during the second 10-second rest period ($p < 0.01$, $g = 0.74$, 95% CI [59.2, 64.5] vs. [56.9, 63.3]) in SJFT, the TSI scores of recreational, but not elite athletes, were increased in the BJ condition compared to the placebo condition. Compared to the placebo condition, BJ increased TSI during the 1-minute recovery after the test in both elite ($p < 0.01$, $g = 0.85$, 95% CI [60.2, 67.7] vs. [63.2, 69.9]) and recreational athletes ($p < 0.001$, $g = 1.7$, 95% CI [57.9, 63.8] vs. [62.8, 68.2]), with a significantly greater effect in the recreational group ($p < 0.05$, $g = 0.7$; **Figure 4)**.

No significant main effects were detected for group ($F = 0.775$, $p = 0.384$, $\eta p^2 = 0.02$) or condition ($F = 0.594$, $p = 0.446$, $\eta p^2 = 0.01$), as well as the group × condition interaction effect ($F = 0.163$, $p = 0.689$, $\eta p^2 = 0.00$) for HR_0. In contrast, HR_1 exhibited significant main effects of group ($F = 48.588$, $p < 0.001$, $\eta p^2 = 0.71$) and condition ($F = 123.029$, $p < 0.001$, $\eta p^2 = 0.76$), as well as a significant group × condition interaction ($F = 13.812$, $p < 0.001$, $\eta p^2 = 0.27$). Specifically, recreational judokas had higher HR_1 than elites under both placebo ($p < 0.001$, $g = 3.4$, 95% CI [156, 162] vs. [134, 140]) and BJ ($p < 0.001$, $g = 2.6$, 95% CI [141, 146] vs. [127, 131]) conditions, and BJ ingestion significantly reduced HR_1 compared to placebo (elite: $p < 0.001$, $g = 1.6$; recreation: $p < 0.001$, $g = 2$). The group × condition interaction indicates that recreational athletes experienced a larger decrease in HR_1 with BJ than elite athletes (**Table 2**).

For TT, only the group effect was significant ($F = 64.480$, $p < 0.001$, $\eta p^2 = 0.63$): elite athletes performed more throws than recreational judokas (placebo: 95% CI [28.2, 29.9] vs. [24.1, 25.7]; BJ: 95% CI [28.1, 30.3] vs. [24.7, 25.8]). There was no significant main effect of condition ($F = 0.947$, $p = 0.337$, $\eta p^2 = 0.02$), and no interaction ($F = 0.232$, $p = 0.633$, $\eta p^2 = 0.01$) on TT (**Table 2**).

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The SJFT index showed significant main effects of group ($F = 37.391$, $p < 0.001$, $\eta p^2 = 0.65$) and condition ($F = 23.927$, $p < 0.001$, $\eta p^2 = 0.39$) as well as their interaction ($F = 5.591$, $p < 0.05$, $\eta p^2 = 0.13$). Elite athletes had a lower SJFT index than recreational judokas under both placebo ($p < 0.001$, $g = 2.7$, 95% CI [10.6, 11.4] vs. [13.3, 14.3]) and BJ ($p < 0.001$, $g = 2.6$, 95% CI [10.3, 11.1] vs. [12.6, 13.3]) conditions, and BJ ingestion led to a lower index (better performance) compared to placebo (elite: $p < 0.05$, $g = 0.68$; recreation: $p < 0.001$, $g = 1$). Additionally, the group × condition interaction suggests that recreational athletes experienced a larger decrease in the SJFT index following BJ supplementation than elite athletes (**Table 2**).

There were no significant main effects of group ($F = 0.578$, $p = 0.482$, $\eta p^2 = 0.01$) or condition ($F = 2.782$, $p = 0.104$, $\eta p^2 = 0.07$), nor interaction effects ($F = 0.917$, $p = 0.344$, $\eta p^2 = 0.02$) for RPE (**Table 2**).

The absolute changes (BJ - placebo) for study outcomes in elite and recreational athletes are presented in **Table S1**. We observed a significant moderate correlation coefficient between $\dot{V}O_2max$ and the absolute change in lactate ($r = - 0.57$, $p < 0.001$), HR_1 ($r = - 0.50$, $p < 0.001$), SJFT index ($r = - 0.43$, $p < 0.01$), and TSI during the third period of SJFT effort ($r = - 0.5$, $p < 0.001$) and during 1-minute recovery ($r = - 0.34$, $p < 0.05$). There was no significant correlation between $\dot{V}O_2max$ and the absolute change in HR_0 ($r = - 0.06$, $p > 0.05$), TT ($r = 0.19$, $p > 0.05$), RPE ($r = - 0.27$, $p > 0.05$), or TSI during the baseline ($r = 0.06$, $p > 0.05$), first period of effort ($r = 0.16$, $p > 0.05$), first period of rest ($r = - 0.04$, $p > 0.05$), second period of effort ($r = - 0.12$, $p > 0.05$), and second period of rest ($r = - 0.3$, $p > 0.05$) in the SJFT (**Figure 5**).

4. Discussion

The primary aim of this study was to assess the acute effects of BJ on judo-specific performance outcomes, and the secondary aim was to determine how training status modulates BJ's ergogenic effects. Our findings indicate that elite judokas generally performed better on the SJFT, executing more throws and having lower HR_1 and SJFT index values compared to recreational judokas; however, they exhibited lower TSI during the SJFT and higher post-SJFT TSI and lactate levels than recreational athletes, regardless of supplement intake. Acute BJ ingestion resulted in almost similar increases in plasma NO_3^- of both elite and recreational athletes (elite: 1587 ± 654% vs. recreational: 1787 ± 1133%, $p = 0.487$, effect size = 0.21). BJ accelerated tissue O_2 re-saturation, attenuated HR_1, and reduced the SJFT index across both groups, indicating faster post-exercise recovery. Importantly, although the SJFT index improved after BJ — largely driven by reductions in HR_1 — the primary task outcome, TT, did not increase significantly in either group. Therefore, the principal finding

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is that acute BJ improved physiological recovery efficiency rather than significantly increasing the performance within the fixed SJFT time. This distinction is critical because a lower SJFT index with unchanged TT indicates faster recovery and lower physiological cost for the same performance output. In addition, recreational athletes experienced a greater reduction in HR_1 (elite: -5.6 ± 3.3% vs. recreational: -9.8 ± 4.7%, $p < 0.01$) and SJFT index (elite: -2.7 ± 5.6% vs. recreational: -6 ± 5.8%, $p < 0.05$) as well as a greater increase in post-SJFT TSI (elite: 2.6 ± 3% vs. recreational: 4.55 ± 2.6%, $p < 0.05$) with BJ than elites. BJ also decreased post-SJFT lactate only in the recreational athletes (-2.86 ± 2.5% in recreational vs. -0.93 ± 2.4% in elite judokas, $p < 0.05$). The inverse correlations between $\dot{V}O_2max$ and BJ-induced improvements in lactate, HR_1, SJFT index, and TSI during 1-minute recovery indicate that less-fit athletes gained more benefit from BJ. These findings suggest that the recovery ergogenic effects of acute BJ are influenced by training status, with more pronounced effects observed in athletes with lower fitness levels.

