JOURNAL OF THE INTERNATIONAL SOCIETY OF SPORTS NUTRITION
2025, VOL. 22, NO. 1, 2502656
https://doi.org/10.1080/15502783.2025.2502656

Taylor & Francis
Taylor & Francis Group

The effect of acute beetroot juice consumption prior to climbing on lower-body isokinetic and isometric strength, aerobic power, and muscle soreness among mountain climbers

Alireza Daneshparvar, Mohammad Hemmatinafar, Mohsen Salesi, Rasoul Rezaei, Babak Imanian and Sepideh Pirmohammadi

Shiraz University, Department of Sport Science, Faculty of Education and Psychology, Shiraz, Iran

ABSTRACT

Background: Beetroot juice (BRJ) contains various bioactive compounds which can enhance athletes" performance. However, there is a limited number of studies assessing the effects of BRJ on climbers" performance and indicators of muscle soreness (MS). Thus, the present study aimed to investigate the effect of consuming beetroot juice acutely before climbing on lower-body isokinetic and isometric strength, aerobic power, and muscle soreness in mountain climbers.

Methods: In a randomized, placebo-controlled, double-blinded study, 27 climbers (14 males and 13 females) were divided into three groups: Control (CON), Placebo (PLA), and Beetroot Juice (BRJ), with 9 participants in each group. The study evaluated swelling around the thigh (Sw-T), pressure pain threshold (PPT), isokinetic and isometric strength, horizontal jump (HJ), wall-sit, handgrip strength (HGS), flexibility, and the Queen's College Step test. Testing occurred in three sessions: baseline, climbing, and posttest. At baseline, all participants completed the full battery of tests at Shiraz University. One week later, during the climbing session, they consumed 70 mL of BRJ (400 mg nitrate), PLA, or water 2.5 hours before ascending to 3720 meters. Functional tests (HJ, wall-sit, and estimated VO_{2max}) were performed at the altitude. After completing these tests, participants immediately descended the mountain. DOMS was assessed using a visual analog scale (VAS) for the quadriceps, hamstrings, and gastrocnemius muscles at the following time points: 2 hours before climbing, and 0 (immediately), 12, 24, 48, and 72 hours after descending. The posttest session, held 72 hours after descending, repeated all baseline assessments.

Results: The results revealed a statistically significant decrease in DOMS in the gastrocnemius muscles 24 hours post-descending in the BRJ group compared to the control group ($p = 0.003$, $pEta^2 = 0.204$). However, no changes in DOMS were observed for the quadriceps ($p = 0.090$, $pEta^2 = 0.090$) and hamstring ($p = 0.254$, $pEta^2 = 0.056$) muscles. Moreover, notable improvements were observed in

ARTICLE HISTORY

Received 15 September 2024
Accepted 1 May 2025

KEYWORDS

Beetroot juice; muscle soreness; climbers; isokinetic and isometric strength; aerobic power

CONTACT Mohammad Hemmatinafar m.hemmatinafar@shirazu.ac.ir Shiraz University, Department of Sport Science, Faculty of Education and Psychology, Shiraz, Iran

PPT ($p = 0.001$, $pEta^2 = 0.374$), Estimated VO_{2max} ($p = 0.016$, $pEta^2 = 0.291$), HGS ($p = 0.004$, $pEta^2 = 0.270$), flexibility ($p = 0.003$, $pEta^2 = 0.407$), HJ ($p = 0.008$, pEta2 = 0.155), and isokinetic (peak torque, average power and rate of force development) and isometric (Maximum voluntary isometric contraction) strength indicators in the BRJ groups compare to the other groups ($p<0.05$). However, no significant differences were observed in Sw-T between groups ($p = 0.305$).

Conclusions: The study suggested that acute consumption of BRJ before climbing improves climbers' lower-body isokinetic and isometric strength, power, and endurance performance, and it is associated with a reduced perception of muscle soreness.

1. Introduction

At altitudes exceeding 5500 meters, atmospheric pressure decreases by 50%, leading to reduced air density and a subsequent decline in oxygen availability despite the constant proportion of atmospheric gases [1]. This reduction in air density impairs oxygen transfer to the lungs, influencing physiological responses and contributing to fatigue even during low-intensity activities. At moderate altitudes (below 4000 meters), the body's adaptive mechanisms generally maintain adequate oxygen supply to vital organs, including the myocardium, through enhanced cardiovascular efficiency [1]. However, as altitude increases, oxygen partial pressure diminishes, potentially affecting maximum oxygen consumption and acting as a limiting factor for performance [2]. Nevertheless, at altitudes relevant to this study (3720 meters), the cardiovascular system typically adapts well, maintaining myocardial oxygenation through increased cardiac output and efficient oxygen transport, reducing the risk of myocardial ischemia [3]. These adaptations help mitigate fatigue and sustain muscle metabolism during physical exertion.

Eccentric muscle contraction is an inherent aspect of climbing [4]. However, excessive eccentric muscle contraction, particularly in unfamiliar physical activity, can lead to increased muscle pain and reduced performance in elite and novice athletes [5]. The pain and discomfort typically peak between 24–72 hours after the activity and subside within 5–7 days, defining a condition known as delayed onset muscle soreness (DOMS), a common sports injury [5]. DOMS encompasses ultrastructural muscle injury and presents as pain, muscle stiffness, swelling, decreased force-generating capacity, reduced joint range of motion, and impaired proprioceptive function [6]. Unaccustomed or intense exercise activities involving abnormal contractions can induce DOMS with neuromuscular changes lasting several days [6]. While the complete mechanism of DOMS remains to be fully elucidated, various theories, such as lactic acid, muscle spasm, inflammation, connective tissue damage, muscle damage, enzyme flow, and, more recently, nerve damage and micro-damage theories, have attempted to explain its occurrence [7,8]. It is pertinent to note that DOMS is distinct from the pain experienced during or immediately after exercise, as it can occur without actual muscle damage [9]. Several interventions can be employed to address these concerns and enhance performance.

Including isokinetic strength measurements in this study is essential for precisely assessing muscle endurance and fatigue under the challenging conditions of high-

altitude climbing. Isokinetic testing allows for a controlled evaluation of muscular performance by measuring force production at a constant angular velocity, making it particularly effective for examining eccentric muscle contractions that are prevalent in climbing and contribute to DOMS and muscle fatigue [10]. This type of testing is especially useful in high-altitude environments where oxygen availability is limited, as it helps quantify the effects of hypoxia on muscle function [11]. Furthermore, isokinetic tests provide valuable insights into how interventions like beetroot juice (BRJ), which enhances muscle oxygenation, may affect muscle recovery and performance during and after climbing [12]. Overall, isokinetic observations offer a comprehensive understanding of climbers' muscular adaptations to the unique stressors of high-altitude sports.

Short- and long-term dietary supplementation offers significant potential for elite and recreational athletes seeking to enhance their performance [13]. BRJ is a standout dietary supplement for athletes, offering a unique nutritional composition. With high nitrate ($NO3^{-}$) concentrations, BRJ has the potential to enhance physical performance by boosting nitric oxide (NO) levels [12]. The pathway, known as the nitrate-nitrite-NO pathway, supplements the body's endogenous NO production, especially under conditions where oxygen levels are low or nitric oxide synthase (NOS) activity is impaired. The enhanced NO availability resulting from dietary nitrate intake has been associated with cardiovascular benefits, including reduced blood pressure and improved endothelial function [14]. BRJ is a nutrient-rich drink containing $NO3^{-}$, carbohydrates, fiber, protein, vitamins, and minerals (sodium, potassium, calcium, and iron), along with beneficial compounds like betalain and flavonoids [12,15]. The endothelial enzyme NO synthase also generates NO, leading to vasodilation and increased blood flow [16]. Research indicates that BRJ consumption could enhance athletic performance by elevating oxygen levels, glucose, and nutrients such as potassium, betaine, sodium, magnesium, and vitamin C [17]. Scientific evidence suggests that BRJ consumption may improve blood flow [18] and promote muscle contraction in type II muscle fibers by stimulating NO production [19]. This, in turn, can effectively reduce phosphocreatine (PCr) degradation and minimize ATP consumption during physical activity [20], thereby enhancing muscle performance and strength as Poredos et al. showed that beetroot juice supplementation moderately and statistically significantly increased the peak rate of torque development in young adult males; however, no significant difference was observed in females [21].

Furthermore, the accelerated conversion of nitrite (NO_2^{-}) to NO in both hypoxic and acidic conditions [22], coupled with the expedited transformation of NO_2^{-} to NO in oxygen-deficient type II muscle fibers [20], further supports the benefits of BRJ. These findings indicate that BRJ could be a valuable aid during high-intensity exercise in hypoxic conditions [20,23,24], mainly due to the extensive recruitment of type II muscle during high-intensity intermittent and all-out sprint exercises [25].

Moreover, the high nitrate content in BRJ, leading to NO production, may indirectly exert antioxidant effects by suppressing the accumulation of leukocytes [26], known as primary producers of reactive oxygen species (ROS), after muscle-damaging exercise [27]. Additionally, the antioxidant capacity of BRJ is attributed to compounds such as phenolic acids, flavonoids, carotenoids, and betalains, with betalain pigments being particularly potent antioxidants [28,29].

Studies have yielded mixed results. Masschelein et al. observed an increase in arterial and muscle oxygenation in physically active males after NO_3^{-} consumption compared to

placebo [30], Arnold et al. found that acute NO3- supplementation did not enhance the performance of trained runners in hypoxic and high-altitude conditions [31]. They also noted that the effects of NO3- supplementation may be heavily influenced by the type, duration, and intensity of exercise [31]. Hemmatinafar et al. demonstrated that BRJ consumption during recovery enhanced isometric strength and horizontal power while reducing DOMS and thigh swelling in female volleyball players after exercise-induced muscle damage [32]. Additionally, Daab et al. (2021) reported that chronic BRJ supplementation reduced post-exercise muscle pain and improved post-exercise recovery performance [33]. Pietrzkowski et al. also found that chronic consumption of BRJ concentrates led to lower visual analog scale (VAS) scores in 40 men and women [34]. Similarly, Clifford and Berntzen observed that high (250 ml) and moderate (150 ml) beetroot juice doses reduced muscle pain following a recovery protocol [35]. Ahmadpour et al. (2024) showed that acute consumption of BRJ improved sports performance and reduced muscle soreness in alpine skiers under hypoxic conditions [36].

Therefore, this study aims to assess the immediate and prolonged effects of acute BRJ supplementation on lower-body isokinetic and isometric strength, aerobic power, and muscle soreness in mountain climbers. Specifically, the study examines these parameters immediately after climbing and continues to monitor changes up to 72 hours post-climb, providing insights into both acute performance outcomes and delayed muscle recovery. By focusing on moderate altitude conditions (3720 meters), this research seeks to determine whether BRJ supplementation can enhance muscular performance, reduce DOMS, and support physiological recovery in the challenging conditions of high-altitude climbing. These findings could contribute to developing nutritional strategies to improve athletic performance and recovery in extreme environments.

2. Methodology

2.1. Participants

In the present study, 27 experienced climbers (14 males and 13 females) with a minimum of 10 years of climbing experience above 3500 meters voluntarily participated. The demographic details of the participants are presented in Table 1. The participants had no known medical conditions, did not use supplements or medications, and refrained from smoking or consuming alcohol or caffeinated beverages during the data collection. Additionally, none of the participants had any known allergy to beetroot. The sample of 27 climbers was drawn from volunteers in Shiraz, Iran. There were no dropouts, and all individuals completed the baseline, climbing, and posttest sessions. The study was conducted with the approval of the Human Research Ethics Committee of Shiraz University under the ethics approval code IR.US.PSYEDU.REC.1403.047, 2024, and in compliance with

Table 1. The anthropometric data of participants.

Characteristic	Mean ± SD ($n = 27$)
Age (years)	37 ± 7
Height (cm)	167 ± 9
Weight (kg)	69 ± 10

the Declaration of Helsinki. Recruitment of participants took place from May 1st to 20 May 2024. Moreover, all participants were part of the same training camp and followed an identical training regimen under the supervision of trainers. Furthermore, participants were instructed to abstain from strenuous exercise 48 hours before and after the intervention sessions.

2.2. Sample size calculation

The sample size was determined using G*Power software (version 3.1) for a repeated-measures ANOVA (within-between interaction) design [37]. The calculation assumed a Type I error rate (α) of 0.05, statistical power (1–β) of 0.80, and a medium effect size (f = 0.25), which is commonly used in sports nutrition and supplementation studies. Drawing from a previous study by Hemmatinafar et al. (2023) on beetroot juice supplementation and its effects on muscle soreness and recovery in athletes [32], it was estimated that nine participants per group (total $n = 27$) would be sufficient to detect statistically significant differences across time and intervention groups. Therefore, 27 participants were recruited and completed the study.

2.3. Study design

This study was randomized, placebo-controlled, and double-blinded. Forty-eight hours before the first test session, the participants underwent a general health check by a general practitioner. They also completed the physical activity readiness questionnaire [38] and provided written consent for the study, demonstrating their understanding of the implementation method, benefits, risks, and possible complications. To ensure participants were adequately prepared for the study procedures, familiarization sessions were conducted before the main trials. During these sessions, participants were introduced to all testing protocols, including the isokinetic and isometric strength tests, the wall-sit test, the handgrip strength test, and the step test. Each participant received detailed instructions on how to perform each test correctly and safely, followed by a supervised practice session. Then, they were randomly divided into three groups of 9 people: Control (CON, comprising 5 males and 4 females), Placebo (PLA, comprising 4 males and 5 females), and Beetroot Juice (BRJ, comprising 5 males and 4 females).

