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Original Research

Consuming Beetroot Juice Improves Slalom Performance and Reduces Muscle Soreness in Alpine Skiers under Hypoxic Conditions

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ABSTRACT

Background: Beetroot juice (BRJ) supplementation has been shown to increase sports performance under hypoxic conditions and to improve athletes' recovery.

Objectives: In the present study, we aimed to investigate the effect of acute BRJ supplementation on slalom (SL) run performance and muscle soreness (MS) in Alpine skiers at moderate to high altitudes.

Methods: Ten male Alpine skiers received 220 mL of BRJ (8.9 mmol/L nitrate) or placebo (PLA) in 2 sessions with a 7-d wash out interval in a randomized, crossover, PLA-controlled, double-blind study. The 90-s box jump (BJ90), agility hexagonal obstacle jump (Hex Jump), and wall-sit tests were measured before on-hill SL runs in both sessions. After the functional tests, SL run performance was measured by time to complete 2 runs on the SL course; immediately after each SL run, the rating of perceived exertion (RPE) was recorded. In addition, perceived MS was recorded using the visual analog scale at 12, 24, and 48 h after the SL runs.

Results: The data were meticulously analyzed using 2-way repeated measures analysis of variance and paired *t* tests with significance set at $P < 0.05$. The findings were significant, indicating that compared with PLA, BRJ notably improved wall-sit and BJ90 performances ($P < 0.05$), while a substantial reduction was observed in RPE, Hex Jump, and MS ($P < 0.05$). A 1.74% shorter time to complete SL runs was observed in the BRJ group compared with the PLA group; however, there were no significant differences between the PLA and BRJ groups ($P > 0.05$).

Conclusions: These results underscore the potential of BRJ supplementation to enhance sports performance and reduce MS in Alpine skiers under hypoxic conditions.

Keywords: beetroot juice, muscle soreness, Alpine ski racing, hypoxic condition, slalom run performance

Introduction

The winter sport of Alpine skiing is a high-intensity intermittent sport that mainly includes technical and speed events [1]. Technical events, such as the slalom (SL) and giant SL (GS), require shorter turns and have higher metabolic costs. On the other hand, the super GS and downhill require quicker turns with a longer radius [1–3]. In the technical disciplines, Alpine ski racers must contend with high total ground-reaction forces repeated every 0.90 ± 0.04 and 1.45 ± 0.11 s [4]. In addition, muscle contraction activity must be sustained between ∼43 and 82 s, depending on the race duration, discipline, slope, and gate setting [1]. Bottollier et al. [1] showed that total, aerobic, and glycolytic energy outputs were not significantly different between SL events with different durations. However, the glycolytic energy output of the SL was higher than that of the GS. Alpine ski training and racing often occur in extreme environments such as cold temperatures, high altitudes (2000–5000 m above sea level), and acute hypoxia, which may result in higher lactate production for a given submaximal workload [5]. At high

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Abbreviations: BJ90, 90-s box jump; BRJ, beetroot juice; DOMS, delayed-onset muscle soreness; EIMD, exercise-induced muscle damage; FIS, International Ski and Snowboard Federation; GS, giant slalom; Hex Jump, hexagonal obstacle jump; LIST, Loughborough Intermittent Walking Test; MD, mean difference; MS, muscle soreness; NO, nitric oxide; NO_2^-, nitrite; NO_3^-, nitrate; PCr, phosphocreatine; PLA, placebo; ROS, reactive oxygen species; RPE, rating of perceived exertion; SL, slalom; VAS, visual analog scale.

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altitudes, oxygen transfer to active muscles is reduced, resulting in fatigue at lower work rates and peak oxygen consumption. During physical activity, muscles and organs compete for oxygen, which can cause premature fatigue if the brain or the respiratory muscles do not receive a sufficient oxygen supply [6,7].

During intense skiing, the lower limb muscles (especially the quadriceps femoris) experience eccentric work during each turn, particularly toward the end of the steering phase. This can result in damage to muscle cells, which can cause symptoms of delayed-onset muscle soreness (DOMS) that may appear a few or even ≤10 h after the physical exertion [8]. During exercise, eccentric contractions can cause microdamage to the muscles and muscle soreness (MS) [9]. This is especially true in skiing, where tense myocytes are subjected to stretching forces at higher speeds and smaller turns, such as in SL runs, resulting in microdamage within myocytes [8,10]. When extreme eccentric or repetitive unaccustomed contractions occur, particularly at the start of the ski season, it can cause discomfort in skeletal muscle [8–10]. According to the cognitive demand-induced acute axonopathy theory, DOMS is caused by acute compression axonopathy, which occurs when repetitive lengthening contractions damage nerve endings in the muscle spindle [11]. Pain intensity usually increases 24 h after the exercise, peaks between 24 and 72 h, and eventually disappears within 5 to 7 d post-exercise [10]. Therefore, it leads to skeletal muscle fatigue through both central and peripheral mechanisms in Alpine skiers and reduces performance [12]. To address these concerns, various interventions can help improve performance.