Our study indicates that elite judokas achieved a higher average TT compared to recreational judokas. However, the modest increases in TT following BJ consumption (0.45 ± 5.5% for elite athletes and 1.7 ± 5.8% for recreational athletes) did not reach statistical significance ($p > 0.05$). Given that the SJFT employs a fixed duration for each segment (A: 15 s; B: 30 s; C: 30 s) and the average time per throw for our athletes was approximately 2.4 seconds (elite) to 2.8 seconds (recreational), the window for acutely increasing the TT within the constrained timeframe is inherently limited. The primary physiological adaptations influenced by BJ, such as improved oxygen utilization and reduced ATP cost of muscle contraction, are more likely to manifest as an enhanced capacity for sustained high-intensity efforts and accelerated recovery kinetics, rather than a direct, acute increase in the rate or force production of individual, near-maximal actions performed in rapid succession. Therefore, while BJ may have conferred subtle benefits to throw efficiency or fatigue resistance, these benefits were insufficient to translate into a statistically significant increase in the TT within the brief, fixed work periods of the SJFT. This finding is consistent with literature in other combat sports where similar fixed-duration, high-intensity tests did not show changes in primary output after BJ supplementation, despite improvements in underlying aerobic capacity or fatigue markers [18]. Moreover, it is more likely that our study was underpowered to detect statistically significant changes in TT and a larger sample size may be need to detect such smaller performance changes.

Our findings of no effects of BJ on HR_0 or RPE are consistent with previous studies indicating that BJ supplementation does not affect RPE [18,28,29] or maximal HR [18,30] immediately at the end of the exercise. HR_1 is a simple

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marker of parasympathetic reactivation after exercise. Faster HR recovery is advantageous in sports like judo, where athletes may need to perform multiple high-intensity efforts during the competition day or when judokas undergo multiple training sessions in a day [31]. In our study, BJ accelerated HR recovery (lower HR_1) in both groups, with a larger effect in recreational athletes. This faster recovery likely underlies the improved SJFT index. The greater impact on recreational judokas and the negative correlation with $\dot{V}O_2max$ suggest that those with lower fitness had more capacity for improvement. The mechanism may involve increased NO availability, enhancing parasympathetic (vagal) activation post-exercise [32]. Additionally, the lower lactate in recreational athletes after acute BJ supplementation suggests reduced physiological cost of equivalent performance. This likely results from BJ-enhanced muscle perfusion and mitochondrial efficiency, which decrease reliance on anaerobic glycolysis and aid post-test recovery.

The SJFT index (which combines HR and throws) improved in both groups after BJ, primarily due to lower HR_1. Since throws did not change significantly, the index gains reflect better recovery. The larger index improvement in recreational judokas (and its inverse relationship with $\dot{V}O_2max$) further supports that lower-fit athletes responded more to BJ. This suggests that an acute dose of BJ can improve physiological recovery in judo-specific performance, especially in recreational athletes.

TSI quantifies the average O_2 saturation of the tissue based on the dynamic balance between O_2 supply and demand [25]. Our NIRS data reveal clear effects on muscle oxygenation during and after the SJFT. TSI declined during each bout of intense throwing, reflecting high O_2 extraction. This desaturation was greater in elite judokas (a larger drop from baseline) than in recreational judokas, indicating that they achieved higher muscle O_2 utilization per effort. In other words, elite muscles extracted more O_2 (lower TSI) under load, consistent with their superior anaerobic/aerobic capacity. During the 1-minute post-SJFT recovery, TSI returned (re-saturated) toward baseline. Elite athletes showed faster re-saturation than recreational athletes, reflecting their better capillarization and blood flow recovery.

Interestingly, acute BJ ingestion accelerated the post-SJFT re-saturation of muscle TSI in both groups. This likely suggests that NO_3^--enhanced NO availability increased blood perfusion to recovering muscles, elevating O_2 supply. In support of this observation, Tan et al. (2022) found that BJ sped reoxygenation (increased TSI) during recovery after resistance exercise [33]. Moreover, dietary NO_3^- has been shown to improve muscle perfusion and oxygenation (e.g., increased microvascular O_2 delivery after exercise) [20]. In this study, BJ increased muscle oxygenation during efforts B-to-C only in

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recreational judokas. In addition, recreational athletes experienced a larger BJ-induced increase in post-SJFT TSI than elites. This disparity again aligns with training status; less-fit muscles are more responsive to augmented NO-mediated blood flow, whereas elite muscles already have efficient perfusion. Therefore, BJ more effectively increased muscle oxygenation during judo efforts as well as during recovery, especially in recreational judokas, which likely facilitates oxygen utilization during exercise and faster clearance of metabolites, thereby promoting performance recovery.

It is important to note that BJ's ergogenic effects may depend on multiple factors, such as the type of exercise, supplementation protocol (acute vs. chronic), dose and timing of intake, control of dietary NO_3^-, and individual characteristics (e.g., sex, fitness level) [18,34,35]. This study provides the first direct comparison of how physical fitness influences acute BJ effects in judo. Our results are consistent with evidence that well-trained athletes often experience minimal benefits from BJ [29,36-38], whereas recreational athletes can gain more benefits [17,39]. For example, Fernández-Elías et al. [36] reported no match performance improvement in professional tennis players after BJ, whereas Wylie et al. [39] found that recreational team-sport players improved their Yo-Yo test by ~4% following BJ supplementation. According to the study by Peacock et al. [40], ingestion of NO_3^- 2.5 h before exercise neither reduced submaximal oxygen consumption during a low-intensity exercise nor enhanced 5-km running performance compared with placebo in well-trained cross-country skiers. Another study by Porcelli et al. [41] demonstrated that less-fit runners improved their 3-km running time with chronic NO_3^- supplementation, while highly trained runners did not. The greater BJ-induced changes in recreational athletes may reflect a larger scope for improvement compared with elite athletes (i.e., a ceiling effect). The concept of a ceiling effect in this context refers not solely to maximal aerobic capacity, but rather to the relative developmental stage of the NO pathway and associated microvascular and mitochondrial efficiencies within a judo-specific elite athlete population. Elite judokas, through years of high-intensity intermittent training, are expected to have already optimized many aspects of their NO bioavailability and downstream physiological processes (e.g., capillary density, mitochondrial function) to a greater extent than recreational counterparts. While their absolute $\dot{V}O_2$max might not reach that of an elite endurance athlete, their specific physiological adaptations for their sport are highly developed. Therefore, the relative possibility for additional improvement from exogenous NO_3^- supplementation, even with a $\dot{V}O_2$max of 58.2 ml/kg/min, is inherently smaller compared to less-trained individuals. Conversely, less-trained individuals frequently have lower baseline NO

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bioavailability, less developed capillary density, less efficient microvascular control, and lower mitochondrial oxidative capacity. Thus, exogenous NO_3^-, despite the same systemic increase in NO_3^-, may produce a larger relative physiological change. Enhanced microvascular recruitment during effort could increase O_2 delivery and allow greater oxidative ATP production, thereby reducing reliance on anaerobic glycolysis and lowering lactate accumulation. This effect could also alter local O_2 extraction dynamics and greater re-saturation during recovery when perfusion is improved [36,41].