The current study comprised three sessions: baseline, climbing, and posttest. In the first session (baseline) at the Sport Sciences laboratory of Shiraz University, swelling around the thigh (Sw-T) and pressure pain threshold (PPT) were measured. Then, after 10 minutes of warming up, the participants performed the Isokinetic and Isometric tests. After 30 minutes of rest, they performed functional tests that included the Horizontal Jump (HJ), Wall-sit, Handgrip strength (HGS), flexibility, and Queen's College Step test to estimate the maximum rate of oxygen consumption (Estimated VO_{2max}). In the second session (climbing), one week later, participants ascended Riz o Boland Mountain (3,720 meters), located in Ardekan, Fars Province, Iran. The ascent began at an elevation of approximately 2,850 meters and reached the summit at 3,720 meters, resulting in a total elevation gain of 870 meters. The one-way distance from the starting point to the summit was approximately 10 kilometers, resulting in a total round-trip distance of 20 kilometers. The ascent took approximately 5 hours (average ascent speed ≈2.0 km/h), and the descent lasted about

4.5 hours (average descent speed ≈2.22 km/h), yielding a total movement time of 9.5 hours (overall average speed ≈2.11 km/h). In this session, participants consumed 70 milliliters of BRJ, PLA, or water 2.5 hours prior to climbing and performed functional tests – including the HJ, Wall-sit, and Queen's College Step test – at altitude (3720 m). The performance measurements at altitude lasted approximately two hours. Immediately after completing these assessments, participants descended the mountain. DOMS was evaluated after their return using a visual analog scale (VAS) for the quadriceps, hamstrings, and gastrocnemius muscles at the following time points: 2 hours before climbing, and at 0 (immediately), 12, 24, 48, and 72 hours after descent [39]. The weather conditions during the climb were as follows: the temperature ranged from 18 to 32 degrees Celsius, humidity ranged from 8 to 32 percent, and the wind speed at the peak was 45 km/h. Then, 72 hours after descending, in the third session (posttest), participants did all the tests done in the baseline (Figure 1). It should be noted that all participants were fed the same breakfast containing 250 kcal (45 g carbohydrates, 9 g protein, and 5 g fat) 1 hour and 30 minutes before the test sessions. Additionally, all three sessions were performed at the same time of day (8:30–13:00), and during the trials, participants were allowed to drink water independently.

Previous research indicates that the menstrual cycle can influence exercise performance in women [40]. To minimize the effects of hormonal changes on the measured variables, all climbing, supplementation, and functional tests were conducted during the follicular phase of the menstrual cycle. The menstrual cycle phase for each female participant was determined using the Menstrual Cycle Questionnaire, and only participants with synchronized menstrual cycles were selected for the study [41]. Female participants were evenly distributed across all experimental groups (BRJ, PLA, and control) to avoid group bias. Additionally, all participants were naturally menstruating and not using hormonal contraceptives.

Before the study, participants completed a 48-hour nutritional control period, during which they were instructed to avoid consuming nitrate-rich foods, including turnips, raw

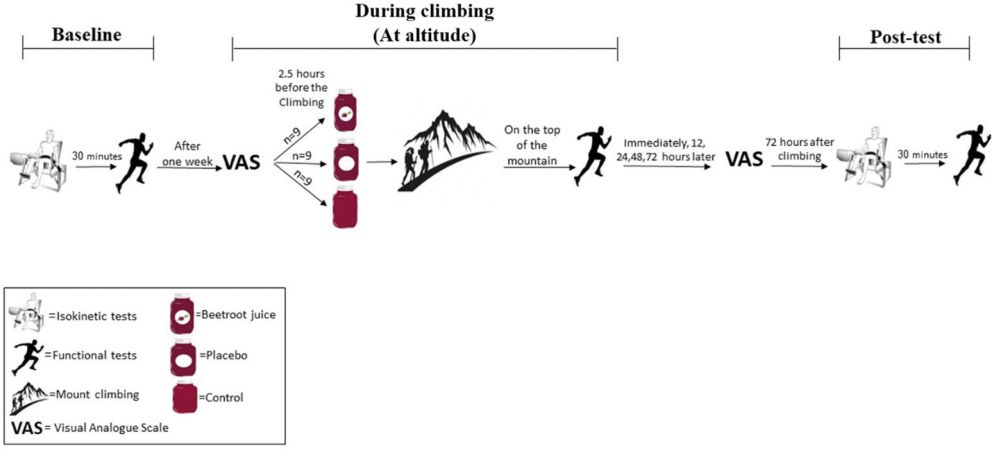

Figure 1. Schematic of the study design. Performance tests were conducted at altitude over ~2 hours, followed by immediate descent. DOMS was assessed before climbing and at multiple time points after descent; posttests were completed 72 hours later in the lab.

onions, cabbage, lettuce, and caffeine. Throughout the testing period, they were advised to maintain their regular diet while avoiding strenuous exercise for 48 hours before each trial. This nutritional control ensured that preexisting dietary nitrate levels did not influence the study outcomes.

3. Blinding procedure

To maintain the integrity of the study, a double-blind design was implemented, ensuring that participants and investigators were blinded to the supplement group allocations. The beetroot juice (BRJ), placebo (PLA), and control (water) supplements were prepared in identical opaque containers labeled with randomly generated codes. An independent researcher, not involved in the data collection or analysis, handled the preparation and coding of the supplements. The placebo was designed to match the taste, color, and appearance of the BRJ to prevent participants from identifying their group allocation. Additionally, all supplements were provided in dark, opaque bottles with the same color and design, ensuring that the contents were invisible to the participants or the investigators. Investigators responsible for administering the supplements received only the coded containers and had no access to information regarding the contents of each container. This approach ensured that the investigators remained blinded throughout the intervention period, minimizing potential bias while administering supplements and assessing outcomes. This blinding procedure was strictly maintained until all data were collected and analyzed, at which point the group codes were revealed solely for statistical analysis purposes.

3.1. Supplementation procedures

The participants in the BRJ group consumed a 70-milliliter shot of Beet It Sport juice (James White Drink Ltd., Ipswich, UK), which contains 400 milligrams of nitrate. More detailed information about the BRJ group's supplement is shown in Table 2. For the PLA group, the participants consumed 70 milliliters of homemade juice containing 3.7 grams of whey protein, 18 grams of carbohydrates, 0.4 grams of salt, 2% lemon juice, and food coloring per 100 ml. Also, the CON group consumed 70 milliliters of water. It should be noted that the shots used by participants in all three groups were opaque and completely similar in appearance. All participants ingested their beverage 2.5 hours before climbing.

Table 2. Nutritional information of Beet it Sport juice and the homemade juice for the PLA.

	Amount per 100 ml	
Details	PLA	BRJ
Energy (kcal)	~88	88
Fat (g)	0	0
- of which saturates (g)	0	0
Carbohydrates (g)	18	18
- of which sugars (g)	-	17
Protein (g)	3.7	3.7
Salt (g)	0.4	0.45

The timing of the supplement ingestion based on the recommendations was 2.5 to 3 hours before starting the functional tests effort to coincide with peak plasma nitrite [42].

3.2. Examination of delayed onset muscle soreness by the VAS scale

The VAS was used to measure the severity of DOMS in the quadriceps, hamstrings, and gastrocnemius muscles. The VAS scale consisted of a 10-centimeter horizontal line, with the left end representing "no pain" and the right indicating "severe DOMS." Participants reported their perceived muscle soreness at the following time points: 2 hours before climbing, and 0 (immediately), 12, 24, 48, and 72 hours after descending from the mountain. The DOMS score was determined by measuring the distance in millimeters from the "no pain" point to the participant's mark, ensuring a consistent and quantitative assessment of muscle soreness [43].

3.3. Swelling around the thigh (sw-T)

To find the femur's midpoint, the dominant leg's greater trochanter and the dominant leg's tibial prominence were marked while the participant stood. The femur's circumference was measured three times (without creating folds in the skin) to determine the amount of swelling around the thigh (Sw-T), using a tape measure accurate to the nearest 1 mm. The average values were recorded as the swelling score around the femur [32].

3.4. Pressure pain threshold (PPT)

The study determined the pressure pain threshold (PPT) using a blood pressure cuff at the midpoint of the femur (Blood Pressure Cuff – Thigh – Double Tube, MDF Instruments, USA). The participants were seated on a chair with their knees bent at a 90-degree angle. A 2.5 cm diameter and 25 cm length plastic tube was placed around the femur midline of the dominant leg. The blood pressure gauge cuff was then placed around the participant's thigh and uniformly inflated. The investigator recorded the pressure level at the onset of pain as the PPT in mmHg [32].

3.5. Functional tests

Isokinetic and Isometric strength tests: An isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY, USA) was used to measure the isokinetic strength of the knee extensor and flexor muscles (concentric phase, at an angular velocity of 60°/s and 180°/s, con/con ratio, dominant leg) with five consecutive repetitions in the direction of extension-flexion and 60 seconds of rest between each set was considered for recovery. Gravity correction of the torque measurements was accomplished using the Biodex software package. The straps were put across the chest, above the knee, around the waist, and above the ankle to stabilize each participant. This arrangement secured the lower leg to the input shaft of the dynamometer. Furthermore, the estimated transverse rotational axis of the knee was visually aligned with the mechanical axis of the dynamometer. A total range of 85° of motion was allowed for knee extension-flexion during the

test, ranging from 90° to 5°. Eventually, Absolute peak torque (PTQ) and Average power (AP) were measured during five repetitions (PTQflx60°/s, PTQext60°/s, PTQflx180°/s, PTQext180°/s, APflx60°/s, APext60°/s, APflx180°/s, APext180°/s). Also, the average rate of force development (RFD) was calculated using the absolute peak torque/time to peak torque equation (RFDflx60°/s, RFDext60°/s, RFDflx180°/s, RFDext180°/s) [44,45]. Furthermore, Maximum voluntary isometric contraction (MVIC) was measured at 60° away (extension) and toward (flexion) action (MVICext60° and MVICflx60°) using the same device. Each repetition consisted of a five-second eccentric phase and a five-second concentric phase [46].

Horizontal Jump (HJ): Participants performed the HJ starting from standing. They commenced the jump by swinging their arms and bending their knees to provide maximal forward drive. A take-off line was drawn on the ground, immediately adjacent to a jump sandbox. The jump-length measurement was determined using a metric tape measure (Lufkin, L716MAGCME; Apex Group, Sparks, Maryland) from the take-off line to the nearest point of landing contact (i.e. back of the heels). Each athlete executed three attempts, and the longest distance was considered [47].

Wall-sit: The wall-sit test was used to evaluate lower-body muscle endurance. The correct posture was sitting, shoulder width straight and attached to the wall, knees at 90 degrees, shoulders to the wall, and arms hanging straight down. For this test, the maximum time to exhaustion was defined as the time interval from the task's start until any of these positions could not be maintained. Participants must do their best to keep the correct position throughout the test while receiving no verbal encouragement [48].

Handgrip Strength (HGS): The hand dynamometry test was carried out to assess the maximum isometric force in the flexors of the fingers with a (Jamar Hydraulic Hand Dynamometer, Warrenville, IL, USA) and a range between 0 and 100 kg. Measurements were performed with the participants standing with their arms fully extended to the side without touching the body. Participants were asked to hold the dynamometer with as much force as possible and alternately move the dominant hand three times for less than three seconds. A rest interval of at least 60 seconds was allowed between each trial, and the best record was recorded as a score [49].

Flexibility: Participants sat shoeless on the floor with their soles 30 cm apart. A meterstick was placed between the participant's legs so the 23 cm mark aligned with the participant's heels [50]. Subjects were later asked to put both hands together and extend forward as far as possible. The best of three attempts was recorded as the final score.

Queen's College Step test: The VO_{2max} was estimated indirectly by following the Queen's College Step test method [51,52]. The step test was performed using a tool of 16.25 inches (41.30 centimeters) in height. Stepping was done for 3 minutes at the rate of 24 steps up per minute for males and 22 steps up per minute for females, which was set by a metronome. After completion of the exercise, the carotid pulse rate was measured from the fifth to the twentieth second of the recovery period. The 15-second pulse rate was converted into beats per minute, and the following equation was used to predict VO_{2max}.

For males: Estimated VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) = 111.33 – (0.42 × pulse rate beats/min)

For females: Estimated VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) = 65.81– (0.1847 × pulse rate beats/min)

3.6. Statistical analysis

All data were analyzed using descriptive and inferential statistical methods. The data distribution normality was determined using the Shapiro-Wilk test. The mixed repeated measure analysis ANOVA test was employed to identify the main effects, and the Bonferroni post hoc test was used to determine pairwise differences by adding different Syntax codes for pre and posttest data, pre-, during, and posttest data, and VAS data. The partial eta squared ($pEta^2$) was calculated as an effect size measure for interaction and main effects. According to Cohen, $pEta^2 \geq 0.01$ indicates small effects, $pEta^2 \geq 0.059$ indicates medium effects, and $pEta^2 \geq 0.138$ indicates large effects [53]. All the data were analyzed using SPSS software (version 26, IBM-SPSS Inc., Chicago, IL, USA), and the level of statistical significance was $p \leq 0.05$. Also, GraphPad Prism software (version 9.0, California, USA) was used to design the graphs.

4. Results

Table 3 details descriptive statistics, encompassing mean and standard deviation measures. Furthermore, Table 4 summarizes the mean and standard deviation values derived from the DOMS report.

The results of the physical activity questionnaire indicated that all participants maintained a moderate to high level of physical activity before the study. The average weekly physical activity across all groups was approximately 5 to 6 hours, including aerobic exercise, strength training, and outdoor activities such as hiking. Almost all participants reported engaging in weekly climbs exceeding 3500 meters, demonstrating a consistent high-altitude experience. There were no significant differences in the baseline physical activity levels among the Control (CON), Placebo (PLA), and Beetroot Juice (BRJ) groups ($p > 0.05$). This baseline homogeneity helped ensure that any observed effects in muscle performance and recovery could be attributed primarily to the intervention rather than preexisting differences in fitness levels.

The mixed repeated measure analysis ANOVA test results showed that the main effect of the intervention was significant on DOMS for gastrocnemius muscles ($F_{2.17} = 6.13$, $p = 0.003$, $pEta^2 = 0.204$). Additionally, the results of the Bonferroni test demonstrated that DOMS for gastrocnemius muscles 24 hours after descending in BRJ was lower compared to CON ($p = 0.003$) (Figure 2C). However, there were no substantial differences between BRJ and PLA ($p = 0.141$) and PLA and CON ($p = 0.086$) simultaneously. Also, no difference was observed before, 0 hours, 12 hours, 48 hours, and 72 hours after descending between the groups of the study ($p > 0.05$) in DOMS for gastrocnemius muscles (Figure 2C). In addition, the results of the analysis indicated that there was no significant difference in before, 0 hours, 12 hours, 48 hours, and 72 hours after descending between the groups of the study in DOMS for quadriceps muscles ($F_{2.50} = 2.37$, $p = 0.090$, $pEta^2 = 0.090$) (Figure 2A), and hamstrings muscles ($F_{1.73} = 1.41$, $p = 0.254$, $pEta^2 = 0.056$) (Figure 2B).

The analysis showed a significant HJ difference between the study groups (F1.31 = 4.38, $p = 0.034$, pEta2 = 0.155). According to the post hoc test, HJ was higher in BRJ compared to PLA ($p = 0.037$) at altitude; however, there were no differences between BRJ and CON ($p = 0.063$) and PLA and CON ($p = 0.792$). Furthermore, there were no differences between the studied groups in both the baseline ($p > 0.05$) and posttest (p

Table 3. Means and standard deviation (SD) of measured variables.