Short- and long-term dietary supplements are a significant option for elite and recreational athletes to enhance their performance [13]. As an intervention, beetroot juice (BRJ) is a dietary supplement containing high nitrate (NO_3^-) concentrations that may improve physical performance by increasing nitric oxide (NO) [14]. In addition, BRJ is a nutritious drink that contains NO_3^-, carbohydrates, fiber, protein, vitamins, minerals (sodium, potassium, calcium, and iron), and other beneficial compounds such as betalain and flavonoids [14–16]. NO is also produced by the endothelial enzyme NO synthase and causes vasodilatation and increased blood flow [17]. It has been reported that BRJ can enhance athletic performance by increasing oxygen levels, glucose, and various nutrients such as potassium, betaine, sodium, magnesium, and vitamin C [18]. Scientific research provides compelling evidence that the consumption of BRJ can enhance blood flow [19] and muscle contraction in type II muscle fibers by stimulating NO production [20]. This, in turn, can effectively mitigate phosphocreatine (PCr) degradation and minimize ATP consumption during physical activity [21], thereby improving muscle performance. The acceleration of nitrite (NO_2^-) to NO conversion in both hypoxic and acidic environments [22], coupled with the expedited transformation of NO_2^- to NO in the scarcity of oxygen in type II muscle fibers [21], further solidifies the scientific basis for the benefits of BRJ. These findings suggest that BRJ could be a valuable tool during high-intensity exercise under hypoxic circumstances [21,23,24], mainly due to the significant recruitment of type II muscle during high-intensity intermittent and all-out sprint exercises [25]. It seems likely that NO_3^- supplementation could enhance short-duration high-intensity exercise performance at altitudes [23]. Indeed, Jodra et al. [26] found that acute BRJ supplementation was accompanied by a lower rate of perceived exertion (RPE) of the leg muscles immediately following the Wingate test [26]. Consistent with these observations, Forbes et al. [27] reported a significant reduction in RPE during cycling at power outputs 50% and 70% of the maximum rate of oxygen uptake. The possible mechanism that could explain the effects of BRJ on RPE is an enhancement in blood flow to the frontal lobe of the brain [28]. Therefore, enhanced brain blood flow could have contributed to the lower RPE and improved performance after BRJ supplementation [26].

Several physical therapy strategies have been investigated to optimize the recovery of body systems and treat symptoms of DOMS [29]. Research has conclusively shown that short-term nutritional supplements can be an effective strategy for athlete recovery [30]. Specifically, BRJ effectively reduces muscle pain and enhances performance recovery [14]. In this regard, Hematinafar et al. [31] showed significantly decreased MS in female volleyball players due to BRJ supplementation (~4.1 mmol NO_3^-) after an exercise-induced muscle damage (EIMD) protocol. In contrast, another study found no effect of BRJ (~210 mg NO_3^-) on reducing inflammation or muscle damage after a marathon [32]. BRJ is rich in NO_3^-, which, via its reduction to NO, might have indirect antioxidant effects by suppressing the accumulation of leukocytes [33], which are thought to be the primary producers of reactive oxygen species (ROS) after muscle-damaging exercise [34]. Moreover, the high antioxidant capacity of BRJ is due to various compounds such as phenolic acids, flavonoids, carotenoids, and betalains, all of which have antioxidant effects [35]. Betalain pigments in BRJ are undoubtedly the most potent antioxidant molecules [36] that efficiently reduce ROS damage, enhance the production of natural antioxidant enzymes, and strengthen the body's defense mechanism [37–40]. Therefore, BRJ supplementation has been suggested to reduce post-exercise perceived MS and enhance recovery from DOMS [14,41]. To date, studies have produced mixed findings. Clifford et al. [42,43] reported that NO_3^--rich BRJ (≥143 mg NO_3^-) attenuated muscle pain and expedited the recovery of countermovement jump performance in the 72 h following exercise, but others found no such effects (210 mg, 12.9 mmol of NO_3^-) [32,44] or only benefits on specific symptoms such as MS [45].

Previous studies have demonstrated the positive impact of BRJ supplementation on athletic performance under hypoxic conditions [23,46]. However, no study has been conducted to investigate its effects on the performance and MS of Alpine skiers. Therefore, this study aimed to examine the acute effect of BRJ supplementation on the performance of Alpine skiers during SL runs at moderate to high altitudes and to assess its impact on MS. These objectives are of utmost importance in advancing our understanding of the effects of BRJ supplementation in a specific athletic context.

Methods

Participants

Ten expert male Alpine skiers participated in this study. The demographic information of the participants is listed in Table 1. All participants had ≥5 y of experience participating in the International Ski and Snowboard Federation (FIS) and national races. They trained on-field ≥5 d/wk, and average FIS point profiles were 165.5 ± 38.1 in the SL. They reside in Sepidan City at an altitude of ~2000 m above sea level. All athletes

TABLE 1

Demographic information of the participants.