Although chronic BJ supplementation is often recommended to maximize ergogenic effects [11,39,41], our study extends previous reports by indicating that acute consumption of BJ induces ergogenic effects on performance recovery. Importantly, this study is the first to show such effects on a judo-specific performance. While our study demonstrated statistically significant improvements in several physiological recovery markers following BJ supplementation, it is crucial to differentiate between statistical significance and practical or competitive relevance, particularly given the absence of a significant effect on TT. The small sample size and/or a fixed, short-duration nature of the SJFT may limit its sensitivity to detect subtle improvements in throw rate that do not directly translate into an increase in whole numbers within the given timeframe. However, the observed attenuation of physiological cost and improved recovery markers hold substantial practical significance for judo athletes. In competitive judo, athletes often engage in multiple high-intensity bouts within a single day or tournament. The ability to recover more rapidly and mitigate cumulative fatigue between these efforts is critical for maintaining performance quality, decision-making, and technique across successive matches. BJ's capacity to reduce the metabolic burden of exercise and accelerate recovery could therefore enhance an athlete's preparation for subsequent bouts, improve training adaptations over time, and potentially reduce the risk of fatigue-related errors or injuries. Thus, while not directly increasing the TT in an isolated test, the enhanced recovery profile observed with BJ may contribute significantly to a judoka's overall competitive endurance and sustained performance in real-world, multi-bout scenarios. BJ represents a natural, accessible, and cost-effective recovery ergogenic aid for judokas at all levels, particularly for recreational or developing athletes who may benefit most from this substance and may not have access to more expensive supplementation strategies.

Several limitations should be considered when interpreting the results. First, the study sample comprised primarily young adults, and results may not directly apply to adolescent or older judokas due to potential age-related differences in physiological responses. Second, although our sample size was

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calculated to detect small to moderate effects, the observed modest increase in TT, though not statistically significant, suggests the statistical power for detecting smaller effects related to this specific outcome might have been insufficient. To provide a more constructive perspective on statistical power for TT, a post-hoc power analysis was performed based on the observed mean differences and SDs for TT and an alpha level of 0.05. The statistical power for detecting the observed effect was approximately 7.8% for elite judokas (Cohen's d = 0.08) and 20.9% for recreational judokas (Cohen's d = 0.25). These low post-hoc power values strongly suggest that our study was indeed underpowered to detect statistically significant changes in TT, increasing the likelihood of a Type II error for this outcome. A larger sample size, therefore, is necessary to fully capture such smaller performance changes. Third, the heterogeneity of our study population, which included both male and female participants across two distinct training levels, warrants discussion. While this design allowed for insights into differential responsiveness based on training status, it introduces variability. To address potential confounding, we performed statistical analyses to test for main effect of sex and sex × intervention interaction effects for study outcomes, and no significant interactions were detected ($p > 0.05$). This suggests that the primary effects of BJ were consistent across sexes within our study cohort. However, we acknowledge that the relatively small sample sizes for each subgroup preclude definitive conclusions regarding subtle sex-specific responses. Therefore, while our findings suggest a generalized effect across sexes for the studied outcomes, the generalizability to specific sex-defined populations should be interpreted with caution. Future research with larger, sex-balanced cohorts is encouraged to explore potential nuanced sex-specific responses to BJ supplementation in judo. Fourth, our pre-test standardization protocol did not control for other acute factors known to influence performance, such as recent sexual activity [42], or account for seasonal/environmental variations [43], which could potentially modulate responses to supplementation or exercise. Regarding measurement, blood lactate was assessed only at 5 minutes post-exercise, a time point chosen based on our pilot data indicating peak lactate occurrence at this interval (12.3 ± 2.1, 14.2 ± 2.7, and 13.7 ± 2.6 mmol/L in 3, 5 and 8 minutes after SJFT, respectively). However, this single time point may not fully capture the complete lactate trajectory due to inter-individual variability in accumulation and clearance rates. While plasma NO_3^- levels increased significantly following BJ supplementation, however, plasma NO_2^- concentrations were below the assay's quantification limit, preventing direct measurement. Similarly, we did not obtain skeletal muscle biopsies or continuous autonomic measures (e.g., HR variability). Therefore, while the

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observed physiological changes (e.g., reduced HR_1, faster TSI re-saturation) are compelling, direct proof that enhanced NO availability mediated these effects via specific vascular or autonomic pathways requires future research incorporating more detailed tissue-level measurements and continuous monitoring.

5. Conclusions

Acute BJ supplementation (~12.8 mmol NO_3^-) primarily reduced the physiological cost and enhanced recovery-related markers during the special judo performance, particularly in less-trained athletes, without significantly increasing performance. These findings suggest that BJ improves recovery efficiency (recovery ergogenic) rather than direct task output (performance ergogenic) in the context of high-intensity explosive bouts like the SJFT, with training status modulating responsiveness.

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Author contributions

Investigation, Conceptualization and Methodology: D.K., H.S., and I.G.; Data curation: I.G., B.F., E.K., and S.A.; Formal analysis: D.K., M.B., and H.S.; Writing – original draft: I.G., B.F., E.K., S.A., M.B., and I.L.; Writing – review and editing: D.K., H.S., and I.L.; Project administration: D.K. All authors have read and agreed to the final manuscript.

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Data availability

All data sets are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no potential conflicts of interest.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors utilized ChatGPT to improve the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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References

1 Miarka, B. *et al.* A comparison of time-motion performance between age groups in judo matches. *Journal of Sports Sciences* **30**, 899–905 (2012).

2 Branco, B. H. *et al.* Association between the rating perceived exertion, heart rate and blood lactate in successive judo fights (randori). *Asian Journal of Sports Medicine* **4**, 125 (2013).

3 Julio, U. F. *et al.* Energy-system contributions to simulated judo matches. *International Journal of Sports Physiology and Performance* **12**, 676–683 (2017).