		Baseline			At altitude			Post-test		
Variables		CON ($n = 9$)	PLA ($n = 9$)	BRJ ($n = 9$)	CON ($n = 9$)	PLA ($n = 9$)	BRJ ($n = 9$)	CON ($n = 9$)	PLA ($n = 9$)	BRJ ($n = 9$)
Sw-T	Means	49.00	53.33	51.55	48.88	50.88	50.55	48.00	51.55	50.88
(cm)	SD	3.87	5.12	6.67	3.75	5.68	5.81	3.46	5.31	3.88
HJ	Means	116.66	116.11	118.33	118.77	115.11	145.55	123.33	120.00	155.00
(cm)	SD	25.49	24.46	22.77	34.13	15.43	33.93	25.61	28.72	34.91
Wall-sit	Means	59.66	60.66	59.66	187.22	167.77	212.88	92.55	92.66	149.33
(s)	SD	6.51	6.65	8.04	114.53	64.15	98.66	43.18	48.10	57.28
Estimated VO_{2max}	Means	50.49	49.45	50.50	51.28	50.70	52.62	50.78	49.22	54.40
($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	SD	1.92	5.21	2.57	2.48	4.99	1.98	2.02	5.11	2.88
HGS	Means	66.66		66.77	67.00		71.11	67.33		92.22
(kg)	SD	5.72		7.10	6.30		16.57	13.99		18.55
Flexibility	Means	28.11		28.88	30.55		28.33	34.88		36.66
(cm)	SD	6.54		6.21	5.02		5.91	5.41		4.44
PPT	Means	257.77		298.88	290.22		236.66	256.66		226.66
(mmHg)	SD	54.03		87.09	39.75		27.83	41.83		13.22
PTQflx60°/s	Means	47.84		43.10	55.14		57.33	59.08		82.01
(Nm)	SD	19.36		11.08	14.35		22.98	21.67		11.07
PTQflx180°/s	Means	35.28		31.22	38.25		46.17	45.90		57.77
(Nm)	SD	7.37		2.62	17.40		11.96	10.64		23.61
APflx60°/s	Means	35.16		30.80	29.31		37.78	33.33		46.52
(watts)	SD	13.49		9.09	7.52		11.14	4.81		11.03
APflx180°/s	Means	49.98		34.49	35.37		61.66	53.90		85.62
(watts)	SD	15.78		15.00	14.68		19.76	20.40		48.98
RFDflx60°/s	Means	66.44		67.46	68.10		132.12	116.84		167.61
(Nm/ms)	SD	23.07		22.46	23.61		35.04	21.82		78.25
RFDflx180°/s	Means	103.01		98.68	115.23		195.77	205.48		255.64
(Nm/ms)	SD	24.08		17.03	23.59		39.06	51.30		154.55
PTQext60°/s	Means	82.94		87.70	95.07		94.36	106.87		141.76
(Nm)	SD	24.72		17.97	5.41		32.27	48.45		38.97
PTQext180°/s	Means	62.17		69.77	69.42		62.62	79.60		92.48
(Nm)	SD	12.89		13.72	9.53		14.41	33.02		32.17
APext60°/s	Means	62.98		56.15	74.38		64.76	55.38		76.01
(watts)	SD	20.33		26.94	22.90		17.21	23.77		33.77
APext180°/s	Means	73.68		68.64	72.15		79.64	79.30		128.61
(watts)	SD	28.12		18.79	22.22		28.54	44.55		57.70
RFDext60°/s	Means	153.17		189.46	226.44		151.40	142.21		236.62
(Nm/ms)	SD	54.95		144.79	98.96		45.60	62.51		68.40
RFDext180°/s	Means	214.73		216.35	215.20		231.66	229.49		366.03
(Nm/ms)	SD	40.17		51.32	27.71		98.52	57.92		184.76
MVICflx60°	Means	80.57		72.80	85.86		94.51	78.02		99.15
(Nm)	SD	16.83		24.48	29.09		19.91	38.81		26.34
MVICext60°	Means	102.10		110.46	134.50		95.53	84.88		151.35
(Nm)	SD	25.26		53.19	48.24		21.56	24.30		39.44

CON: Control, PLA: Placebo, BRJ: Beetroot juice, SD: Standard deviation, Sw-T: Swelling around the thigh, HJ: Horizontal jump, Estimated VO2max: maximum rate of oxygen consumption, HGS: Handgrip strength, PPT: Pressure pain threshold, ext: Extension, flx: Flexion, PTQ: Absolute peak torque, AP: Average power, RFD: Average rate of force development, MVIC: Muscle voluntary isometric contraction, ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, Nm: Newton meters, ms: Millisecond.

> 0.05). Additionally, significant increases were observed in the posttest ($p = 0.008$) and at altitude ($p = 0.049$) compared to the baseline in the BRJ group. However, no significant differences existed between the timelines in the CON and PLA groups ($p > 0.05$). These results are presented in Tables 5 and 6 and Figure 3.

The analysis revealed significant disparities in Wall-sit performance among the study groups (F1.43 = 35.56, $p = 0.001$, pEta2 = 0.597). Subsequent Bonferroni tests showed higher Wall-sit performance in the BRJ group compared to CON ($p = 0.024$) and CON

Table 4. Mean ± SD values for DOMS scores across all time points for quadriceps, hamstrings, and gastrocnemius muscles.

	DOMS (mm)	CON ($n = 9$)	PLA ($n = 9$)	BRJ ($n = 9$)
Quadriceps	Baseline	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	0 h	6.66 ± 8.66	2.22 ± 4.40	3.88 ± 9.93
	12 h	3.88 ± 11.66	2.22 ± 4.40	10.00 ± 17.85
	24 h	7.77 ± 13.01	2.22 ± 4.40	1.66 ± 3.53
	48 h	0.55 ± 1.66	5.55 ± 10.13	0.55 ± 1.66
	72 h	2.22 ± 4.40	1.11 ± 2.20	0.00 ± 0.00
Hamstrings	Baseline	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	0 hr	3.88 ± 6.00	0.00 ± 0.00	2.77 ± 6.66
	12 h	1.11 ± 3.33	0.00 ± 0.00	5.00 ± 13.22
	24 h	0.00 ± 0.00	1.11 ± 2.20	0.55 ± 1.66
	48 h	0.00 ± 0.00	8.88 ± 17.63	0.55 ± 1.66
	72 h	2.22 ± 4.40	6.66 ± 13.22	0.00 ± 0.00
Gastrocnemius	Baseline	0.00 ± 0.00	1.11 ± 2.20	0.00 ± 0.00
	0 hr	10.55 ± 12.85	10.55 ± 14.67	10.00 ± 19.52
	12 h	10.55 ± 12.85	16.66 ± 25.98	8.88 ± 18.33
	24 h	9.66 ± 8.27	4.44 ± 6.82	0.00 ± 0.00
	48 h	4.11 ± 6.58	2.22 ± 3.63	0.00 ± 0.00
	72 h	2.22 ± 4.40	2.22 ± 4.40	0.00 ± 0.00

Assessments were conducted at 2 hours before climbing and at 0 (immediately), 12, 24, 48, and 72 hours after the participants had descended from altitude. CON: Control, PLA: Placebo, BRJ: Beetroot juice, DOMS: delayed onset muscle soreness, mm: Millimeter.

compared to the PLA ($p = 0.024$) in the posttest. However, there were no differences between BRJ and PLA ($p = 0.996$) in the posttest. Notably, no differences were observed between the groups at altitude ($p > 0.05$) or in the baseline ($p > 0.05$) (Table 5). Further post-hoc analysis revealed that Wall-sit performance in the CON group significantly improved at altitude compared to the baseline ($p = 0.002$) and the posttest ($p = 0.007$), but no improvement was observed between the posttest and baseline ($p = 0.212$). Similarly, in the PLA group, Wall-sit performance was significantly higher at altitude compared to the baseline ($p = 0.010$) and posttest ($p = 0.038$), with no difference between the posttest and baseline ($p = 0.234$). In the BRJ group, Wall-sit performance substantially improved at altitude ($p = 0.001$) and posttest ($p = 0.001$) compared to the baseline, with no significant difference between the posttest and at altitude ($p = 0.094$) (Table 6, Figure 3).

The outcomes from the mixed repeated measures analysis of variance (ANOVA) test revealed a significant main effect of the intervention on Estimated VO_{2max} ($F2.00 = 4.16$, $p = 0.016$, $pEta2 = 0.291$). Subsequent Bonferroni tests demonstrated a substantial improvement in Estimated VO_{2max} in the BRJ group compared to the PLA group in the posttest ($p = 0.016$). However, there was no significant difference between BRJ ($p = 0.128$) and PLA ($p = 1.000$) compared to the CON group in the posttest. Notably, no differences were observed between the groups during the baseline ($p > 0.05$) and at altitude ($p > 0.05$) (refer to Table 5). Furthermore, Bonferroni tests revealed that in the CON group, Estimated VO_{2max} showed significant increases at altitude compared to the baseline ($p = 0.001$) and posttest ($p = 0.005$). Moreover, Estimated VO_{2max} in the posttest was significantly higher than in the baseline ($p = 0.001$). In the PLA group, Estimated VO_{2max} was substantially higher at altitude compared to the baseline ($p = 0.049$) and posttest ($p = 0.023$); however, there was no difference between the posttest and baseline ($p = 1.000$). Additionally, in the BRJ group, there were no significant

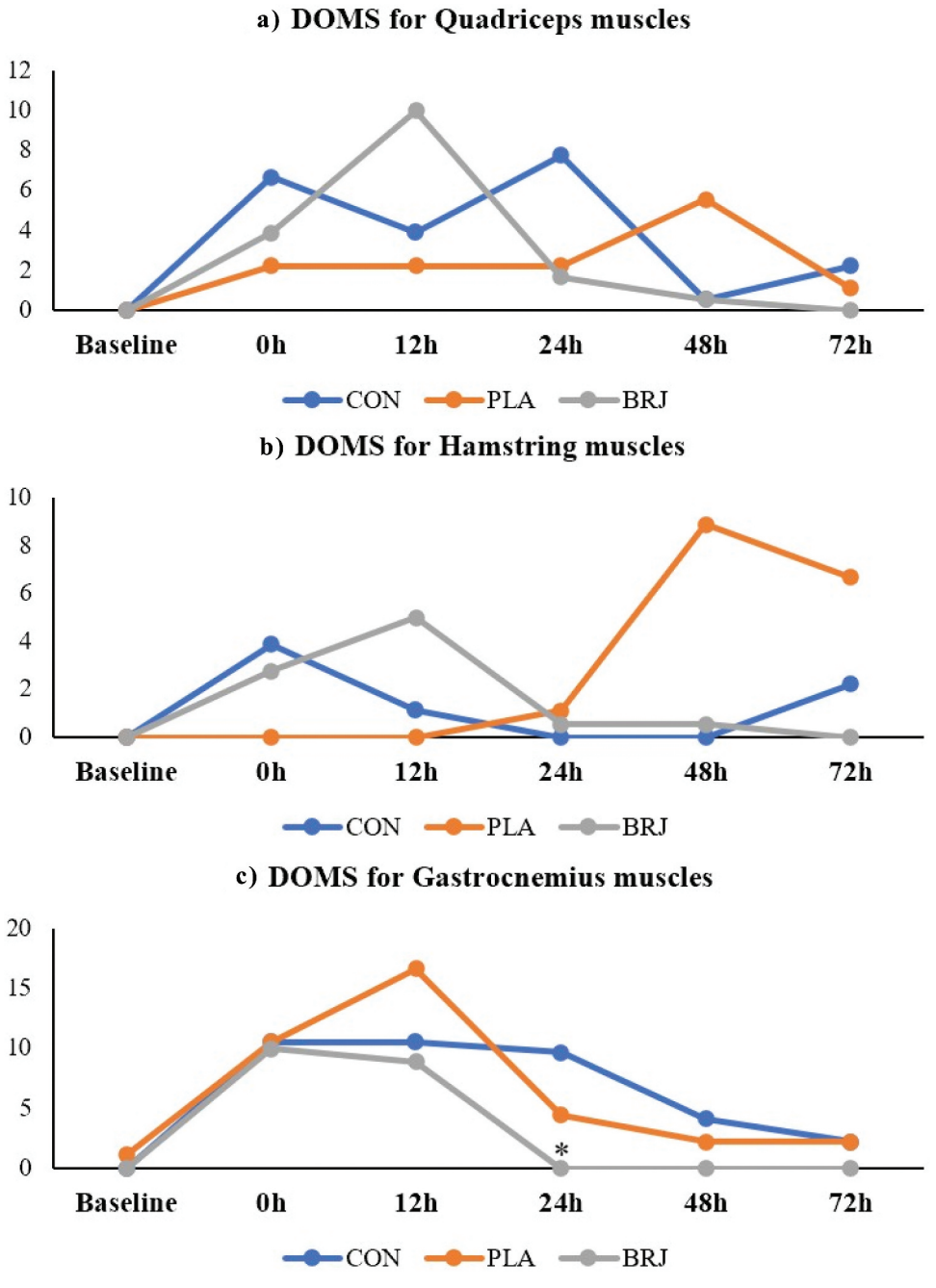

Figure 2. DOMS values for quadriceps (A), hamstrings (B), and gastrocnemius (C) muscles in the BRJ, PLA, and CON groups. DOMS was assessed using a VAS at 2 hours before climbing and at 0 (immediately), 12, 24, 48, and 72 hours after descending from the mountain. CON: control, PLA: placebo, BRJ: beetroot juice. *: Significant difference compared to CON at the same time

Table 5. Comparison of the variables data between three groups at different times.