Variable	Mean ± SD
Age, y	22 ± 3.6
Height, cm	172.4 ± 5.6
Body mass, kg	68.1 ± 14.1
BMI, kg/m^2	22.78 ± 3.54
Training level, h/wk	18.9 ± 2.02

Abbreviations: BMI, body mass index; SD, standard deviation.

participated in this study with SL skis (length: 165 cm) and standard helmets according to FIS rules. Participants had no known diseases or medical issues and no history of allergy to beetroot; they did not smoke and were not consuming any alcohol or caffeinated beverages before and during data collection. In addition, participants were instructed to avoid strenuous exercise 48 h before and after the test. Before the tests, the study procedures were explained to the participants in a familiarization session, and informed written consent was obtained from them before the experimental session. This research was conducted in accordance with the Declaration of Helsinki and was approved by the research ethics committees of Shahid Beheshti University (Iran) with the ethics identifier IR.SBU.REC.1402.057. The current study recruited participants from 22 February to 10 March, 2023. Additionally, all participants were members of the same training camp, and their training regime was the same under the supervision of trainers.

Study design

This study had a randomized, double-blind, placebo (PLA)-controlled, and crossover design (as shown in Figure 1). Before the beginning of the study, the participants had a familiarization session to become acquainted with the testing protocols and procedures. The study was conducted over 2 d with a 7-d wash out interval at Pooladkaf Ski Resort in Ardekan Town, Fars province, Iran. During each test session, participants were randomly assigned to 1 of 2 conditions: BRJ ($n = 5$) or PLA ($n = 5$). Forty-five minutes after eating the same breakfast containing 250 kcal (45 g carbohydrates, 9 g protein, and 5 g fat) at 07:45, participants consumed BRJ or PLA [47]. Each day, 2.5 h after BRJ consumption at 2800 m altitude near the ski slope, the 90-s box jump (BJ90), agility hexagonal obstacle jump (Hex Jump), and wall-sit tests were recorded. Following this, athletes were on the ski slope from 11:00 to 11:30, where they inspected the SL course and did 3 free ski runs and 5 min of dynamic stretches to warm up before 2 SL performance runs. The time duration between each run on the SL course was 15 min. The SL performance run start line was 3060 m above sea level, and the finish line was 2860 m, with a 200 m vertical drop. Therefore, SL run performance was measured by the time it took to complete 2 runs of the SL course. Immediately after each SL run, the RPE was recorded. Moreover, the perceived MS was recorded using the visual analog scale (VAS) at baseline and 12, 24, and 48 h after the SL runs.

Supplementation procedures

Participants were supplemented with BRJ (prepared from red beetroot in Zarghan, Lepoi Fars, Shiraz, Iran) or PLA (Geernosense, Shiraz, Iran) 2.5 h before functional tests. The timing of BRJ ingestion based on the recommendations was 2.5 to 3 h before starting the functional test effort to coincide with peak plasma NO_2^- [48]. Participants were given either 220 mL of BRJ or PLA in the study. The NO_3^- concentration in 220 mL of BRJ was ~8.9 mmol (250 mg/dL) and <0.5 mmol in PLA. Table 2 in the report from the Parhamgostar laboratory (located in Shiraz, Iran) provides more detailed information about the composition of the BRJ and PLA drinks. The study objectives were hidden from the participants, who were unaware of the investigation of BRJ or PLA. In each test session, the participants were provided 1 sealed bottle containing 220 mL of BRJ or PLA. Additionally, the participants tested their sensitivity to BRJ by drinking ~50 mL of BRJ. To ensure that the PLA's color and taste matched that of the BRJ, cherry food coloring (Abyaz Chimie Company) was added as well as sugar as the source of carbohydrates. In addition, black bottles were used to prevent participants from detecting any potential color difference between the BRJ and PLA. To minimize possible adverse effects, participants refrained from using

TABLE 2

Nutritional details of BRJ and PLA (estimated) drinks.

	BRJ	PLA
Volume, mL	220	220
Energy, cal	70	68
Carbohydrates (sugar), g	14.2	14.3
Fats, g	0	0
Protein, g	2.9	0.5
Nitrates, mmol/L	8.9	<0.5

Abbreviations: BRJ, beetroot juice; PLA, placebo.

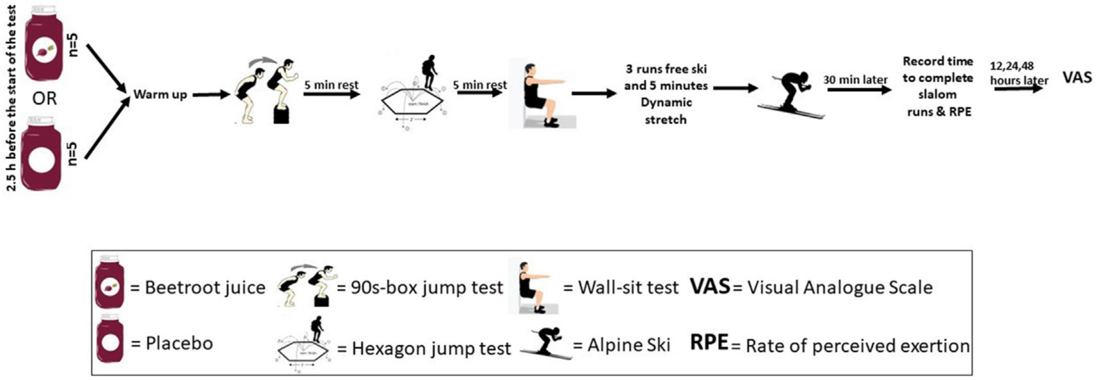

FIGURE 1. Supplementation and testing protocol.