4 Abdo, E., et al. Nutritional evaluation of beetroots (Beta vulgaris L.) and its potential application in a functional beverage. Plants 9, (12), 1752 (2020).

5 Balsalobre-Fernández, C. *et al.* The effects of beetroot juice supplementation on exercise economy, rating of perceived exertion and running mechanics in elite distance runners: A double-blinded, randomized study. *PloS One* **13**, e0200517 (2018).

6 Fulford, J. *et al.* Influence of dietary nitrate supplementation on human skeletal muscle metabolism and force production during maximum voluntary contractions. *Pflügers Archiv-European Journal of Physiology* **465**, 517–528 (2013).

7 Hemmatinafar, M. *et al.* Effect of Beetroot Juice Supplementation on Muscle Soreness and Performance Recovery after Exercise-Induced Muscle Damage in Female Volleyball Players. *Nutrients* **15**, 3763 (2023).

8 McMahon, N. F., Leveritt, M. D. & Pavey, T. G. The effect of dietary nitrate supplementation on endurance exercise performance in healthy adults: a systematic review and meta-analysis. *Sports Medicine* **47**, 735–756 (2017).

9 Ranchal-Sanchez, A. *et al.* Acute effects of beetroot juice supplements on resistance training: A randomized double-blind crossover. *Nutrients* **12**, 1912 (2020).

10 Thompson, C. *et al.* Dietary nitrate improves sprint performance and cognitive function during prolonged intermittent exercise. *European Journal of Applied Physiology* **115**, 1825–1834 (2015).

11 Wong, T. H., Sim, A. & Burns, S. F. The effect of beetroot ingestion on high-intensity interval training: a systematic review and meta-analysis. *Nutrients* **13**, 3674 (2021).

12 Shannon, O. M. *et al.* “Beet-ing” the mountain: a review of the physiological and performance effects of dietary nitrate supplementation at simulated and terrestrial altitude. *Sports Medicine* **47**, 2155–2169 (2017).

13 Bakker, E. *et al.* Acute dietary nitrate supplementation improves arterial endothelial function at high altitude: a double-blinded randomized controlled cross over study. *Nitric Oxide* **50**, 58–64 (2015).

14 Jones, A. M. Dietary nitrate supplementation and exercise performance. *Sports Medicine* **44**, 35–45 (2014).

ARTICLE IN PRESS

15 Larsen, F., Weitzberg, E., Lundberg, J. & Ekblom, B. Effects of dietary nitrate on oxygen cost during exercise. *Acta Physiologica* **191**, 59–66 (2007).
16 Larsen, F. J. *et al.* Dietary inorganic nitrate improves mitochondrial efficiency in humans. *Cell Metabolism* **13**, 149–159 (2011).
17 de Oliveira, G. V., do Nascimento, L. D., Volino-Souza, M., do Couto Vellozo, O. & Alvares, T. S. A single oral dose of beetroot-based gel does not improve muscle oxygenation parameters, but speeds up handgrip isometric strength recovery in recreational combat sports athletes. *Biology of Sport* **37**, 93–99 (2020).
18 Miraftabi, H. *et al.* Effects of beetroot juice supplementation on cognitive function, aerobic and anaerobic performances of trained male taekwondo athletes: A pilot study. *International journal of Environmental Research and Public Health* **18**, 10202 (2021).
19 Antonietto, N. R. *et al.* Beetroot extract improves specific performance and oxygen uptake in taekwondo athletes: A double-blind crossover study. *Ido Movement for Culture* **21** (2021).
20 Jones, A. M. *et al.* Dietary nitrate and nitric oxide metabolism: mouth, circulation, skeletal muscle, and exercise performance. *Medicine & Science in Sports & Exercise* **53**, 280–294 (2021).
21 Siahkouhian, M., Khodadadi, D. & Bolboli, L. Diurnal variation of haemostatic response to exercise in young sedentary males. *Biology of sport* **30**, 125–130 (2013).
22 Turki, O. *et al.* Dynamic warm-up with a weighted vest: Improvement of repeated change-of-direction performance in young male soccer players. *International Journal of Sports Physiology and Performance* **15**, 196–203 (2020).
23 Merola, P. K. *et al.* High load inspiratory muscle warm-up has no impact on Special Judo Fitness Test performance. *Idō Movement for Culture* **19** (2019).
24 Štefanovský, M., Poliak, M., Augustovičová, D., Kraček, S. & Hadža, R. Test and re-test reliability of the Special Judo Fitness Test. *Acta Facultatis Educationis Physicae Universitatis Comenianae* **61**, 97–106 (2021).
25 Perrey, S. & Ferrari, M. Muscle oximetry in sports science: a systematic review. *Sports Medicine* **48**, 597–616 (2018).
26 Tsikas, D. Analysis of nitrite and nitrate in biological fluids by assays based on the Griess reaction: appraisal of the Griess reaction in the L-arginine/nitric oxide area of research. *Journal of Chromatography B* **851**, 51–70 (2007).
27 Khodadadi, D. *et al.* Habitual Caffeine Consumption and Training Status Affect the Ergogenicity of Acute Caffeine Intake on Exercise Performance. *Sports Health*, 19417381251315093 (2025).
28 Collins, S. M. & Kearns, D. The effect of beetroot supplementation on high-intensity functional training performance. *International Journal of Exercise Science* **13**, 667 (2020).
29 Garnacho-Castaño, M. V. *et al.* Effects of a single dose of beetroot juice on cycling time trial performance at ventilatory thresholds intensity in male