Variables	Condition	Group	Mean ± SD	95% CI	Sig	MD
Sw-T (cm)	Baseline	CON	49.00 ± 3.87	−10.82–2.15	0.295	−4.33
		PLA	53.33 ± 5.12	−9.04–3.93	0.962	−2.55
		BRJ	51.55 ± 6.67	−2.15–10.82	0.295	4.33
	At altitude	CON	48.88 ± 3.75	−8.27–4.27	1.000	−2.00
		PLA	50.88 ± 5.68	−7.94–4.60	1.000	−1.66
		BRJ	50.55 ± 5.81	−4.27–8.27	1.000	2.00
	Post-test	CON	48.00 ± 3.46	−8.76–1.65	0.276	−3.55
		PLA	51.55 ± 5.31	−8.10–2.32	0.500	−2.88
		BRJ	50.88 ± 3.88	−1.65–8.76	0.276	3.55
HJ (cm)	Baseline	CON	116.66 ± 25.49	−23.05–24.17	0.962	0.55
		PLA	116.11 ± 24.46	−25.28–21.94	0.885	−1.66
		BRJ	118.33 ± 22.77	−24.17–23.05	0.962	−0.55
	At altitude	CON	118.77 ± 34.13	−24.72–32.05	0.792	3.66
		PLA	115.11 ± 15.43	−55.16–1.61	0.063	−26.77
		BRJ	145.55 ± 33.93	−32.05–24.72	0.792	−3.66
	Post-test	CON	123.33 ± 25.61	−25.85–32.52	0.816	3.33
		PLA	120.00 ± 28.72	−60.85 – −2.47	0.035	−31.66
		BRJ	155.00 ± 34.91	−32.52–25.85	0.816	−3.33
Wall-sit (s)	Baseline	CON	59.66 ± 6.51	−7.91–5.91	0.768	−1.00
		PLA	60.66 ± 6.65	−6.91–6.91	1.000	0.00
		BRJ	59.66 ± 8.04	−5.91–7.91	0.768	1.00
	At altitude	CON	187.22 ± 114.53	−47.13–137.36	0.323	45.11
		PLA	167.77 ± 64.15	−66.58–117.91	0.571	25.66
		BRJ	212.88 ± 98.66	−137.36–47.13	0.323	−45.11
	Post-test	CON	92.55 ± 43.18	8.14–105.18	0.024	55.66
		PLA	92.66 ± 48.10	8.25–105.29	0.024	56.77
		BRJ	149.33 ± 57.28	−105.18 – −8.14	0.024	−56.66
Estimated VO_{2max} ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)	Baseline	CON	50.49 ± 1.92	−3.24–5.33	1.000	1.04
		PLA	49.45 ± 5.21	−4.30–4.28	1.000	−0.01
		BRJ	50.50 ± 2.57	−5.33–3.24	1.000	−1.04
	At altitude	CON	51.28 ± 2.48	−3.57–4.72	1.000	0.57
		PLA	50.70 ± 4.99	−5.49–2.80	1.000	−1.34
		BRJ	52.62 ± 1.98	−4.72–3.57	1.000	−0.57
	Post-test	CON	50.78 ± 2.02	−2.79–5.90	1.000	1.55
		PLA	49.22 ± 5.11	−7.97–0.72	0.128	−3.62
		BRJ	54.40 ± 2.88	−5.90–2.79	1.000	−1.55

CON: Control, PLA: Placebo, BRJ: Beetroot juice, SD: Standard deviation, Sw-T: Swelling around the thigh, HJ: Horizontal jump, Estimated VO2max: maximum rate of oxygen consumption, ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, MD: Mean Difference, sig: Significant, CI: Confidence Interval.

differences between the baseline, at altitude, and posttest ($p > 0.05$) (refer to Table 6, Figure 3).

The analysis revealed a notable difference in hand grip strength (HGS) among the study groups (F1.00 = 8.58, $p = 0.007$, pEta2 = 0.270). Subsequent Bonferroni tests indicated significantly higher HGS in the BRJ group compared to the PLA ($p = 0.004$) and CON ($p = 0.012$) groups in the posttest. However, there was no significant difference between the PLA and CON groups ($p = 0.606$). Notably, no difference was found between the study groups in the baseline ($p > 0.05$) (Table 7). Furthermore, post-hoc test results demonstrated a considerable increase in posttest HGS compared to the baseline in the BRJ group ($p = 0.001$). Conversely, there were no differences between the posttest and baseline in the CON ($p = 0.456$) and PLA ($p = 0.925$) groups (Table 8, Figure 4).

The analysis results demonstrated a significant difference in flexibility between the study groups (F1.00 = 16.48, $p = 0.001$, pEta2 = 0.407). Furthermore, post hoc testing revealed notable improvements in BRJ ($p = 0.003$) and PLA ($p = 0.015$) compared to CON

Table 6. Comparison of the variables data between three times in different groups.

Est- VO_{2max} 95%CI	Est- VO_{2max} sig	Est- VO_{2max} MD	Wall sit (s) 95%CI	Wall sit (s) sig	Wall sit (s) MD	HJ (cm) 95%CI	HJ (cm) Sig	HJ (cm) MD	Sw-T (cm) 95%CI	Sw-T (cm) sig	Sw-T (cm) MD	Variables Statistical Summary		
−3.38 – −0.85	0.001	−2.11	−237.33 – −69.11	0.001	−153.22	−29.60–25.38	1.000	−2.11	−1.98–3.98	1.000	1.00	At altitude	Baseline	CON
−5.26 – −2.53	0.001	−3.89	−134.40 – −44.92	0.001	−89.66	−34.76–21.42	1.000	−6.66	−2.57–3.90	1.000	0.66	Post-test		
0.85–3.38	0.001	2.11	69.11–237.33	0.001	153.22	−25.38–29.60	1.000	2.11	−3.98–1.98	1.000	−1.00	Baseline	At altitude	
−3.08 – −0.47	0.005	−1.78	−8.04–135.15	0.094	63.55	−17.23–8.12	1.000	−4.55	−2.70–2.03	1.000	−0.33	Post-test		
2.53–5.26	0.001	3.89	44.92–134.40	0.001	89.66	−21.42–34.76	1.000	6.66	−3.90–2.57	1.000	−0.66	Baseline	Post-test	
0.47–3.08	0.005	1.78	−135.15–8.04	0.094	−63.55	−8.12–17.23	1.000	4.55	−2.03–2.70	1.000	0.33	At altitude	Post-test	
−2.51 – −0.01	0.049	−1.25	−191.21 – −23.00	0.010	−107.11	−26.49–28.49	1.000	1.00	−0.54–5.43	0.138	2.44	At altitude	Baseline	PLA
−1.13–1.58	1.000	0.22	−76.73–12.73	0.234	−32.00	−31.98–24.20	1.000	−3.88	−1.45–5.01	0.511	1.77	Post-test		
0.01–2.51	0.049	1.25	23.00–191.21	0.010	107.11	−28.49–26.49	1.000	−1.000	−5.43–0.54	0.138	−2.44	Baseline	At altitude	
0.17–2.77	0.023	1.47	3.51–146.71	0.038	75.11	−17.56–7.78	0.993	−4.88	−3.03–1.70	1.000	−0.66	Post-test		
−1.58–1.13	1.000	−0.22	−12.7–76.73	0.234	32.00	−24.20–31.98	1.000	3.88	−5.01–1.45	0.511	−1.77	Baseline	Post-test	
−2.77 – −0.17	0.023	−1.47	−146.71 – −3.51	0.038	−75.11	−7.78–17.56	0.993	4.88	−1.70–3.03	1.000	0.66	At altitude		
−2.04–0.47	0.369	−0.78	−211.66 – −43.44	0.002	−c	−54.71 – −0.27	0.049	−27.22	−2.87–3.09	1.000	0.11	At altitude	Baseline	BRJ
−1.64–1.07	1.000	−0.28	−77.62–11.85	0.212	−32.88	−64.56 – −8.57	0.008	−36.66	−2.23–4.23	1.000	1.00	Post-test		
−0.47–2.04	0.369	0.78	43.44–211.66	0.002	76.73	0.27–54.71	0.049	27.22	−3.09–2.87	1.000	−0.11	Baseline	At altitude	
−0.80–1.80	1.000	0.49	23.06–166.26	0.007	94.66	−22.12–3.23	0.202	−9.44	−1.47–3.25	1.000	0.88	Post-test		
−1.07–1.64	1.000	0.28	−11.85–77.62	0.212	32.88	8.57–64.56	0.008	36.66	−4.23–2.23	1.000	−1.00	Baseline	Post-test	
−1.80–0.80	1.000	−0.49	−166.26 – −23.06	0.007	−94.66	−3.23–22.12	0.202	9.44	−3.25–1.47	1.000	−0.88	At altitude		

CON: Control, PLA: Placebo, BRJ: Beetroot juice, SD: Standard deviation, Sw-T: Swelling around the thigh, HJ: Horizontal jump, Est- VO2max: Estimated VO2max (ml·kg – 1 ·min −1), ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, MD: Mean Difference, sig: Significant, CI: Confidence Interval.

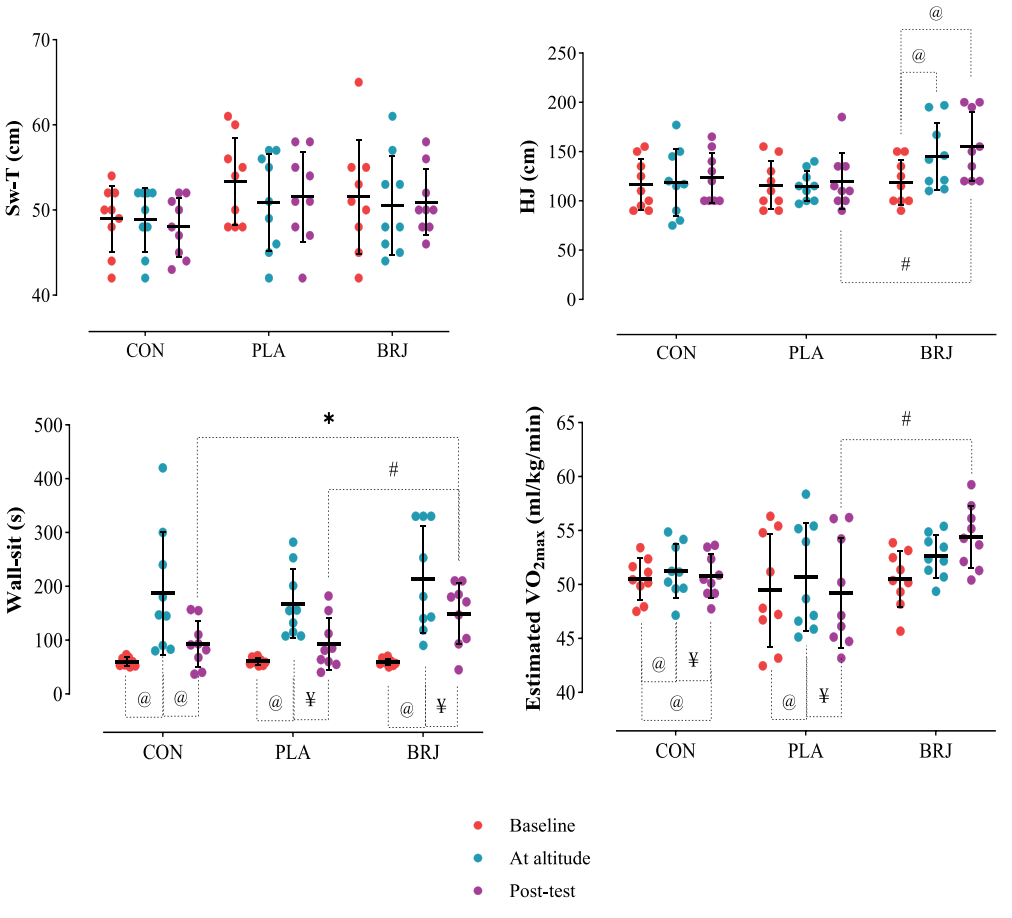

Figure 3. Functional performance outcomes (horizontal jump, Wall-Sit, estimated VO_{2max}) measured at three time points: baseline (laboratory), at altitude (3720 m, during climb), and posttest (72 hours after descent). The altitude performance assessments were conducted during a two-hour testing period at the mount, followed by descent. CON: control, PLA: placebo, BRJ: beetroot juice. *: Significant difference compared to CON. #: Significant difference compared to PLA. @: Significant difference compared to the baseline. ¥: Significant difference compared to at altitude.

in the posttest, with no significant differences observed between BRJ and PLA ($p = 0.483$). The Bonferroni results indicated no significant difference between the groups in the baseline (Table 7). Additionally, the posttest flexibility was significantly higher in the BRJ ($p = 0.002$) and PLA ($p = 0.002$) groups compared to the baseline, whereas no difference was observed between the baseline and posttest in the CON ($p = 0.900$) (Table 8, Figure 4).

The mixed repeated measure analysis ANOVA results reveal a significant difference between the study groups in PPT (F1.00 = 14.32, $p = 0.001$, pEta2 = 0.374). The subsequent Bonferroni test indicates a substantial decrease in PPT in the BRJ group compared to the PLA group in the posttest ($p = 0.044$). However, no significant difference was found between BRJ ($p = 0.170$) and PLA ($p = 0.486$) compared to CON in the posttest. Notably, there were no significant differences between the groups in the baseline ($p > 0.05$) (Table 7). Furthermore, the results show a considerable decrease in PPT in the BRJ

Table 7. Comparison of the variables data between three groups in baseline and posttest.