mouthwash during the study period [49]. Finally, the food reminder and prohibited foods questionnaires were delivered to them. Before each intervention session, a 48-h nutritional control was carried out to avoid the consumption of dietary sources rich in NO_3^- such as beetroot, celery, arugula, lettuce, spinach, turnip, endives, leek, parsley, cabbage, etc. The participant's habitual diets were monitored via a food diary template to avoid consuming prohibited foods.

Functional tests

After 2.5 h of BRJ consumption and 10 min of warming up (static and dynamic stretches), functional tests were performed in the following order: anaerobic BJ90, agility Hex Jump, and wall-sit.

The BJ90 was used to evaluate anaerobic capacity. We set this functional test based on the Norwegian Ironman Test batteries [50] and Swiss-Ski Power Test [51]. During the BJ90, participants stood on a box 40 cm high and 51 cm wide. Upon the start command, the participants jumped down laterally to one side and back up, then jumped down laterally to the other side and back up. The total number of correctly performed jumps during 90 s was recorded [50].

The Hex Jump was used to assess the agility of the skiers [50, 52]. Participants started the test with both feet together inside the hexagonal obstacle. This test consists of 6 hurdles measured in 20, 25, 32, and 35 cm [50]. At the start command, the subjects jumped laterally across the starting 20-cm hurdle and back. Participants turned and jumped over the next hurdle over and back for 2 complete revolutions. The test consisted of a minimum of 2 and a maximum of 3 attempts in clockwise and counterclockwise directions. Athletes would then get a 2- to 3-min break between each trial and do 2 to 3 trials in each direction (with a minimum of 2 clockwise and 2 counterclockwise). Athletes performed all the clockwise attempts first and then the counterclockwise ones [50]. Time was measured with a stopwatch. The best times in each order were summed up, and the sum was recorded as the final score.

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°, 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 maintain the correct position throughout the test while receiving no verbal encouragement [53].

SL run performance

In addition to administering a functional test for skiers, we recorded the total time it took to complete 2 runs of the SL course. This was done to evaluate SL run performance using standard methods of course setting, as described in previous studies [1,3]. To record the times accurately, we utilized a professional electronic TAG HEUER FIS timing system (Chronoprinter 540, Docking HL-540-BATT). The skiers' SL run time began when they skied through the start wand at the top of the course and ended when they crossed the infrared beam 10 m vertically from the last gate. If skiers did not finish their runs, they were given another opportunity until they completed 2 runs correctly. The number of gates relative to the vertical drop adhered to FIS rules. Before each testing session, coaches used measuring tape to meticulously prepare the course with 42 singles, 5 hairpins (double), and 1 banana gate on a groomed slope. The length between gates was 11 m for singles, 6 m for hairpins (double), and 16 m for banana gates [1]. Each gate was labeled with a specific number in each lane to ensure a consistent course setting. Finally, we recorded the sum of the 2 correct run times resulting from the SL run performance. After each SL run, participants rated their perceived exertion using the 1-10 RPE Borg scale [54]. All tests were conducted under similar environmental conditions, with sunny weather and no clouds each day an air temperature between -2 and $+4$°C, snow temperature of -1 ± 0°C, and wind speeds between 5 and 10 km/h.

MS monitoring

The VAS was used to measure lower limb MS. Participants were presented a piece of paper with a horizontal 10-cm line. The line was labeled "No pain" on one end and "Maximum pain" on the other. Participants indicated their discomfort level by marking the line [55]. Participants marked an "×" on a line to indicate their perception of MS intensity before and after consuming BRJ or PLA at baseline and 12, 24, and 48 h after the SL runs. Moreover, VAS measurements were made between 12 and 48 h after drinking BRJ at 1800 meters above sea level.

Data analysis

Statistical tests were performed using SPSS (version 25, IBM SPSS Inc.). All data were initially tested for normal distribution using Shapiro–Wilk tests. For perceived MS data [34], 2-way analysis of variance with repeated measures [Condition (BRJ or PLA) × time (baseline, 12 h, 24 h, and 48 h post-SL runs)] was used. When appropriate, post hoc comparisons were made with the Bonferroni test. Paired *t* tests were used for other data. Statistical significance was set at $P < 0.05$.

Results

According to the paired *t* test, there was a significant increase in leg muscle endurance in BRJ compared to PLA after the wall-sit test ($P < 0.05$) (Figure 2 and Table 3). Furthermore, after the BJ90, there was a significant increase in the number of jumps in BRJ compared to PLA ($P < 0.05$) (Figure 2 and Table 3). Additionally, the time taken to change directions in the Hex Jump and the RPE were significantly lower in BRJ than in PLA ($P < 0.05$) (as shown in Figure 2 and Table 3). Although there was no significant difference between PLA and BRJ in terms of time to complete SL runs ($P > 0.05$), a shorter total time was observed in the BRJ condition compared to PLA (Figure 2 and Table 3).