ARTICLE IN PRESS

triathletes. *Journal of the International Society of Sports Nutrition* **15**, 1–12 (2018).
30 de Castro, T. F., Manoel, F. d. A., Figueiredo, D. H., Figueiredo, D. H. & Machado, F. A. Effect of beetroot juice supplementation on 10-km performance in recreational runners. *Applied Physiology, Nutrition, and Metabolism* **44**, 90–94 (2019).
31 Franchini, E., Artioli, G. G. & Brito, C. J. Judo combat: time-motion analysis and physiology. *International journal of Performance Analysis in sport* **13**, 624–641 (2013).
32 Benjamim, C. J. R. *et al.* Negligible Effects of Nutraceuticals from Beetroot Extract on Cardiovascular and Autonomic Recovery Response following Submaximal Aerobic Exercise in Physically Active Healthy Males: A Randomized Trial. *International Journal of Environmental Research and Public Health* **20**, 4019 (2023).
33 Tan, R. *et al.* Effects of dietary nitrate supplementation on performance and muscle oxygenation during resistance exercise in men. *Nutrients* **14**, 3703 (2022).
34 Kokkinoplitis, K. & Chester, N. The effect of beetroot juice on repeated sprint performance and muscle force production. *Journal of Physical Education and Sport* **14**, 242 (2014).
35 Wylie, L. J. *et al.* Beetroot juice and exercise: pharmacodynamic and dose-response relationships. *Journal of Applied Physiology* **115**, 325–336 (2013).
36 Fernandez-Elias, V. *et al.* Acute beetroot juice supplementation does not improve match-play activity in professional tennis players. *Journal of the American Nutrition Association* **41**, 30–37 (2022).
37 López-Samanes, Á., Gómez Parra, A., Moreno-Pérez, V. & Courel-Ibáñez, J. Does acute beetroot juice supplementation improve neuromuscular performance and match activity in young basketball players? A randomized, placebo-controlled study. *Nutrients* **12**, 188 (2020).
38 Muggeridge, D. J. *et al.* The effects of a single dose of concentrated beetroot juice on performance in trained flatwater kayakers. *International Journal of Sport Nutrition and Exercise Metabolism* **23**, 498–506 (2013).
39 Wylie, L. J. *et al.* Dietary nitrate supplementation improves team sport-specific intense intermittent exercise performance. *European Journal of Applied Physiology* **113**, 1673–1684 (2013).
40 Peacock, O. *et al.* Dietary nitrate does not enhance running performance in elite cross-country skiers. *Med Sci Sports Exerc* **44**, 2213–2219 (2012).
41 Porcelli, S. *et al.* Aerobic fitness affects the exercise performance responses to nitrate supplementation. *Medicine and science in sports and exercise* **47**, 1643–1651 (2015).
42 Dhahbi, W. *et al.* Acute and delayed effects of sexual activity on athletic performance: a scoping review across sex, age, and ethnicity. *International Journal of Sports Physiology and Performance* **1**, 1–12 (2026).

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43 Dhahbi, W. *et al.* Seasonal weather conditions affect training program efficiency and physical performance among special forces trainees: A long-term follow-up study. *PloS One* **13**, e0206088 (2018).

Table 1. Participant baseline characteristics.

	Elite (n = 17)	**Recreational** (n = 23)
Age (y)	24.7 ± 3.7	22.9 ± 2.9
Sex	Male = 11, Female = 6	Male = 15, Female = 8
Height (cm)	177.3 ± 6.6	178.8 ± 8.2
Body mass (kg)	84 ± 21.3	81.5 ± 19.2
Body fat (%)	13.7 ± 3.2	15.5 ± 3.8
$\dot{V}O_2$max (ml/kg/min)	58.2 ± 5.9*	45.4 ± 3.4
Judo experience (year)	7.7 ± 2.6*	2.2 ± 1.3
Training hours/week (h)	24.4 ± 6.1*	7.2 ± 1.6

Data are presented as mean ± standard deviation. The judo athletes spanned multiple weight categories from -49 to +100 kg. * $P < 0.001$ different from recreational athletes. $\dot{V}O_2$max, maximal oxygen consumption.

Table 2. SJFT outcomes following BJ and placebo consumption in elite and recreational judo athletes.

	BJ		**Placebo**	
	Elite	**Recreational**	**Elite**	**Recreational**
TT (n)	29.2 ± 2.1*	25.2 ± 1.3	29 ± 1.6*	24.9 ± 1.9
HR0 (beats/min)	180.8 ± 6.3	182.4 ± 6.6	181 ± 6.4	183 ± 6.8
HR_1 (beats/min)	129.3 ± 3.6*#	143.3 ± 6.2#$	137.2 ± 5.5*	159.1 ± 6.6
SJFT index	10.7 ± 0.8*#	12.9 ± 0.9#$	11 ± 0.7*	13.8 ± 1.2
RPE	13.2 ± 1.6	13.3 ± 1.5	13.4 ± 1.4	13.9 ± 1.4

Data are presented as mean ± standard deviation. SJFT, Special Judo Fitness Test; TT, total number of throws; HR0, heart rate immediately at the end of SJFT; HR_1, heart rate 1 minute after SJFT; RPE, rate of perceived exertion. * $P < 0.05$ different from recreational athletes; # $P < 0.05$ different from placebo condition. $ $P < 0.05$ larger change with BJ than elite athletes.

Figure legend

Figure 1. The CONSORT flow diagram.

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Figure 2. Plasma nitrate (NO_3^-) concentration after a single dose ingestion of beetroot juice (BJ) and Special Judo Fitness Test (SJFT). * $P < 0.001$ different from baseline (pre-supplement); # $P < 0.001$ different from placebo condition.

Figure 3. Plasma lactate concentration after Special Judo Fitness Test (SJFT) following beetroot juice (BJ) or placebo. * $P < 0.001$ different from baseline (pre-supplement); # $P < 0.01$ different from placebo condition; $ $P < 0.05$ different from recreational athletes.

Figure 4. Tissue saturation index (TSI) during Special Judo Fitness Test (SJFT) after beetroot juice (BJ) or placebo intake in elite (**A**) and recreational athletes (**B**). The absolute changes (BJ - placebo) of TSI scores during the SJFT (**C**). * $P < 0.01$ different from baseline; # $P < 0.05$ different between BJ and placebo condition; $ $P < 0.05$ different between elite and recreational athletes.

Figure 5. Correlation coefficients between training status expressed by $\dot{V}O_2max$ and the absolute change in Special Judo Fitness Test (SJFT), heart rate immediately at the end of SJFT (HR_0), heart rate 1 minute after SJFT (HR_1), total number of throws (TT), rate of perceived exertion (RPE), and tissue saturation index (TSI) during different periods of the SJFT.