		Baseline						Post-test					
		CON		PLA		BRJ		CON		PLA		BRJ	
Variables		PLA	BRJ	CON	BRJ	CON	PLA	PLA	BRJ	CON	BRJ	CON	PLA
HGS	**MD**	−0.11	−0.33	−0.11	−0.22	0.33	0.22	3.77	−21.11	−3.77	−24.88	21.11	24.88
(kg)	**Sig**	0.971	0.913	0.971	0.942	0.913	0.942	0.631	0.012	0.631	0.004	0.012	0.004
	95%CI	−6.34–6.11	−6.56–5.89	−6.11–6.34	−6.45 – −6.00	−5.89–6.56	−6.00–6.45	−12.25–19.81	−37.14 – −5.07	−19.81–12.25	−40.92 – −8.85	5.07–37.14	8.85–40.92
Flexibility	**MD**	−0.77	−2.44	0.77	−1.66	2.44	1.66	−6.55	−8.33	6.55	−1.77	8.33	1.77
(cm)	**Sig**	0.784	0.393	0.784	0.559	0.393	0.559	0.015	0.003	0.015	0.483	0.003	0.483
	95%CI	−6.58–5.02	−8.24–3.35	−5.02–6.58	−7.47–4.13	−3.35–8.24	−4.13–7.47	−11.70 – −1.40	−13.48 – −3.18	1.40–11.70	−6.92–3.37	3.18–13.48	−3.37–6.92
PPT	**MD**	−41.11	−32.44	41.11	8.66	32.44	−8.66	−20.00	10.00	−10.00	30.00	20.00	−30.00
(mmHg)	**Sig**	0.182	0.289	0.182	0.775	0.289	0.775	0.170	0.486	0.486	0.044	0.170	0.044
	95%CI	−102.86–20.64	−94.19–29.30	−20.64–102.86	−53.08–70.42	−29.30–94.19	−70.42–53.08	−49.18–9.18	−19.18–39.18	−39.18–19.18	0.81–59.18	−9.18–49.18	−59.18 – −0.81
PTQflx60°/s	**MD**	4.74	−7.30	−4.74	−12.04	7.30	12.04	−1.75	−24.67	1.75	−22.92	24.67	22.92
(Nm)	**Sig**	0.517	0.322	0.517	0.108	0.322	0.108	0.849	0.012	0.849	0.019	0.012	0.019
	95%CI	−10.15–19.64	−22.20–7.60	−19.64–10.15	−26.94–2.85	−7.60–22.20	−2.85–26.94	−20.56–17.05	−43.48 – −5.87	−17.05–20.56	−41.72 – −4.11	5.87–43.48	4.11–41.72
PTQflx180°/s	**MD**	4.06	−2.96	−4.06	−7.03	2.96	7.03	0.27	−11.60	−0.27	−11.87	11.60	11.87
(Nm)	**Sig**	0.441	0.573	0.441	0.188	0.573	0.188	0.972	0.148	0.972	0.139	0.148	0.139
	95%CI	−6.65–14.78	−13.68–7.75	−14.78–6.65	−17.75–3.68	−7.75–13.68	−3.68–17.75	−15.74–16.30	−27.62–4.42	−16.30–15.74	−27.90–4.14	−4.42–27.62	−4.14–27.90
APflx60°/s	**MD**	4.36	5.85	−4.36	1.48	−5.85	−1.48	4.45	−8.73	−4.45	−13.18	8.73	13.18
(watts)	**Sig**	0.380	0.242	0.380	0.763	0.242	0.763	0.328	0.062	0.328	0.007	0.062	0.007
	95%CI	−5.70–14.43	−4.21–15.92	−14.43–5.70	−8.58–11.56	−15.92–4.21	−11.56–8.58	−13.67–4.76	−17.94–0.48	−4.76–13.67	−22.40 – −3.97	−0.48–17.94	3.97–22.40
APflx180°/s	**MD**	10.49	14.61	−10.49	4.11	−14.61	−4.11	7.76	−23.95	−7.76	−31.72	23.95	31.72
(watts)	**Sig**	0.155	0.062	0.155	0.570	0.062	0.570	0.619	0.133	0.619	0.049	0.133	0.049
	95%CI	−4.26–25.25	−0.14–29.36	−25.25–4.26	−10.64–18.87	−29.36–0.14	−18.87–10.64	−24.04–39.57	−55.76–7.85	−39.57–24.04	−63.52 – −0.08	−7.85–55.76	0.08–63.52
RFDflx60°/s	**MD**	−1.02	−1.66	1.02	−0.63	1.66	0.63	15.27	−35.49	−15.27	−50.77	35.49	50.77
(Nm/ms)	**Sig**	0.926	0.880	0.926	0.954	0.880	0.954	0.532	0.153	0.532	0.046	0.153	0.046
	95%CI	−23.45–21.40	−24.09–20.76	−21.40–23.45	−23.06–21.79	−20.76–24.09	−21.79–23.06	−34.42–64.97	−85.19–14.20	−64.97–34.42	−100.46–-1.07	−14.20–85.19	1.07–100.46
RFDflx180°/s	**MD**	4.32	−12.22	−4.32	−16.55	12.22	16.55	−9.71	−59.87	9.71	−50.15	59.87	50.15
(Nm/ms)	**Sig**	0.677	0.246	0.677	0.120	0.246	0.120	0.833	0.201	0.833	0.282	0.201	0.282
	95%CI	−16.89–25.55	−33.44–8.99	−25.55–16.89	−37.77–4.66	−8.99–33.44	−4.66–37.77	−103.78–84.35	−153.94–34.19	−84.35–103.78	−144.22–43.91	−34.19–153.94	−43.91–144.22
PTQext60°/s	**MD**	4.24	−12.13	−4.24	−16.37	12.13	16.37	−12.51	−47.40	12.51	−34.88	47.40	34.88
(Nm)	**Sig**	0.620	0.164	0.620	0.064	0.164	0.064	0.518	0.020	0.518	0.080	0.020	0.080
	95%CI	−13.19–21.68	−29.57–5.30	−21.68–13.19	−33.81–1.06	−5.30–29.57	−1.06–33.81	−51.86–26.84	−86.75 – −8.04	−26.84–51.86	−74.24–4.46	8.04–86.75	−4.46–74.24
PTQext180°/s	**MD**	−7.60	−7.24	7.60	0.35	7.24	0.35	−16.97	−29.86	16.97	−12.88	29.86	12.88
(Nm)	**Sig**	0.198	0.219	0.198	0.951	0.219	0.951	0.209	0.032	0.209	0.337	0.032	0.337
	95%CI	−19.45–4.25	−19.10–4.61	−4.25–19.45	−11.50–12.21	−4.61–19.10	−12.21–11.50	−44.11–10.15	−57.00 – −2.73	−10.15–44.11	−40.02–14.24	2.73–57.00	−14.24–40.02
APext60°/s	**MD**	6.83	−11.40	−6.83	−18.23	11.40	18.23	9.37	−11.24	−9.37	−20.62	11.24	20.62
(watts)	**Sig**	0.544	0.315	0.544	0.114	0.315	0.114	0.449	0.365	0.449	0.103	0.365	0.103
	95%CI	−16.08–29.74	−34.31–11.51	−29.74–16.08	−41.14–4.68	−11.51–34.31	−4.68–41.14	−15.75–34.51	−36.37–13.88	−34.51–15.75	−45.75–4.51	−13.88–36.37	−4.51–45.75
APext180°/s	**MD**	5.04	1.53	−5.04	−3.51	−1.53	3.51	0.342	−48.96	−0.342	−49.30	48.96	49.30
(watts)	**Sig**	0.651	0.890	0.651	0.753	0.890	0.753	0.987	0.031	0.987	0.030	0.031	0.030
	95%CI	−17.69–27.78	−21.20–24.26	−27.78–17.69	−26.24–19.22	−24.26–21.20	−19.22–26.24	−43.63–44.32	−92.94 – −4.98	−44.32–43.63	−93.28 – −5.33	4.98–92.94	5.33–93.28

(*Continued*)

Table 7. (Continued).

		Baseline						Post-test					
		CON		PLA		BRJ		CON		PLA		BRJ	
Variables		PLA	BRJ	CON	BRJ	CON	PLA	PLA	BRJ	CON	BRJ	CON	PLA
RFDext60°/s	**MD**	−36.28	−73.27	36.28	−36.98	73.27	36.98	9.19	−85.21	−9.19	−94.40	85.21	94.40
(Nm/ms)	**Sig**	0.475	0.156	0.475	0.467	0.156	0.467	0.746	0.006	0.746	0.003	0.006	0.003
	95%CI	−139.52–66.95	−176.50–29.96	−66.95–139.52	−140.22–66.25	−29.96–176.50	−66.25–140.22	−48.82–67.20	−143.23 – −27.19	−67.20–48.82	−152.42 – −36.39	27.19–143.23	36.39–152.42
RFDext180°/s	**MD**	−1.61	−0.46	1.61	1.15	0.46	−1.15	2.16	−134.37	−2.16	−136.53	134.37	136.53
(Nm/ms)	**Sig**	0.934	0.981	0.934	0.953	0.981	0.953	0.971	0.032	0.971	0.030	0.032	0.030
	95%CI	−41.40–38.16	−40.25–39.31	−38.16–41.40	−38.63–40.93	−39.31–40.25	−40.93–38.63	−119.87–124.20	−256.41 – −12.32	−124.20–119.87	−258.57 – −14.49	12.32–256.41	14.49–258.57
MVICflx60°	**MD**	7.77	−5.28	−7.77	−13.06	5.28	13.06	16.48	−4.64	−16.48	−21.13	4.64	21.13
(Nm)	**Sig**	0.499	0.644	0.499	0.260	0.644	0.260	0.246	0.741	0.246	0.141	0.741	0.141
	95%CI	−15.58–31.13	−28.64–18.06	−31.13–15.58	−36.42–10.29	−18.06–28.64	−10.29–36.42	−12.13–45.11	−33.26–23.97	−45.11–12.13	−49.75–7.49	−23.97–33.26	−7.49–49.75
MVICext60°	**MD**	−8.36	−32.40	8.36	−24.03	32.40	24.03	10.64	−55.81	−10.64	−66.46	55.81	66.46
(Nm)	**Sig**	0.703	0.148	0.703	0.256	0.148	0.256	0.470	0.001	0.470	0.001	0.001	0.001
	95%CI	−53.18–36.45	−77.21–12.41	−36.45–53.18	−67.51–19.44	−12.41–77.21	−19.44–67.51	−19.30–40.60	−85.77 – −25.86	−40.60–19.30	−95.52 – −37.40	25.86–85.77	37.40–95.52

CON: Control, PLA: Placebo, BRJ: Beetroot juice, SD: Standard deviation, HGS: Handgrip strength, PPT: Pressure pain threshold, ext: Extension, flx: Flexion, PTQ: Absolute peak torque, AP: Average power, RFD: Average rate of force development, MVIC: Muscle voluntary isometric contraction, ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, MD: Mean Difference, sig: Significant, CI: Confidence Interval, Nm: Newton meters, ms: Millisecond.

Table 8. Comparison of the variables data between baseline and posttest in three groups.

			CON	PLA	BRJ
Variables			Post-test		
HGS (kg)	Baseline	MD	4.44	0.55	25.22
		Sig	0.456	0.925	0.001
		95%CI	−7.65–16.54	−11.54–12.65	13.12–37.32
Flexibility (cm)	Baseline	MD	0.22	6.00	6.11
		Sig	0.900	0.002	0.002
		95%CI	−3.39–3.84	2.38–9.62	2.49–9.73
PPT (mmHg)	Baseline	MD	−21.11	−33.55	−72.22
		Sig	0.286	0.096	0.001
		95%CI	−61.06–18.84	−73.51–6.40	−112.17 – −32.26
PTQflx60°/s (Nm)	Baseline	MD	9.48	15.98	26.86
		Sig	0.088	0.006	0.001
		95%CI	−1.52–20.50	4.97–27.00	15.85–37.88
PTQflx180°/s (Nm)	Baseline	MD	10.88	14.67	19.52
		Sig	0.021	0.003	0.001
		95%CI	1.75–20.02	5.54–23.81	10.39–28.65
APflx60°/s (watts)	Baseline	MD	2.62	2.53	17.21
		Sig	0.367	0.383	0.001
		95%CI	−3.25–8.50	−3.34–8.41	11.33–23.09
APflx180°/s (watts)	Baseline	MD	11.67	14.40	50.24
		Sig	0.256	0.164	0.001
		95%CI	−9.03–32.39	−6.30–35.12	29.53–70.95
RFDflx60°/s (Nm/ms)	Baseline	MD	65.67	49.37	99.50
		Sig	0.001	0.005	0.001
		95%CI	32.88–98.47	16.58–82.17	66.71–132.30
RFDflx180°/s (Nm/ms)	Baseline	MD	92.76	106.80	140.40
		Sig	0.008	0.003	0.001
		95%CI	27.06–158.45	41.11–172.50	74.71–206.10
PTQext60°/s (Nm)	Baseline	MD	11.42	28.17	46.68
		Sig	0.368	0.033	0.001
		95%CI	−14.28–37.12	2.47–53.87	20.98–72.38
PTQext180°/s (Nm)	Baseline	MD	0.44	9.82	23.06
		Sig	0.951	0.183	0.004
		95%CI	−14.35–15.24	−4.97–24.61	8.27–37.86
APext60°/s (watts)	Baseline	MD	1.77	−0.76	1.62
		Sig	0.752	0.892	0.773
		95%CI	−9.71–13.27	−12.26–10.72	−9.87–13.11
APext180°/s (watts)	Baseline	MD	5.95	10.65	56.45
		Sig	0.638	0.402	0.001
		95%CI	−31.75–19.84	−15.13–36.45	30.65–82.25
RFDext60°/s (Nm/ms)	Baseline	MD	1.77	47.25	−10.17
		Sig	0.949	0.095	0.711
		95%CI	−54.27–57.81	−103.29–8.79	−66.21–45.87
RFDext180°/s (Nm/ms)	Baseline	MD	16.92	13.14	150.83
		Sig	0.699	0.763	0.002
		95%CI	−72.19–106.05	−75.98–102.26	61.70–239.95
MVICflx60° (Nm)	Baseline	MD	13.93	5.21	13.28
		Sig	0.079	0.499	0.093
		95%CI	−1.73–29.60	−10.45–20.88	−2.38–28.95
MVICext60° (Nm)	Baseline	MD	−6.56	−25.57	16.85
		Sig	0.585	0.032	0.145
		95%CI	−31.10–17.97	−48.71 – −2.44	−6.28–39.99

CON: Control, PLA: Placebo, BRJ: Beetroot juice, SD: Standard deviation, HGS: Handgrip strength, PPT: Pressure pain threshold, ext: Extension, flx: Flexion, PTQ: Absolute peak torque, AP: Average power, RFD: Average rate of force development, MVIC: Muscle voluntary isometric contraction, ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, MD: Mean Difference, sig: Significant, CI: Confidence Interval, Nm: Newton meters, ms: Millisecond.