The results of a 2-way repeated measure analysis of variance revealed a significant main effect of interaction (condition × time) ($F = 26.814$; $P < 0.001$) for perceived MS. No significant differences were found in the baseline MS (MS-baseline) between conditions (mean difference [MD] $= 0.4$; $P = 0.223$). However, significant increases in MS were observed between MS-baseline and MS-12 after functional tests and SL runs in both BRJ (MD $= 32.5$; $P = 0.001$) and PLA ($P = 0.001$; MD $= 46.3$). The post hoc test revealed that MS-24 was significantly decreased compared to MS-12 after BRJ ($P = 0.001$) and PLA ($P = 0.017$). After PLA, there was a significant increase between

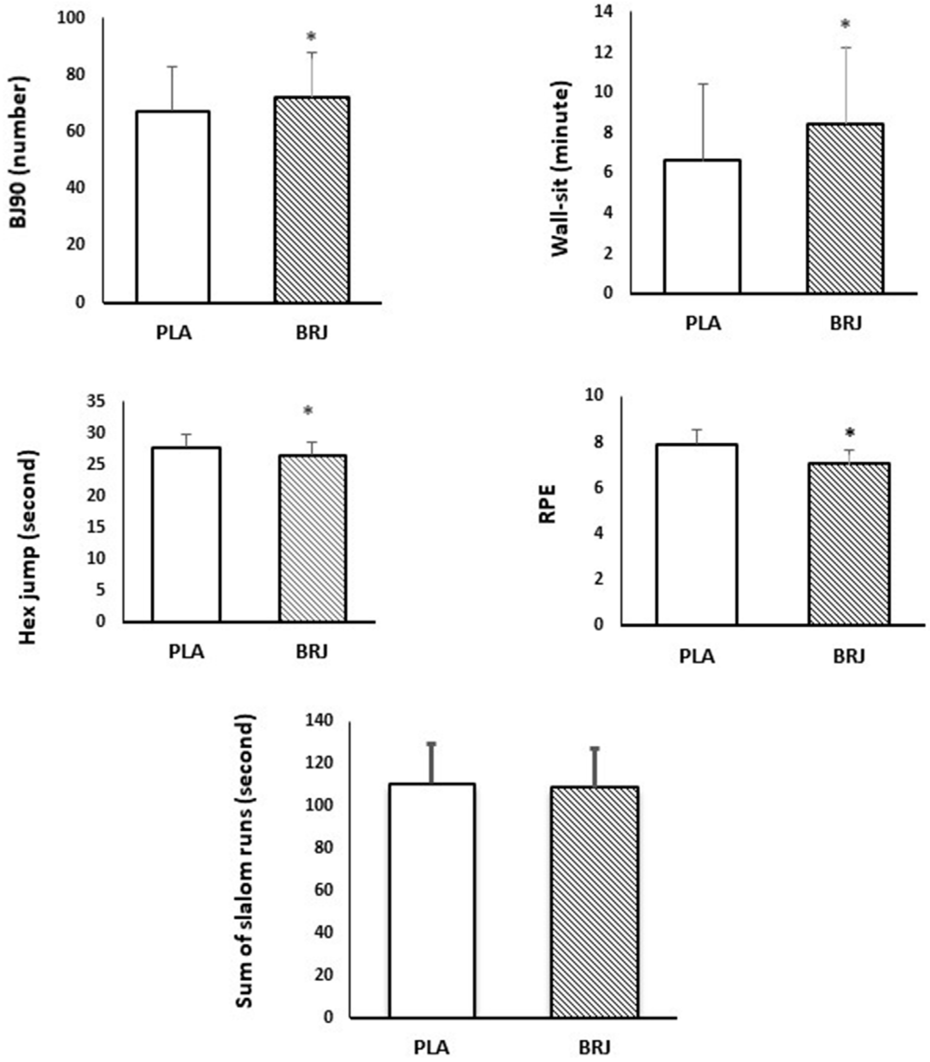

FIGURE 2. Changes in results of functional tests, rating of perceived exertion (RPE), and slalom performance after placebo (PLA) or beetroot juice (BRJ) consumption. Shown are the results of 90-s Box Jump (BJ90), hexagonal obstacle jump (Hex Jump), wall-sit, RPE [42], and change in time to complete 2 correct slalom runs with either BRJ or PLA. *significant difference in the BRJ compared with the PLA condition ($P < 0.05$).

TABLE 3
Comparison of functional tests, slalom performance, RPE, and muscle soreness variables in BRJ and PLA conditions.