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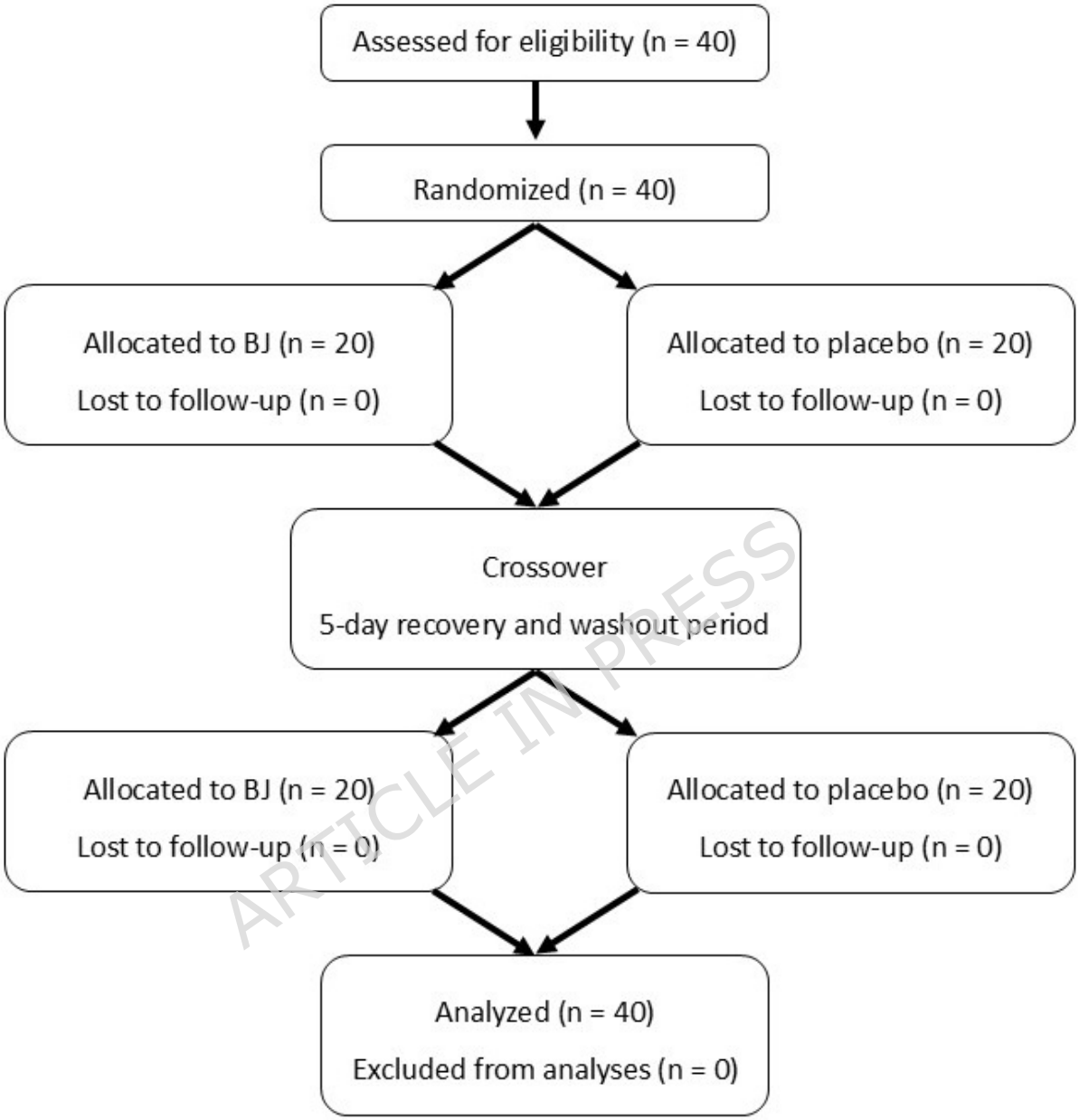

Figure 1.

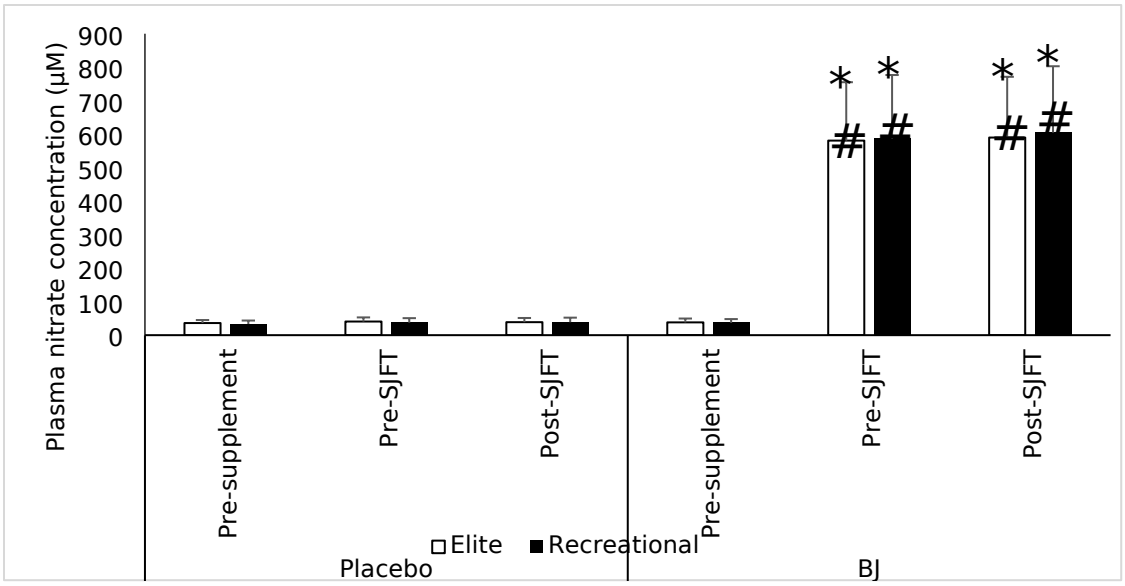

Figure 2.

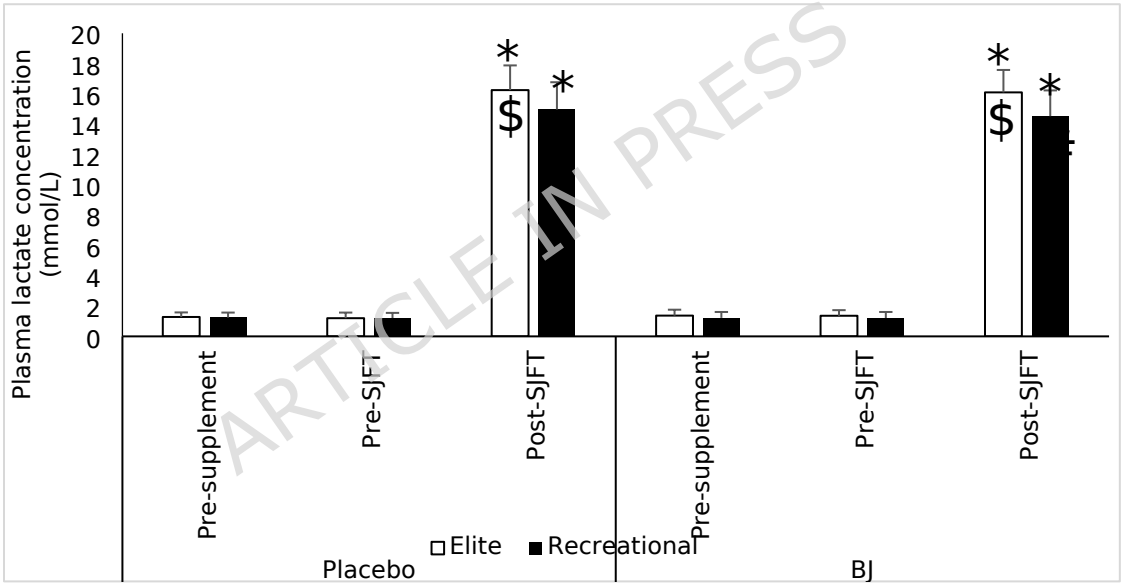

Figure 3.