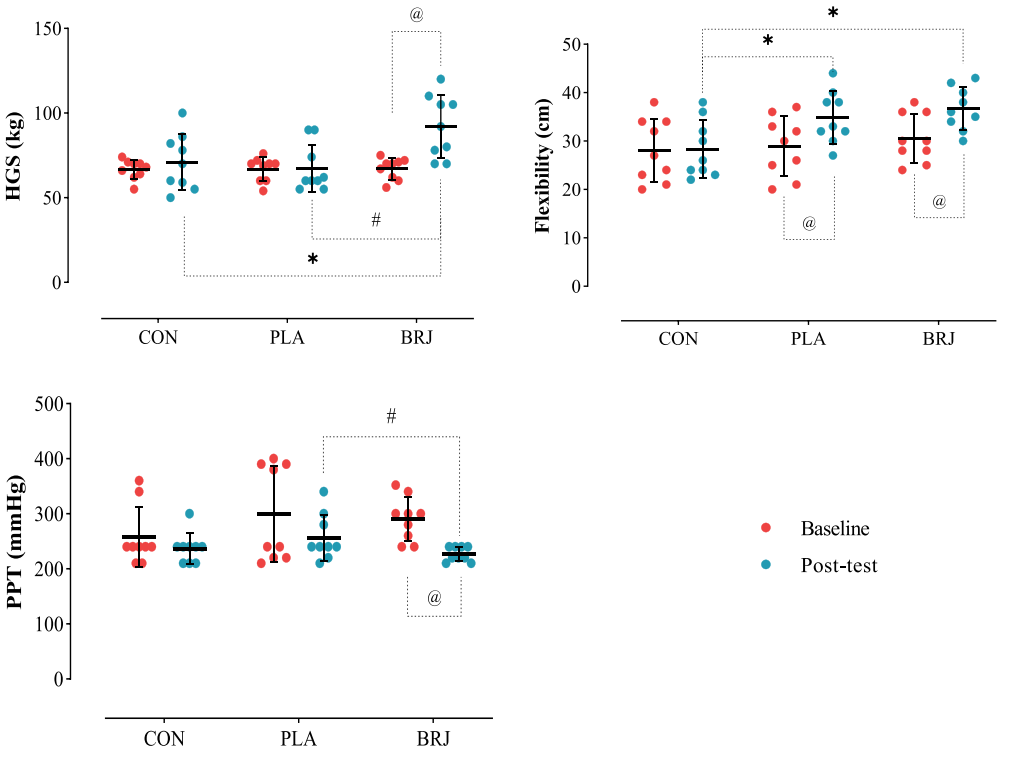

Figure 4. Means and standard deviations of handgrip strength (HGS), flexibility, and pressure pain threshold (PPT) in the baseline and posttest in the three groups. CON: control, PLA: placebo, BRJ: beetroot juice. *: Significant difference compared to CON. #: Significant difference compared to PLA. @: Significant difference compared to the baseline.

group in the posttest compared to the baseline ($p = 0.001$). In contrast, no differences were observed between the posttest and baseline in the CON ($p = 0.286$) and PLA ($p = 0.096$) groups (Table 8, Figure 4).

The analysis results demonstrate a significant difference in PTQflx60°/s among the study groups (F1.00 = 32.06, $p = 0.001$, pEta2 = 0.572). Post-hoc Bonferroni analysis reveals that PTQflx60°/s in the BRJ group significantly exceeded that of the CON ($p = 0.012$) and PLA ($p = 0.019$) groups in the posttest. However, no significant differences existed between the PLA and CON groups ($p = 0.849$). Notably, there were no significant differences among the groups in the baseline ($p > 0.05$) (Table 7). Furthermore, the posttest analysis showed that PTQflx60°/s significantly improved in the BRJ ($p = 0.001$) and PLA ($p = 0.006$) groups compared to the baseline, while no substantial difference was observed in the CON group ($p = 0.088$) (Table 8, Figure 5).

The mixed repeated measure analysis ANOVA test outcomes revealed a noteworthy variance among the study groups in PTQflx180°/s (F1.00 = 34.61, $p = 0.001$, pEta2 = 0.591). The Bonferroni test results indicated no significant differences between the groups during the baseline and posttest ($p > 0.05$) (Table 7). Furthermore, the findings revealed a substantial improvement in PTQflx180°/s during the posttest compared to the baseline in the BRJ ($p = 0.001$), PLA ($p = 0.003$), and CON ($p = 0.021$) groups (Table 8, Figure 5).

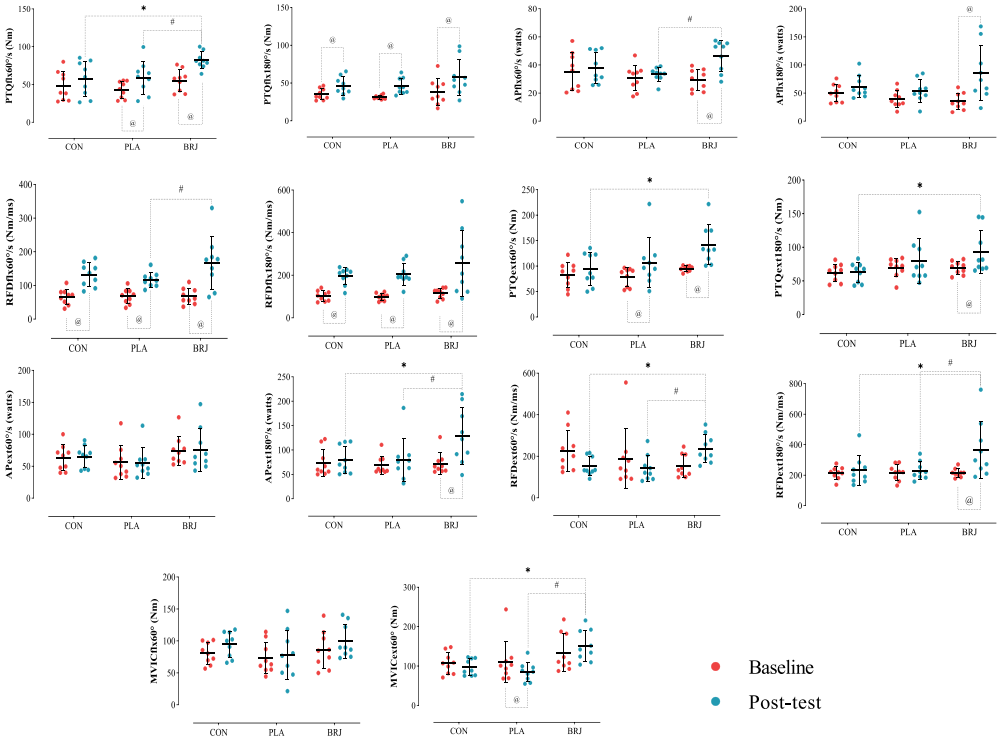

Figure 5. Means and standard deviations of isokinetic and isometric parameters in the baseline and posttest, in the three groups. CON: Control, PLA: Placebo, BRJ: Beetroot juice, ext: Extension, flx: Flexion, PTQ: Absolute peak torque, AP: Average power, RFD: Average rate of force development, MVIC: Muscle voluntary isometric contraction, ml: Milliliter, kg: Kilogram, min: Minutes, s: Second, cm: Centimeter, Nm: Newton meters. *: Significant difference compared to CON. #: Significant difference compared to PLA. @: Significant difference compared to baseline.

The analysis revealed significant differences among the study groups at APflx60°/s ($F2.00 = 4.23$, $p = 0.027$, $pEta2 = 0.261$). The Bonferroni test results demonstrated a substantial increase in BRJ compared to PLA ($p = 0.007$) in the posttest, while no significant differences were found in PLA ($p = 0.328$) and BRJ ($p = 0.062$) compared to CON. There were no significant differences between the groups in the baseline ($p > 0.05$) (Table 7). Furthermore, the post hoc test results indicated a substantial improvement in the BRJ group in the posttest compared to the baseline ($p = 0.001$). In contrast, no differences were observed between the posttest and baseline in the CON ($p = 0.208$) and PLA ($p = 0.383$) groups (Table 8, Figure 5).

The analysis revealed a significant difference among the studied groups ($F1.00 = 19.27$, $p = 0.001$, $pEta2 = 0.445$) in APflx180°/s. Furthermore, the results of the Bonferroni test indicated no significant differences between the studied groups in the baseline and posttest ($p > 0.05$) (refer to Table 7). Additionally, the findings demonstrated a substantial improvement in APflx180°/s in the posttest compared to the baseline in the BRJ group ($p = 0.001$). However, there were no differences between the posttest and baseline in the CON ($p = 0.256$) and PLA ($p = 0.164$) groups (see Table 8, Figure 5).

The mixed repeated measure analysis ANOVA test outcomes demonstrated a significant variance among the study groups in RFDflx60°/s (F1.00 = 60.78, p = 0.001, pEta2 = 0.717). Subsequent Bonferroni testing indicated that post-testing revealed a significantly greater RFDflx60°/s in the BRJ group compared to PLA (p = 0.046). However, no significant differences were found in PLA (p = 0.532) and BRJ (p = 0.153) compared to CON. Notably, no substantial variance was noted among the groups in the baseline (p > 0.05) (Table 7). Furthermore, results indicated a significant improvement in RFDflx60°/s during the posttest compared to the baseline in CON (p = 0.001), PLA (p = 0.005), and BRJ (p = 0.001) groups (Table 8, Figure 5).

The findings indicate a significant variance among the researched groups in RFDflx180°/s (F1.00 = 38.02, p = 0.001, pEta2 = 0.613). Post hoc analysis using the Bonferroni test revealed no notable distinctions between the groups in the baseline and posttest (p > 0.05) (Table 7). Nevertheless, RFDflx180°/s demonstrated significant enhancement in the posttest in comparison to the baseline within the CON (p = 0.008), PLA (p = 0.003), and BRJ (p = 0.001) groups (Table 8, Figure 5).

The analysis revealed a significant difference among the studied groups (F1.00 = 16.00, p = 0.001, pEta2 = 0.400) in PTQext60°/s. Post-hoc test results indicated that in the posttest, the PTQext60°/s was significantly higher than CON (p = 0.020), while no significant differences were observed between PLA with CON (p = 0.518) and BRJ (p = 0.080). However, in the baseline, no significant differences were found between the groups (p > 0.05) (Table 7). Notably, the results demonstrated a significant improvement in PTQext60°/s in the posttest compared to the baseline for the PLA (p = 0.033) and BRJ (p = 0.001) groups. Conversely, there was no difference between the posttest and baseline in CON (p = 0.368) (Table 8, Figure 5).

The mixed repeated measure analysis of variance (ANOVA) findings indicate a substantial difference between the study groups in PTQext180°/s (F1.00 = 7.20, p = 0.013, pEta2 = 0.231). Further examination using the Bonferroni test revealed a significant increase in PTQext180°/s in the BRJ group compared to the CON group (p = 0.032) during the posttest. However, no significant differences were observed in PTQext180°/s between the PLA group and the CON group (p = 0.209) or the BRJ group (p = 0.337). Notably, there were no significant differences between the groups in the baseline (p > 0.05) (Table 7). Additionally, the results indicated a noteworthy enhancement in the PTQext180°/s for the BRJ group from the baseline to the posttest (p = 0.004). Conversely, no differences were observed between the baseline and posttest for the CON group (p = 0.951) and the PLA group (p = 0.183) (Table 8, Figure 5).

The analysis revealed a statistically significant difference among the groups in APext180°/s (F1.00 = 11.39, p = 0.003, pEta2 = 0.322). Post hoc comparisons using the Bonferroni test indicated that APext180°/s was significantly higher in the BRJ group compared to the CON (p = 0.031) and PLA (p = 0.030) groups in the posttest. However, no significant difference was found between the PLA and CON groups in the posttest (p = 0.987). Furthermore, there were no significant differences among the groups in the baseline (p > 0.05) (Table 7). The results also demonstrated a considerable improvement in APext180°/s in the posttest compared to the baseline in the BRJ group (p = 0.001). Conversely, there were no differences between the baseline and posttest in the CON (p = 0.638) and PLA (p = 0.402) groups (Table 8, Figure 5).

The analysis indicates a significant intervention effect in the RFDext60°/s for the study groups (F2.00 = 2.81, $p = 0.048$, pEta2 = 0.190). Furthermore, Bonferroni results reveal that in the posttest, BRJ significantly outperformed CON ($p = 0.006$) and PLA ($p = 0.003$), while no significant differences were noted between CON and PLA ($p = 0.746$). Before the intervention, no differences were observed between the study groups in RFDext60°/s ($p > 0.05$) (Table 7). Notably, analysis reveals no significant difference in RFDext60°/s between the study groups from baseline to posttest ($p > 0.05$) (Table 8, Figure 5).

The mixed repeated measure analysis ANOVA test results revealed a significant disparity between the study groups in RFDext180°/s (F1.00 = 5.85, $p = 0.024$, pEta2 = 0.196). Subsequent Bonferroni tests indicated that in the posttest, RFDext180°/s exhibited a significant increase in the BRJ group compared to the PLA ($p = 0.030$) and CON ($p = 0.032$) groups. However, no notable difference was observed between the CON and PLA groups ($p = 0.971$). Notably, no significant variances were found among the three study groups in the baseline ($p > 0.05$) (Table 7). Additionally, the findings demonstrated a substantial rise in the posttest in the BRJ group as compared to the baseline ($p = 0.002$). Conversely, no disparities were observed in the CON ($p = 0.699$) and PLA ($p = 0.763$) groups between the baseline and posttest (Table 8, Figure 5).

The analysis indicates that the intervention had a significant effect on the study groups regarding MVICext60° (F2.00 = 3.61, $p = 0.043$, pEta2 = 0.239). Furthermore, the Bonferroni results reveal that BRJ significantly increased in the posttest compared to CON ($p = 0.001$) and PLA ($p = 0.001$). However, CON and PLA had no significant differences ($p = 0.470$). In the baseline for RFDext60°/s, no significant differences were observed between the studied groups ($p > 0.05$) (Table 7). Moreover, the results indicate a considerable increase in MVICext60° between the baseline and posttest in the PLA group ($p = 0.032$). Meanwhile, no difference was observed between the baseline and posttest in the CON ($p = 0.585$) and BRJ ($p = 0.145$) groups (Table 8, Figure 5).

The analysis indicated that there were no variations between the groups under study in Sw-T (F2.00 = 1.24, $p = 0.305$, pEta2 = 0.094), APext60°/s (F2.00 = 1.58, $p = 0.226$, pEta2 = 0.117), and MVICflx60° (F2.00 = 1.17, $p = 0.325$, pEta2 = 0.089) during the baseline and posttest (Table 7). Moreover, no noteworthy variances were evident within the study groups between the baseline and posttest for Sw-T, APext60°/s, and MVICflx60° ($p > 0.05$) (Table 8, Figure 5).

5. Discussion

5.1. Overview of findings

The primary objective of the current study was to examine the effect of acute BRJ consumption before climbing on lower-body isokinetic and isometric strength, aerobic power, and muscle soreness among climbers. The study results revealed a statistically significant decrease in DOMS in the gastrocnemius muscles 24 hours post-descending in the BRJ group compared to the control group. However, no changes in DOMS were observed for the quadriceps and hamstring muscles. Furthermore, the findings indicated notable alterations in specific DOMS monitoring parameters (PPT & Sw-T), functional tests (Estimated $VO_{2max,}$ HGS, and HJ), and isokinetic and isometric strength measures following the interventions. Nonetheless, some indicators demonstrated no changes post-intervention.