Variable	PLA	BRJ	RC%	MD	*P*	95% CI
	Mean ± SD	Mean ± SD				
BJ90, number	67.30 ± 15.90	72.40 ± 15.91	7.57%	−5.10	0.005	1.98–8.21
Hex Jump, s	27.82 ± 1.98	26.48 ± 2.11	−4.81%	1.34	0.001	−1.95 to–0.72
Wall-sit, min	6.63 ± 3.79	8.48 ± 5.40	27.9%	−1.84	0.049	0.007–3.67
Slalom performance, s	110.65 ± 18.36	108.72 ± 18.06	−1.74%	1.93	0.061	−0.107 to 3.96
RPE	7.92 ± 0.60	7.06 ± 0.38	−10.80%	0.86	0.002	0.42–1.30
MS-baseline, mm	16.10 ± 2.96	15.70 ± 2.31	−2.48%	0.40	0.223	−0.291 to 1.09
MS-12h, mm	62.40 ± 5.31	48.20 ± 5.49	−22.75%	14.20	0.000	12.21–16.18
MS-24h, mm	58.50 ± 4.45	40.70 ±1.05	−30.42%	17.80	0.000	1.42–14.58
MS-48h, mm	67.30 ± 4.78	41.9 ± 0.99	−37.74%	25.40	0.000	1.53–21.92

Abbreviations: BJ90, 90-s box jump; BRJ, beetroot juice; CI, confidence interval; Hex Jump, hexagonal obstacle jump; MD, mean difference; MS, muscle soreness; PLA, placebo; RC, relative change [(BRJ−PLA)/PLA]; RPE, rating of perceived exertion; SD, standard deviation.

MS-12 and MS-48 (MD = 4.9; $P = 0.001$), while after BRJ, it was significantly lower (MD = 6.3; $P = 0.004$). Additionally, MS-48 showed a significant increase compared to MS-24 after PLA (MD = 8.8; $P = 0.001$) and BRJ (MD = 1.2; $P = 0.001$). Furthermore, a comparison of MS between PLA and BRJ showed that MS-12 (MD = 14.2; $P = 0.001$), MS-24 (MD = 17.8; $P = 0.001$), and MS-48 (MD = 25.4; $P = 0.001$) decreased significantly after BRJ compared to PLA (Figure 3 and Table 3).

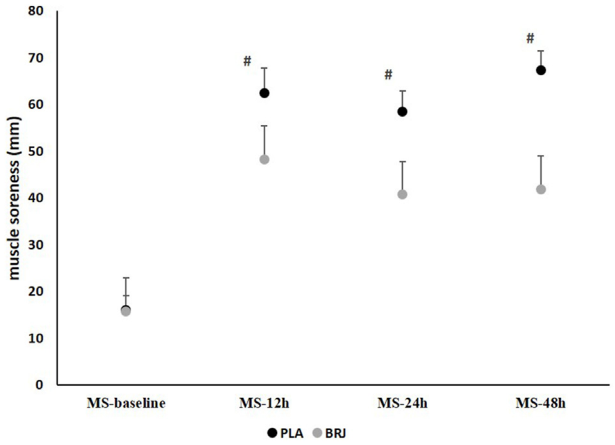

FIGURE 3. Changes in perceived muscle soreness using the VAS scale in PLA or BRJ. #: significant difference between PLA and BRJ ($P < 0.05$). BRJ, beetroot juice; MS, muscle soreness; PLA, placebo; VAS, visual analog scale.

Discussion

The current study aimed to determine the effect of acute BRJ consumption on the specific performance and delayed MS of Alpine skiers. The findings of our study indicated that acute BRJ supplementation not only enhanced anaerobic capacity (BJ90), isometric muscle endurance (wall-sit), and change of directions (Hex Jump) but also decreased the RPE after SL runs and MS 12, 24, and 48 h after SL runs. Despite these significant changes, there was no substantial reduction in time to complete SL runs after BRJ consumption. Because the differences between first and second place in highly competitive Alpine ski racing are often measured by a mere fraction of a second [56], small reduction changes in time to finish runs can lead to improvement in performance.

Supplementation with BRJ can enhance isometric endurance performance in Alpine skiers, as evidenced by an increase in the duration of the wall-sit test at altitude. Like wall-sit, Alpine skiers mostly get into isometric contractions during each turn. Accordingly, BRJ consumption may improve skiing performance. Other studies have shown different effects of BRJ supplementation on muscle endurance. Consistent with the results of this study, Ranchal-Sanchez et al. [57] reported that acute supplementation of BRJ positively affected muscle endurance during resistance training. In addition, Hemmatinafar et al. [31] showed improvement in wall-sit performance after EIMD protocol in female volleyball players. Also, other studies have shown the positive effect of BRJ consumption on muscle endurance [58,59]. In contrast with our findings, Jonvik et al. [60] found that 6 d of BRJ supplementation did not significantly enhance muscle strength or endurance performance in recreationally active men compared to PLA. However, the disparity in the findings can be explained by differences in the type of sports test, measurement tools, participant characteristics, environmental conditions, and the dose of NO_3^- used in the studies.