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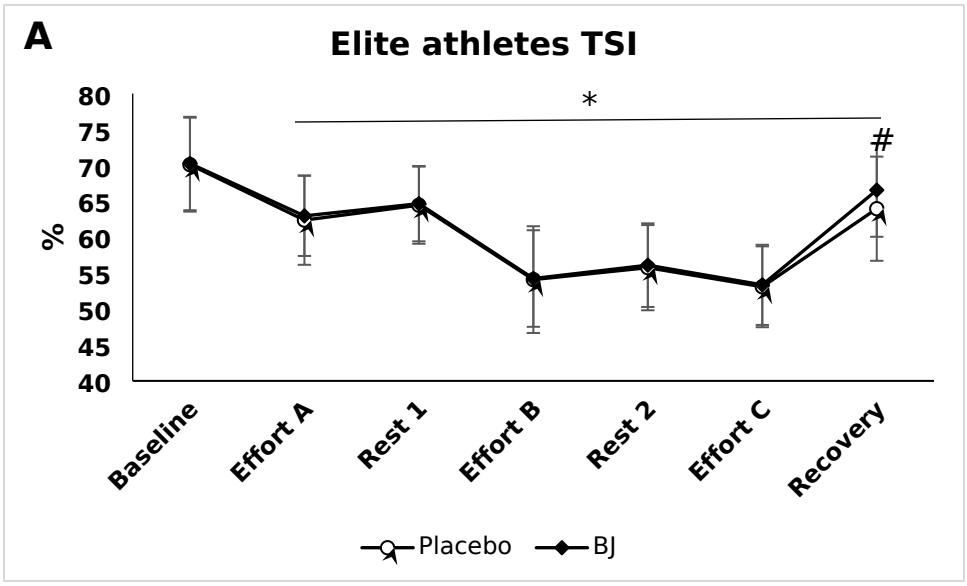

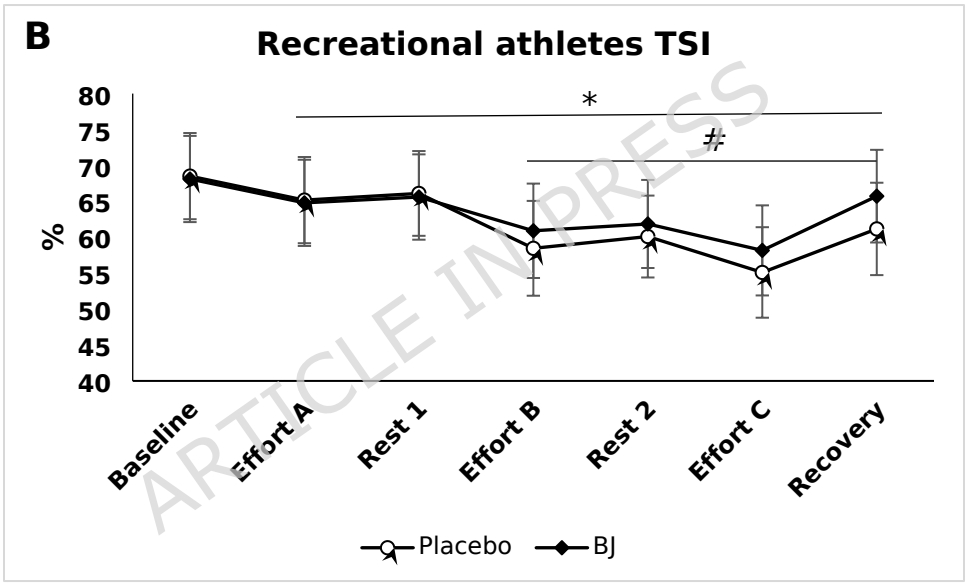

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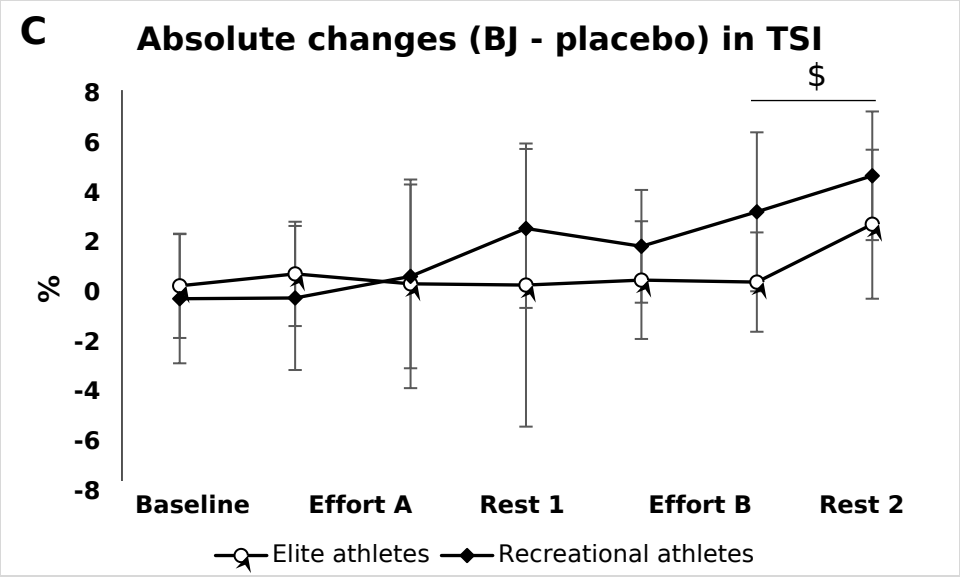

Figure 4.