5.2. BRJ supplementation and DOMS

The current investigation has revealed that DOMS in the gastrocnemius muscles 24 hours after descending was notably lower in the group supplemented with BRJ than in the CON group. However, no significant changes in DOMS were observed in the quadriceps and hamstring muscles. Analysis of Figure 2 indicates a distinct decrease in DOMS for the three muscle groups in the BRJ group after 12 hours, suggesting a more rapid recovery than the other groups. These findings are consistent with Daab et al. (2021), who proposed that chronic beetroot juice supplementation reduces post-exercise perceived muscle soreness and supports enhanced performance during the recovery period in soccer players [33]. Furthermore, Clifford et al. (2016) demonstrated that consuming beetroot juice four days after muscle-damaging resistance exercise attenuated muscle pain [35]. In addition, Ahmadpour et al [36] and Hemmatinafar et al. [32] showed that BRJ supplementation can reduce muscle soreness in alpine skiers and female volleyball players. Conversely, the results of Clifford et al. (2017) contradict the present study, showing that consuming beetroot juice for three days after a marathon race did not reduce inflammation, injury, muscle pain, or improve recovery [54]. The analgesic effects of BRJ supplementation have been primarily attributed to its active phytochemicals, including betalain and plant polyphenols [54]. Therefore, the reduction of DOMS 24 hours after descending in the present study may be caused by the anti-inflammatory and antioxidant compounds of BRJ. However, some studies have shown the analgesic effects of BRJ to be independent of changes in inflammatory markers [35,55]. A recent meta-analysis suggests further research on the interaction of BRJ's analgesic effects and muscle inflammation pathways [56]. In addition to plant polyphenols, BRJ contains high levels of nitrates, which increase the body's available nitric oxide (NO) levels [56]. Based on existing evidence, NO can activate C-fiber nociceptors and increase pain sensation, potentially counteracting the analgesic effects of polyphenols in BRJ [57].

A notable spike in hamstring DOMS was observed in the PLA group at 48 hours post-descent, despite the absence of statistically significant between-group differences. While the PLA and CON groups followed identical protocols, this divergence may be attributed to several plausible physiological and methodological factors. First, individual variability in eccentric loading during prolonged downhill walking – particularly in the hamstring-dominant control of deceleration – may have caused disproportionate microtrauma in some participants. Previous research has shown that downhill locomotion increases eccentric strain on the posterior chain, particularly in the hamstrings, due to the braking action required to control descent. This strain is often amplified when compensatory gait patterns are adopted in response to fatigue or unfamiliarity with terrain [58]. Second, the PLA group demonstrated a higher standard deviation compared to CON and BRJ, suggesting inter-individual differences in susceptibility to muscle damage. Such variability can mask statistical significance even when mean group differences appear pronounced. Importantly, the absence of nitrate and antioxidant compounds in the placebo group may have exacerbated inflammatory responses in more sensitive individuals. Taken together, these findings highlight the complex interplay of biomechanics, supplementation, and recovery, and suggest that future studies should consider incorporating biomechanical and neuromuscular profiling to better understand individual responses to muscle-damaging activities.

Moreover, NO has been suggested to activate satellite cells and increase Follistatin, thereby facilitating muscle repair following pain-induced damage [57]. However, a study comparing nitrated beverages and BRJ indicated that BRJ was more effective than nitrated beverages in reducing muscle pain, with any analgesic effects likely due to phytonutrients in BRJ rather than nitrates [54]. Furthermore, recent evidence has suggested that DOMS is an acute compression axonopathy characterized by tissue microdamage and increased oxidative stress resulting from immune-mediated inflammation [7]. According to this theory, NO plays a role in the secondary phase of micro-neurological damage after eccentric exercise, further promoting inflammation and repair by the immune system [7]. Therefore, considering the complex underlying mechanisms of DOMS and the limited research on the role of NO in its control, further studies should be conducted on the interaction of NO resulting from BRJ consumption and DOMS.

5.3. Effects of BRJ on strength and endurance performance

Our study indicates that the supplementation of BRJ resulted in concurrent reductions in DOMS and increases in wall-sit, HGS, MVICext60° (muscular isometric strength), estimated VO_{2max}, and isokinetic strength parameters, especially the RFD in flexor and extensor muscles. However, no significant difference was observed in HJ, APext60°/s, and MVICext60°. While several studies have demonstrated the positive effect of BRJ on recovery indicators such as MVIC, vertical jump, and aerobic endurance, some investigations have reported contrasting results [59,60]. A meta-analysis by Jones et al. (2021) suggested that the time interval of functional tests and exercise can affect the improvements in MVIC during recovery [56]. For example, the beneficial effect of BRJ supplementation on MVIC recovery was observed only at 72 hours after exercise, while at intervals of 30 minutes, 24 hours, and 48 hours after exercise, BRJ supplementation had no effect compared to a placebo [56]. Our study suggests that extending the duration of the wall-sit test reveals that BRJ supplementation can improve isometric endurance performance recovery.

Conversely, Jonvik et al. (2020) found that six days of BRJ did not significantly improve endurance performance and muscle strength in recreationally active men compared to a placebo [61]. However, it is worth noting that the placebo supplementation used by Jonvik et al. (2020) was nitrate-depleted beet juice, which may have influenced the observed outcomes [61]. In contrast, other BRJ nutrients may have influenced the observed results. The disparity in findings between our study and that of Jonvik et al. (2020) may be partially explained by the differences in the measurement tools used. Our evaluation of muscle endurance performance involved an isometric wall-sit test and an isometric device test at a speed of 60 degrees. In contrast, Jonvik et al. (2020) calculated the workload resulting from 30 bilateral voluntary isokinetic contractions at a speed of 180 degrees [61]. Therefore, the difference in the measurement tools can partially explain the disparity in the findings. In line with our findings, Ranchal-Ranchal-Sanchez et al. (2020) also demonstrated the positive effects of BRJ supplementation on improving muscle endurance in resistance training [62]. Several other studies have likewise shown the positive effect of BRJ supplementation on muscle endurance [36,63–65]. Furthermore, Reimer et al. (2016) found that acute consumption of BRJ supplements increased the maximum muscle power and contraction speed in athletes from various disciplines [66].

Tatlici (2021) also reported that BRJ supplementation enhanced the peak and average isokinetic strength of trained Greco-Roman wrestlers' lower and upper body muscles [67].

The precise mechanisms underlying these improvements have yet to be fully elucidated. However, the increase in high angular velocities may be attributed to greater recruitment of type II and fast-twitch fibers following nitrate supplementation, which leads to enhanced force production in fast-twitch muscle fibers due to increased intracellular calcium concentration [18,19,68]. Additionally, increased blood flow and vascular conductance have been observed in type II muscles more significantly than in type I muscles following beetroot juice intake in rats [18]. Moreover, dietary nitrate supplementation has been reported to increase force production of the knee extensors during electrical stimulation of isometric contractions [69]. These results appear to be consistent with other studies conducted on mice [19], where muscle force increases due to increased free calcium concentration in the sarcoplasm, improved intracellular calcium handling, and hence augmented force generation [19,69]. One study has also observed that dietary nitrate acutely increases muscle power and speed during maximal multi-joint actions in trained athletes, possibly due to NO's direct and indirect effects [66]. NO appears to directly enhance acetylcholine action in fast-twitch muscle fibers by alteration in the motor end-plate currents [70]. While Petrov et. al study demonstrated that nitric oxide enhances acetylcholine action in fast-twitch muscle fibers through alterations in motor end-plate currents in rats [70], caution should be taken when translating these findings to human physiology. Although rodent models provide valuable insights into muscle function and nitric oxide mechanisms, differences in muscle composition, metabolism, and neuromuscular control between rodents and humans may influence the direct applicability of these results. Further research in human studies is needed to validate these mechanisms. Indirectly, the stimulation of soluble guanylate cyclase (sGC) and, hence, an increase in cyclic guanosine monophosphate (cGMP) can lead to augmented maximal shortening velocity via NO, particularly in muscle fibers type II [68,71].

5.4. BRJ supplementation and performance recovery

The current investigation revealed a substantial decrease in PPT in the BRJ group during the posttest, indicating a potential reduction in DOMS and associated mechanisms. Additionally, the BRJ group exhibited increased flexibility, while Sw-T showed no significant changes posttest. The noticeable improvement in wall-sit performance and isokinetic strength parameters could be attributed to the reduction of PPT, control of Sw-T, and alleviation of DOMS [60,72]. DOMS is linked to symptoms such as diminished muscle force production, pain, mechanical damage to skeletal muscles, and tissue edema [60,72,73]. Further, nitrate-rich dietary supplements, like BRJ, have been shown to enhance neuromuscular efficiency significantly, especially during fatigue [74]. This improved neuromuscular efficiency partly explains the enhanced performance in the wall-sit and isometric tests. Moreover, the vasodilatory effects of NO may positively influence muscle endurance performance by enhancing blood flow and providing more oxygen to muscle tissue [62]. Increased NO levels can influence pain perceptions after eccentric exercise and affect neuromuscular efficiency and muscle recovery [57]. However, the effects of NO on blood flow redistribution and its role in muscle performance require further investigation. Notably, manipulating NO

production in skeletal muscles may not always increase performance. Therefore, according to Radak et al. (2012), "you may have to pay a little pain to increase your endurance capacity" [57]. Nevertheless, specific stimuli to enhance muscle NO can potentially increase blood flow to muscle tissue during exercise, facilitate muscle repair, and improve performance by activating satellite cells and increasing Follistatin expression. [57]. Further studies are warranted to clarify the interplay between NO production and neuromuscular efficiency following BRJ supplementation, particularly in muscle performance and recovery at altitude. In addition to its role in stimulating NO availability, BRJ contains bioactive compounds with potential anti-inflammatory and antioxidant effects, which may contribute to reducing exercise-induced muscle soreness and enhancing post-exercise recovery [75]. Future investigations should evaluate immune, metabolic, and hormonal markers to establish additional mechanisms through which BRJ influences performance recovery. While improvements in neuromuscular efficiency were inferred from enhanced functional performance tests, direct measurements using tools such as electromyography (EMG) were not conducted in this study. Incorporating objective assessments of neuromuscular efficiency in future studies would provide a more precise understanding of BRJ's effects. To ensure a clear focus, future research should prioritize exploring the optimal dosage, timing, and specific effects of BRJ on recovery and performance, particularly in climbing and high-altitude conditions.

5.5. Study limitations and future research directions

The present study has several limitations that should be acknowledged. Firstly, due to financial constraints, changes in plasma nitrate levels and biomarkers associated with muscle damage were not measured following BRJ consumption. Additionally, cognitive indicators, arousal, and other psychological variables that might influence muscle function were not assessed. The climbing conditions also restricted the ability to conduct all performance tests at altitude. Moreover, while participants were instructed to avoid nitrate-rich foods at the study's outset, a detailed dietary log was not maintained to monitor their nitrate intake throughout the study accurately. This lack of dietary monitoring may have introduced a potential confounding factor, as variations in dietary nitrate consumption outside of the supplementation could have influenced the study's outcomes. Furthermore, neuromuscular efficiency was inferred through performance tests rather than direct measurement, highlighting a need for future research incorporating objective assessments like electromyography (EMG) to provide more precise insights. Addressing these limitations in future studies could enhance the reliability and applicability of the findings.

6. Conclusion

The study's findings suggested that acute BRJ supplementation improves climbers' lower-body isokinetic and isometric strength, power, and endurance performance. This improvement is associated with a reduced perception of muscle pain and soreness. However, some specific isokinetic strength indicators and Sw-T showed no significant changes. The results imply that BRJ could benefit climbers, particularly during altitude

training camps and climbing sessions, by enhancing strength, power, and endurance performance while expediting recovery from muscle soreness. The study recommends further research into the timing, dosage, and manipulation of BRJ compounds, specifically their effects on the recovery of performance indicators and DOMS in athletes, to build upon the outcomes obtained.

Acknowledgments

We want to thank all the participants who supported us in examining and implementing the current study.

Disclosure statement

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

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Mohammad Hemmatinafar http://orcid.org/0000-0001-7585-7592

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Consent for publication

Informed consent was obtained from all individual participants included in the study.

References

1. Wyatt FB. Physiological responses to altitude: a brief review. J Exercise Physiol Online. 2014:**17** (1).
2. Calbet JA, Lundby C. Air to muscle O2 delivery during exercise at altitude. High Alt Med Biol. 2009;10(2):123–134. doi: 10.1089/ham.2008.1099
3. Naeije R. *Physiological adaptation of the cardiovascular system to high altitude*. progress in cardiovascular diseases. Prog Cardiovasc Dis. 2010;52(6):456–466. doi: 10.1016/j.pcad.2010.03.004
4. Werner I, Valero-Cuevas FJ, Federolf P. Mountain hiking: prolonged eccentric muscle contraction during simulated downhill walking perturbs sensorimotor control loops needed for safe dynamic foot–ground interactions. Int J Environ Res Public Health. 2023;20(7):5424. doi: 10.3390/ijerph20075424
5. Lambert M, Dennis S. Delayed-onset-muscle-soreness. South Afr J Sports Med. 1973;1 (1):18–20.