Theoretically, BRJ supplementation can improve the performance of high-intensity exercise modalities relying on type II muscle fibers, especially under hypoxic conditions [21,23,24]. Also, BRJ supplementation increases blood flow [19], vascular conductance [61], and intracellular calcium handling [20], decreases the rate of PCr degradation, and reduces the amount of ATP required during exercise [21]. To determine the effect of dietary NO_3^- on the anaerobic performance of Alpine skiers, we analyzed the number of jumps during the BJ90 after the BRJ and PLA conditions. We observed that BRJ consumption increased the total number of jumps in the BJ90 test compared with PLA. Consistent with our research, Miraftabi et al. [62] reported a positive effect of NO_3^- supplementation on the anaerobic performance of taekwondo athletes during the kick test. However, Conger et al. [63] found no improvement in short-duration, maximal-intensity exercise performance during a 30-s or 60-s Wingate test in hockey players. Furthermore, Tatlici et al. [64] showed that dietary NO_3^- supplementation did not positively affect boxers in the 30-s anaerobic Wingate test. Similar to our study, Conger et al. [63] supplemented BRJ containing 496 mg (~8 mmol) NO_3^-, while it was 400 and 800 mg NO_3^- in Miraftabi et al. [62] study. Unlike previous studies, our tests were performed under hypoxic conditions. Currently, the most conceivable explanation for this effect includes a reduction in the oxygen cost of fixed work-rate submaximal exercise in hypoxia [65], a decrease in the ATP cost of muscle force production [66], and the NO-mediated modulation of vasodilation [67], which may improve oxygen delivery to hypoxic muscle tissue. Various dosages and intake durations, test protocols, and environmental conditions have been implemented, making a direct comparison to the current study difficult. Thus, more investigation is needed to determine the possible impact of acute BRJ supplementation on anaerobic long-duration performance (60–90 s), especially under extreme environments.

During Alpine skiing, specifically in SL turns, the ability to change directions plays a vital role in performance [53]. Our study observed a significant difference in direction change (−4.81% relative change) after BRJ ingestion compared with PLA. Previous studies have reported controversial findings regarding the ergogenic effect of BRJ on agility and sprint performance. Although Rogers et al. [68] suggested improvement in agility performance after acute BRJ supplementation, and Thompson et al. [69] found benefits from BRJ ingestion on sprint performance and reaction time, other investigations did not report significant effects of BRJ ingestion on agility performance [70,71]. To our knowledge, this is the first study to analyze the impact of BRJ on the agility performance of Alpine skiers under hypoxic conditions. Although there is no apparent physiological underpinning for agility performance due to BRJ ingestion [68], our findings, in agreement with those of Rogers et al. [68], support the acute effect of BRJ supplementation on agility performance. Previous studies have demonstrated that NO_3^- supplementation enhances intracellular Ca^{2+} handling, increasing muscle force output, particularly in fast-twitch muscle fibers [20]. Because more fast-twitch fibers are recruited during explosive ability, increased calcium release and fast-twitch fiber recruitment from BRJ may improve agility performance. However, these mechanisms remain largely speculative until further research is performed [68]. Thus, more studies are needed to fully understand the underlying mechanisms resulting from the effect of BRJ consumption on skiers' agility performance.

Muscle contractions must be sustained for ~43 and 82 s during Alpine skiing, particularly under hypoxic conditions [4].

Thus, muscle contractile properties during ski courses play a crucial role. Vanhatalo et al. [72] reported a positive effect of NO_3^- supplementation on high-intensity exercise tolerance at moderate to high altitudes and in conditions where oxygen delivery to muscle is reduced; this effect was accompanied by a reduction in the rate of muscle metabolic perturbation (as indicated by PCr degradation and inorganic phosphate accumulation) during hypoxic exercise. Masschelein et al. [73] also showed partial restoration of oxygen delivery and utilization at a simulated 5000-m altitude, reporting increased arterial and muscle oxygenation during exercise after NO_3^- ingestion compared with PLA. In addition to all these effects of BRJ, Coggan et al. [74] reported enhancement of skeletal muscle contractile properties via changes in Ca^{2+} signaling due to increased NO bioavailability. This study did not find significant differences in time to complete high-intensity SL runs between BRJ and PLA conditions. However, the time to complete SL runs decreased by 1.74% after BRJ ingestion. The previous results regarding the effect of BRJ supplementation on high-intensity intermittent exercise have been equivocal. Also, in their review study, Domínguez et al. [75] showed that BRJ given as a single dose or over a few days may improve performance at intermittent, high-intensity efforts with short rest periods that involve the predominance of glycolytic metabolism. This effect was attributed to faster PCr resynthesis, which could delay its depletion during repetitive exercise efforts. On the other hand, in a review article, Alsharif et al. [76] suggested that more likely improvement of performance during single and repeated bouts of high-intensity exercise due to multiple-day supplementation with a daily NO_3^- dose $\geq$8 mmol compared to acute ingestion of $<$8 mmol. Therefore, based on previous findings [75,76], athletes competing in sports requiring single bouts of high-intensity exercise may benefit from acute and chronic supplementation of BRJ. Robinson et al. [77] showed that short-term (7 d) BRJ supplementation (12.4 mmol) did not improve high-intensity intermittent running performance in endurance-trained males at doses of normobaric hypoxia. In this regard, a study by Kent et al. [65] found that acute ingestion of NO_3^- may not enhance repeat-sprint performance in hypoxic conditions simulated at an altitude of 3000 m. Finally, according to the current study, the time to complete SL runs did not significantly change in BRJ compared with PLA. However, as discussed in the study by Hébert-Losier et al. [56], a slight reduction in time to finish runs can enhance performance during Alpine skiing. To our knowledge, this is the first study that examines the effect of BRJ consumption on the SL run performance of Alpine skiers at an altitude of 3000 m. Thus, further research is needed to clarify possible mechanisms by which BRJ may improve performance during high-intensity intermittent exercise.