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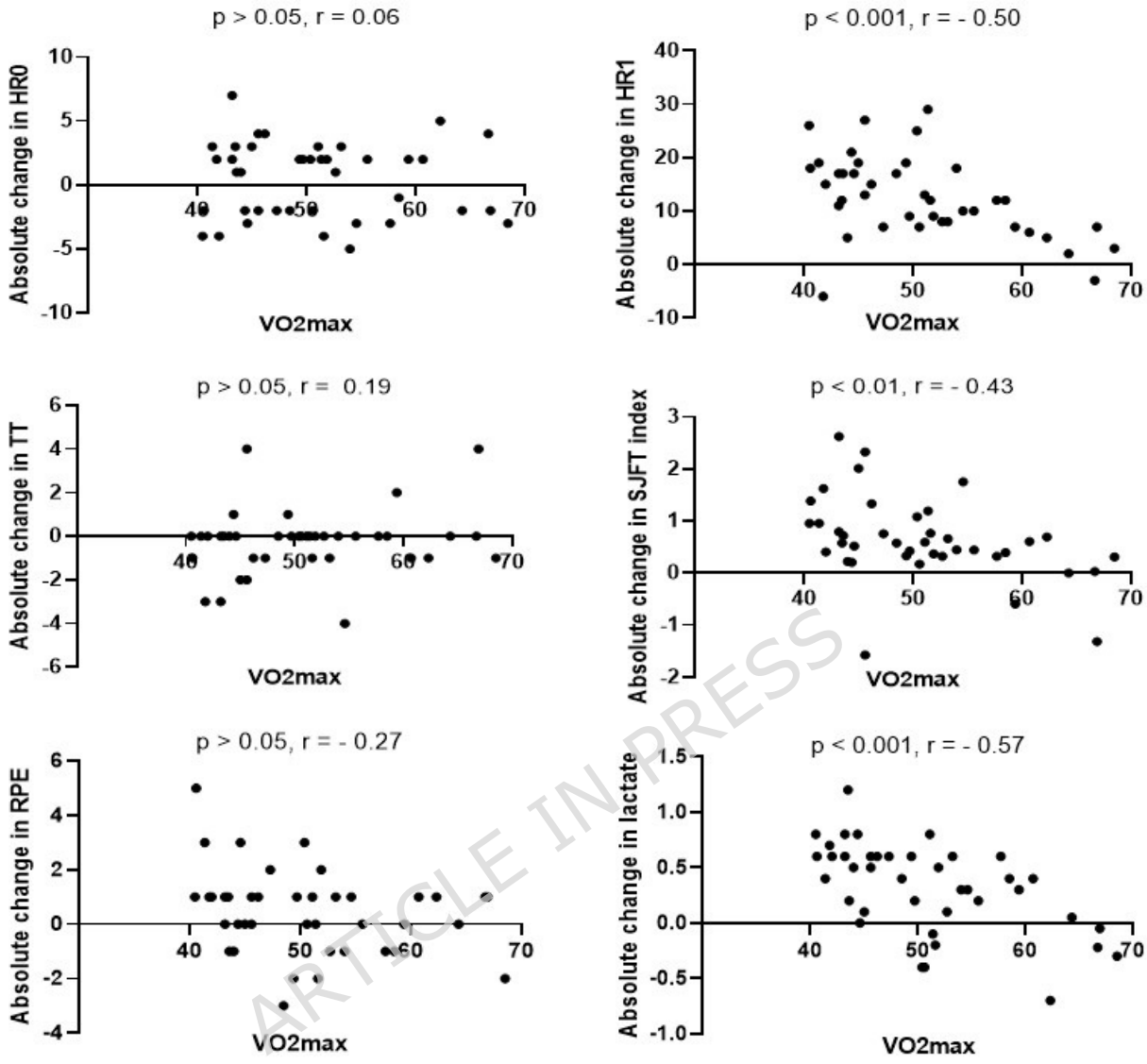

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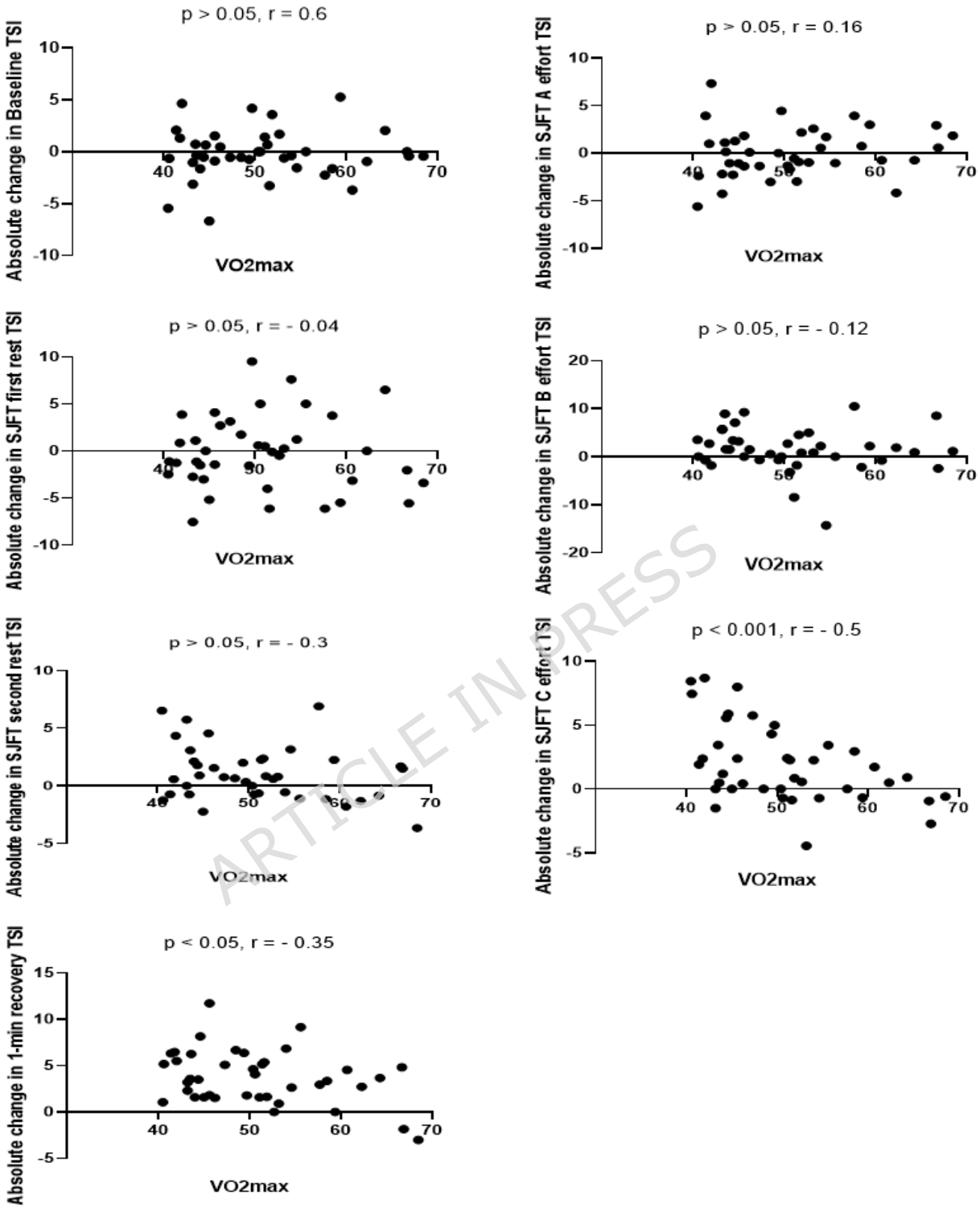

Figure 5.