6. Sonkodi B. Delayed onset muscle soreness and critical neural microdamage-derived neuroinflammation. Biomolecules. 2022;12(9):1207. doi: 10.3390/biom12091207
7. Sonkodi B, Berkes I, Koltai E. *Have we looked in the wrong direction for more than 100 years? Delayed onset muscle soreness is, in fact, neural microdamage rather than muscle damage*. Antioxidants. 2020;9(3):212. doi: 10.3390/antiox9030212
8. Sonkodi B, Kopa Z, Nyirády P. Post orgasmic illness syndrome (POIS) and delayed onset muscle soreness (DOMS): do they have anything in common? Cells. 2021;10(8):1867. doi: 10.3390/cells10081867
9. Hayashi K. Degenerative histological alteration is not required for the induction of muscular mechanical hyperalgesia after lengthening contraction in rats. J Physiol Sci. 2015;65:S277.
10. Cheung K, Hume P, Maxwell L. Delayed onset muscle soreness treatment strategies and performance factors. Sports Med. 2003;33(2):145–164.
11. Murray AJ. Metabolic adaptation of skeletal muscle to high altitude hypoxia: how new technologies could resolve the controversies. Genome Med. 2009;1(12):1–9. doi: 10.1186/gm117
12. Rojano-Ortega D, Peña Amaro J, Berral-Aguilar AJ, et al. Effects of beetroot supplementation on recovery after exercise-induced muscle damage: a systematic review. Sports Health. 2022;14(4):556–565. doi: 10.1177/19417381211036412
13. Olsson H, Al-Saadi J, Oehler D, et al. Physiological effects of beetroot in athletes and patients. Cureus. 2019:11(12. doi: 10.7759/cureus.6355
14. Rocha BS. The nitrate-nitrite-nitric oxide pathway on healthy ageing: a review of pre-clinical and clinical data on the impact of dietary nitrate in the elderly. Front Aging. 2021;2:778467. doi: 10.3389/fragi.2021.778467
15. Arazi H, Eghbali E. Possible effects of beetroot supplementation on physical performance through metabolic, neuroendocrine, and antioxidant mechanisms: a narrative review of the literature. Front Nutr. 2021;8:660150. doi: 10.3389/fnut.2021.660150
16. Maiorana A, O???driscoll G, Taylor R, et al. Exercise and the nitric oxide vasodilator system. Sports Med. 2003;33(14):1013–1035. doi: 10.2165/00007256-200333140-00001
17. Ormsbee MJ, Lox J, Arciero PJ. Beetroot juice and exercise performance. Nutr Dietary Suppl. 2013:27–35. doi: 10.2147/NDS.S52664
18. Ferguson SK, Hirai DM, Copp SW, et al. Impact of dietary nitrate supplementation via beetroot juice on exercising muscle vascular control in rats. J Physiol. 2013;591(2):547–557. doi: 10.1113/jphysiol.2012.243121
19. Hernández A, Schiffer TA, Ivarsson N, et al. Dietary nitrate increases tetanic [ca 2+] i and contractile force in mouse fast-twitch muscle. J Physiol. 2012;590(15):3575–3583. doi: 10.1113/jphysiol.2012.232777
20. Jones AM, Ferguson SK, Bailey SJ, et al. *Fiber type-specific effects of dietary nitrate*. exercise and sport sciences reviews. Exerc Sport Sci Rev. 2016;44(2):53–60. doi: 10.1249/JES.0000000000000074
21. Poredoš D, Jenko Pražnikar Z, Kozinc Ž. Acute effects of beetroot juice supplementation on isometric muscle strength, rate of torque development and isometric endurance in young adult men and women: a randomized, double-blind, controlled cross-over Pilot study. Nutrients. 2022;14(22):4759. doi: 10.3390/nu14224759
22. Lundberg JO, Weitzberg E, Gladwin MT. The nitrate–nitrite–nitric oxide pathway in physiology and therapeutics. Nat Rev Drug Discov. 2008;7(2):156–167. doi: 10.1038/nrd2466
23. Shannon OM, McGawley K, Nybäck L, et al. "Beet-ing" the mountain: a review of the physiological and performance effects of dietary nitrate supplementation at simulated and terrestrial altitude. Sports Med. 2017;47(11):2155–2169. doi: 10.1007/s40279-017-0744-9
24. Nyakayiru J, Jonvik K, Trommelen J, et al. Beetroot juice supplementation improves high-intensity intermittent type exercise performance in trained soccer players. Nutrients. 2017;9(3):314. doi: 10.3390/nu9030314
25. Essén B. Glycogen depletion of different fibre types in human skeletal muscle during intermittent and continuous exercise. Acta Physiologica Scandinavica. 1978;103(4):446–455. doi: 10.1111/j.1748-1716.1978.tb06239.x

26. Jädert C, Petersson J, Massena S, et al. Decreased leukocyte recruitment by inorganic nitrate and nitrite in microvascular inflammation and NSAID-induced intestinal injury. Free Radical Biol Med. 2012;52(3):683–692. doi: 10.1016/j.freeradbiomed.2011.11.018
27. Nikolaidis MG, Jamurtas AZ, Paschalis V, et al. The effect of muscle-damaging exercise on blood and skeletal muscle oxidative stress: magnitude and time-course considerations. Sports Med. 2008;38(7):579–606. doi: 10.2165/00007256-200838070-00005
28. Jones L, Bailey SJ, Rowland SN, et al. The effect of nitrate-rich beetroot juice on markers of exercise-induced muscle damage: a systematic review and meta-analysis of human intervention trials. J Diet Suppl. 2022;19(6):749–771. doi: 10.1080/19390211.2021.1939472
29. Wootton-Beard PC, Ryan L. A beetroot juice shot is a significant and convenient source of bioaccessible antioxidants. J Funct Foods. 2011;3(4):329–334. doi: 10.1016/j.jff.2011.05.007
30. Masschelein E, Van Thienen R, Wang X, et al. Dietary nitrate improves muscle but not cerebral oxygenation status during exercise in hypoxia. J Appl Physiol. 2012;113(5):736–745. doi: 10.1152/japplphysiol.01253.2011
31. Arnold JT, Oliver SJ, Lewis-Jones TM, et al. Beetroot juice does not enhance altitude running performance in well-trained athletes. Appl Physiol Nutr Metab. 2015;40(6):590–595. doi: 10.1139/apnm-2014-0470
32. Hemmatinafar M, Zaremoayedi L, Koushkie Jahromi M, et al. Effect of beetroot juice supplementation on muscle soreness and performance recovery after exercise-induced muscle damage in female volleyball players. Nutrients. 2023;15(17):3763. doi: 10.3390/nu15173763
33. Daab W, Bouzid MA, Lajri M, et al. Chronic beetroot juice supplementation accelerates recovery kinetics following simulated match play in soccer players. J Am Coll Nutr. 2021;40(1):61–69. doi: 10.1080/07315724.2020.1735571
34. Pietrzkowski Z, Pietrzkowski Z, Argumedo R, et al. Betalain-rich red beet concentrate improves reduced knee discomfort and joint function: a double blind, placebo-controlled pilot clinical study. Nutr Dietary Suppl. 2014:9–13. doi: 10.2147/NDS.S59042
35. Clifford T, Berntzen B, Davison G, et al. Effects of beetroot juice on recovery of muscle function and performance between bouts of repeated sprint exercise. Nutrients. 2016;8(8):506. doi: 10.3390/nu8080506
36. Ahmadpour A, Fashi M, Hemmatinafar M. Consuming beetroot juice improves slalom performance and reduces muscle soreness in alpine skiers under hypoxic conditions. Curr Dev Nutr. 2024;8(8):104408. doi: 10.1016/j.cdnut.2024.104408
37. Faul F, Erdfelder E, Lang A-G, et al. G* power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175–191. doi: 10.3758/BF03193146
38. Adams R. Revised physical activity readiness questionnaire. Can Fam Physician. 1999;45:992.
39. Rashki M, Hemmatinafar M, Safari K, et al. Capsaicin's role in mitigating muscle soreness and enhancing futsal players' recovery after exercise-induced muscle damage. Nutrients. 2025;17(5):813. doi: 10.3390/nu17050813
40. McNulty KL, Elliott-Sale KJ, Dolan E, et al. The effects of menstrual cycle phase on exercise performance in eumenorrheic women: a systematic review and meta-analysis. Sports Med. 2020;50(10):1813–1827. doi: 10.1007/s40279-020-01319-3
41. Matteson KA. Menstrual questionnaires for clinical and research use. Best Pract Res Clin Obstet Gynaecol. 2017;40:44–54. doi: 10.1016/j.bpobgyn.2016.09.009
42. Wylie LJ, Kelly J, Bailey SJ, et al. Beetroot juice and exercise: pharmacodynamic and dose-response relationships. J Appl Physiol. 2013;115(3):325–336. doi: 10.1152/japplphysiol.00372.2013
43. Bijur PE, Silver W, Gallagher EJ. Reliability of the visual analog scale for measurement of acute pain. Academic Emerg Med. 2001;8(12):1153–1157. doi: 10.1111/j.1553-2712.2001.tb01132.x
44. Daneshjoo A, Mokhtar AH, Rahnama N, et al. The effects of injury preventive warm-up programs on knee strength ratio in young male professional soccer players. PLoS One. 2012;7(12):e50979. doi: 10.1371/journal.pone.0050979
45. McCleary RW, Andersen J. Test-retest reliability of reciprocal isokinetic knee extension and flexion peak torque measurements. J Athl Train. 1992;27(4):362.

46. Yoon TS, Park DS, Kang SW, et al. Isometric and isokinetic torque curves at the knee joint. Yonsei Med J. 1991;32(1):33–43. doi: 10.3349/ymj.1991.32.1.33
47. Loturco I, Pereira LA, Cal Abad CC, et al. Vertical and horizontal jump tests are strongly associated with competitive performance in 100-m dash events. J Strength Cond Res. 2015;29 (7):1966–1971. doi: 10.1519/JSC.0000000000000849
48. Invernizzi PL, Signorini G, Bosio A, et al. Validity and reliability of self-perception-based submaximal fitness tests in young adult females: an educational perspective. Sustainability. 2020;12(6):2265. doi: 10.3390/su12062265
49. Roberts HC, Denison HJ, Martin HJ, et al. A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach. Age Ageing. 2011;40 (4):423–429. doi: 10.1093/ageing/afr051
50. López-Miñarro P. Comparison between sit-and-reach test and V sit-and-reach test in young adults. Gazz Medica Ital. 2008;167(4):135–142.
51. Chatterjee S, Chatterjee P, Bandhopadhyay A. Cardiorespiratory fitness of obese boys. Indian J Physiol Pharmacol. 2005;49(3):353.
52. Chatterjee S, Chatterjee P, Bandyopadhyay A. ENUMERATION of VALIDITY for PREDICTED VO~ 2~~ M~ A~ XBY QUEEN COLLEGE STEP TEST in BENGALEE BOYS. Indian J Physiol Allied Sci. 2001;55(3):123–127.
53. Cohen J. Statistical power analysis for the behavioral sciences. New York: Routledge; 2013.
54. Clifford T, Howatson G, West DJ, et al. Beetroot juice is more beneficial than sodium nitrate for attenuating muscle pain after strenuous eccentric-bias exercise. Appl Physiol Nutr Metab. 2017;42(11):1185–1191. doi: 10.1139/apnm-2017-0238
55. Rojano-Ortega D, Peña Amaro J, Berral-Aguilar AJ, et al. Effects of beetroot supplementation on recovery after exercise-induced muscle damage: a systematic review. Sports Health. 2021;14(4):556–565. doi: 10.1177/19417381211036412
56. Jones L, Bailey SJ, Rowland SN, et al. The effect of nitrate-rich beetroot juice on markers of exercise-induced muscle damage: a systematic review and meta-analysis of human intervention trials. J Diet Suppl. 2021;19(6):1–23. doi: 10.1080/19390211.2021.1939472
57. Radak Z, Naito H, Taylor AW, et al. Nitric oxide: Is it the cause of muscle soreness? Nitric Oxide. 2012;26(2):89–94. doi: 10.1016/j.niox.2011.12.005
58. Eston RG, Mickleborough J, Baltzopoulos V. Eccentric activation and muscle damage: biomechanical and physiological considerations during downhill running. Br J Sports Med. 1995;29 (2):89–94. doi: 10.1136/bjsm.29.2.89
59. Carriker CR, Rombach P, Stevens BM, et al. Acute dietary nitrate supplementation does not attenuate oxidative stress or the hemodynamic response during submaximal exercise in hypobaric hypoxia. Appl Physiol Nutr Metab. 2018;43(12):1268–1274. doi: 10.1139/apnm-2017-0813
60. Larsen RG, Thomsen JM, Hirata RP, et al. Impaired microvascular reactivity after eccentric muscle contractions is not restored by acute ingestion of antioxidants or dietary nitrate. Physiol Rep. 2019;7(13):e14162. doi: 10.14814/phy2.14162
61. Jonvik KL, Hoogervorst D, Peelen HB, et al. The impact of beetroot juice supplementation on muscular endurance, maximal strength and countermovement jump performance. Eur J Sport Sci. 2021;21(6):871–878. doi: 10.1080/17461391.2020.1788649
62. Ranchal-Sanchez A, Diaz-Bernier VM, De La Florida-Villagran CA, et al. Acute effects of beetroot juice supplements on resistance training: a randomized double-blind crossover. Nutrients. 2020;12(7):1912. doi: 10.3390/nu12071912
63. Bailey SJ, Fulford J, Vanhatalo A, et al. Dietary nitrate supplementation enhances muscle contractile efficiency during knee-extensor exercise in humans. J Appl Physiol. 2010;109 (1):135–148. doi: 10.1152/japplphysiol.00046.2010
64. Bender D, Townsend JR, Vantrease WC, et al. Acute beetroot juice administration improves peak isometric force production in adolescent males. Appl Physiol Nutr Metab. 2018;43 (8):816–821. doi: 10.1139/apnm-2018-0050

65. Williams TD, Martin MP, Mintz JA, et al. Effect of acute beetroot juice supplementation on bench press power, velocity, and repetition volume. J Strength Cond Res. 2020;34(4):924–928. doi: 10.1519/JSC.0000000000003509
66. Rimer EG, Peterson LR, Coggan AR, et al. Acute dietary nitrate supplementation increases maximal cycling power in athletes. Int J Sports Physiol Perform. 2016;11(6):715. doi: 10.1123/ijspp.2015-0533
67. Tatlici A. The effects of acute beetroot juice supplementation on lower and upper body isokinetic strength of the wrestlers. J Men's Health. 2021;17(4):249–254.
68. Maréchal G, Gailly P. Effects of nitric oxide on the contraction of skeletal muscle. Cellular Mol Life Sci CMLS. 1999;55(9):1088–1102. doi: 10.1007/s000180050359
69. Haider G, Folland JP. *Nitrate supplementation enhances the contractile properties of human skeletal muscle*. medicine and science in sports and exercise. Med Sci Sports Exercise. 2014;46 (12):2234–2243. doi: 10.1249/MSS.0000000000000351
70. Petrov KA, Malomouzh AI, Kovyazina IV, et al. Regulation of acetylcholinesterase activity by nitric oxide in rat neuromuscular junction via N -methyl- d -aspartate receptor activation. Eur J Neurosci. 2013;37(2):181–189. doi: 10.1111/ejn.12029
71. Maréchal G, Beckers-Bleukx G. Effect of nitric oxide on the maximal velocity of shortening of a mouse skeletal muscle. Pflügers Arch. 1998;436(6):906–913. doi: 10.1007/s004240050722
72. Vitti S, Bruneau M, Leyshon K, et al. The effects of betalain-rich concentrate supplementation in attenuating muscle damage following eccentric exercise. J Hum Sport Exercise. 2021;16(1). doi: 10.14198/jhse.2021.161.10
73. Heiss R, Lutter C, Freiwald J, et al. Advances in delayed-onset muscle soreness (DOMS)–part II: treatment and prevention. Sportverletzung Sportschaden. 2019;33(1):21–29. doi: 10.1055/a-0810-3516
74. Flanagan SD, Looney DP, Miller MJS, et al. The effects of nitrate-rich supplementation on neuromuscular efficiency during heavy resistance exercise. J Am Coll Nutr. 2016;35 (2):100–107. doi: 10.1080/07315724.2015.1081572
75. Domínguez R, Cuenca E, Maté-Muñoz J, et al. Effects of beetroot juice supplementation on cardiorespiratory endurance in athletes. A Syst Rev Nut. 2017;9(1):43. doi: 10.3390/nu9010043