Several studies have assessed the effect of BRJ supplementation on RPE. Consistent with our findings, previous studies reported significant RPE reduction after acute BRJ ingestion [26,27,78]. Jodra et al. [26] and Casado et al. [78] reported performance improvements concurrent with a drop in RPE; however, Forbes et al. [27] observed lower RPE without any significant impact on exercise economy in well-trained female Ringette athletes after acute BRJ consumption. A possible mechanism that could explain the lowering RPE after BRJ ingestion is an increase in brain perfusion [28] or a lower muscle metabolic perturbation [66], which would subsequently reduce type III/IV muscle afferent feedback to the central nervous system and the potential for significant fatigue development [79]. Therefore, enhanced brain blood flow may have contributed to the lower RPE and improved performance after BRJ supplementation in the current study.

In a 2021 narrative review [16], the anti-inflammatory and antioxidant features of BRJ were attributed to different sources of chemical compounds, including ascorbic acid, carotenoids, phenolic acid, flavonoids, and betalains (a group of bioactive pigments). In a meta-analysis by Jones et al. [35], the beneficial effects of BRJ supplementation on reducing the perception of MS (especially at 48 and 72 h) after various exercises was shown. Daab et al. [41] showed that after consuming BRJ, semi-professional male soccer players experienced lower MS immediately and 24 h after the Loughborough Intermittent Walking Test (LIST) compared to a PLA. In agreement with our findings, Hemmatinafar et al. [31] reported that BRJ supplementation after EIMD significantly decreased MS in female volleyball players. Unlike the present study, no significant differences between PLA and BRJ were observed for MS in soccer players 48 and 72 h after simulated match play [41]. However, in the Daab et al. [41] study, BRJ ingestion occurred for 7 d (3 d pre-exercise, on the day of the trial, and 3 d post-exercise, 150 mL twice per day), and in the Hemmatinafar et al. [31] study, participants were supplemented 48 h after EIMD, while in the present study, the supplement was consumed 2.5 h before functional tests and SL run performance. Also, Daab et al. [41] appraised MS after the LIST protocol [31,41]; however, in the present study, we evaluated MS after a functional test and repeated eccentric contractions during the SL runs. Other studies have produced different findings; a survey of trained runners showed that BRJ supplementation within 2 d after a marathon had no significant effect on the perception of MS (48 h after exercise) [44]. Similarly, Larsen et al. [32] found no significant impact of BRJ supplementation on MS (using a Likert scale) following outdoor exercise in recreationally active men and women. Also, according to Clifford et al. [45], BRJ increased the pressure-pain threshold of active men 72 h after EIMD (100 drop jumps) in comparison to PLA. It seems that factors such as the sex of the participants [31,41,45], type of physical activity, training volume (100 compared with 200 jumps) [41], and environmental conditions could potentially explain the discrepancy between the results of this study and previous studies.

It is essential to acknowledge the limitations of our investigation. First, we could not measure the changes in plasma levels of NO_3^- and biomarkers related to muscle damage after consuming BRJ due to financial constraints. Moreover, as our participants were male Alpine skiers, we must exercise caution when generalizing our findings to other athletes under similar environmental conditions. Additionally, it is worth noting that the sample size in this research could have been more extensive due to the number of available Alpine skiers in the same training camp and fitness situations. Therefore, future studies should consider the limitations of this study to expand on our findings.

Overall, the present study's findings showed that acute consumption of BRJ improves static muscular endurance, anaerobic capacity, agility, and SL performance in male Alpine skiers. Also, BRJ ingestion was associated with reduced MS and RPE under hypoxic conditions. These findings suggest that BRJ could be beneficial for male Alpine skiers, particularly during altitude training camps and the competition season, to enhance performance and expedite recovery from MS. However, more studies are required to determine the optimal timing and dosage of BRJ compounds for Alpine skiers, thereby expanding our understanding of its effects on muscle performance and recovery.

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Author contributions

The authors' responsibilities were as follows – AA, MF, MH: designed the study; AA, MF: were involved in data collection; AA, MH, MF: responsible for data entry, statistical analysis, and writing the manuscript; MF, MH, AA: primary responsibility for the final content; all authors: contributed to the interpretation of the findings; and all authors: read and approved the final manuscript.

Conflict of interest

The authors report no conflicts of interest.

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Data availability

Data described in the manuscript, code book, and analytic code will be available upon reasonable request.

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