

Effects of Blood Flow Restriction Training on Blood Perfusion and Work Ability of Muscles in Elite Para-alpine Skiers

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ABSTRACT

GENG, Y., L. ZHANG, and X. WU. Effects of Blood Flow Restriction Training on Blood Perfusion and Work Ability of Muscles in Elite Para-alpine Skiers. *Med. Sci. Sports Exerc.*, Vol. 54, No. 3, pp. 489–496, 2022. **Purpose:** The effects of short-term blood flow restriction (BFR) exercise on muscle blood flow perfusion and performance during high-intensity exercise were determined in elite para-alpine standing skiers to assess whether this would be an effective training regimen for elite athletes with disabilities. **Methods:** Nine national-level para-alpine standing skiers (mean age, 20.67 ± 1.34 yr; four women) were recruited. Nondominant lower limbs were trained with BFR (eight in final analyses), and dominant lower limbs were trained without BFR (seven in final analyses). The 2-wk protocol included high-load resistance, local muscle endurance (circuit resistance training), and aerobic endurance (stationary cycling) training performed 4 times a week, with BFR during local muscle endurance and aerobic endurance sessions. Muscle strength was measured by maximal voluntary isometric contraction (MVIC) in the knee extensors; microcirculatory blood perfusion (MBP), by laser Doppler blood flow; and muscle strength and endurance, by the total amount of work (TW) performed during high-intensity centrifugal and concentric contractions. **Results:** BFR significantly increased absolute and relative MVIC ($P < 0.001$, $P = 0.001$), MBP ($P = 0.011$, $P = 0.008$), and TW ($P = 0.006$, $P = 0.007$) from pretraining values, whereas only absolute MVIC increased without BFR ($P = 0.047$). However, the MVIC increase with BFR exercise (35.88 ± 14.83 N·m) was significantly greater ($P = 0.040$) than without BFR exercise (16.71 ± 17.79 N·m). **Conclusions:** Short-term BFR exercise significantly increased strength endurance, muscle strength, and MBP in national-level para-alpine standing skiers. Our study provides new evidence that BFR exercise can improve local muscle blood perfusion during high-intensity exercise and informs BFR exercise strategies for athletes with disabilities. **Key Words:** VASCULAR OCCLUSION TRAINING, LASER DOPPLER, EXERCISE BLOOD PERFUSION, STRENGTH ENDURANCE, RESIST FATIGUE, ATHLETES WITH DISABILITIES

Elite alpine ski racing is a physically demanding sport involving high speeds and large external loads imposed on lower limbs (1–6). Athletes who compete in the standing category of paralympic alpine skiing have the same physical requirements as athletes who are not living with a disability (7). Alpine skiers perform repeated bidirectional turns with forceful eccentric and concentric muscle contractions

(2,3), and the large external loads make lower limb muscle strength a key factor in sports performance (2,8,9).

Previous research has found that alpine skiing is dominated by high-force, slow-velocity eccentric contractions, followed by isometric and concentric contractions (2,6,10–14). The high-force eccentric and isometric contractions during skiing increase intramuscular pressure, which restricts blood flow to the working skeletal muscle (3,15–21) to reduce the delivery of oxygen, resulting in muscle fatigue and a consequent decline in performance (6).

The American College of Sports Medicine recommends that significant adaptation to resistance exercise requires at least 70% of a one-repetition maximum (1RM) to increase strength and muscle hypertrophy (22). However, mounting evidence indicates that the use of low-intensity resistance exercise (20%–40% 1RM) combined with blood flow restriction (BFR) results in strength and morphological responses comparable to those observed during high-intensity resistance exercise (23–26). In addition to observing increased muscle strength and hypertrophy, several studies have also demonstrated that adding BFR to low-intensity resistance or endurance exercise increases skeletal muscle expression of the messenger RNA related to angiogenesis

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as well as maximal oxygen uptake, aerobic capacity, and muscular endurance compared with training without BFR or before training (27–31).

However, to our knowledge, whether BFR exercise improves blood perfusion and performance during high-intensity exercise has not been explored, particularly in athletes. Although several studies have reported that BFR exercise affects vascular endothelial growth factor secretion and angiogenesis (26,31–33), direct evidence showing that BFR exercise improves blood perfusion during exercise is still lacking. Therefore, the goal of the present study was to compare the effects of 2 wk of physical training with or without BFR on muscular blood flow perfusion, torque, strength, and endurance in the knee extensors of elite standing alpine ski racers with disabilities. We hypothesized that compared with conventional training methods, training with BFR would more effectively increase torque, blood perfusion, and local muscular strength and endurance.

METHODS

Participants. Nine (five men and four women) athletes (mean \pm SD age, 20.67 \pm 1.34 yr) with disabilities who were in the standing category were recruited through the China National Paralympic alpine ski team. All participants were China's top para-alpine skiers and free from any cardiopulmonary or musculoskeletal disorder. One athlete was in sport class LW2 (athletes who have a significant impairment in one leg and use only one ski), and the other eight athletes were in sport classes LW5–8 (skiers with arm impairments). However, in the tests conducted after physical training, two participants completed the test for only one lower limb owing to personal reasons. Therefore, the BFR exercise group included eight samples, and the no-BFR exercise group included seven samples. The study was approved by the Shanghai University of Sport Ethics Committee (No. 102772020RT052). All participants provided written informed consent after the nature and goals of the study were thoroughly explained.

Study design. Because of the importance of bilateral lower limbs symmetry for competitive alpine ski racers with disabilities, with the consent of the head coach, using the grouping method of Evans et al. (34), we trained the nondominant lower limbs with BFR (BFR condition, $n = 8$) and the contralateral dominant lower limbs without BFR (no-BFR condition, $n = 7$). The skier in sport class LW2 (unilateral amputation above the knee joint) was randomly assigned to BFR condition because

for him, there is no lower limb asymmetry problem. During the 2-wk training, all the athletes, except the skier in sport class LW2, performed bilateral exercises. The only difference between the BFR and no-BFR legs was that the BFR legs were restricted with cuffs. A maximal voluntary isometric contraction (MVIC) test, muscle work ability test, and blood perfusion test were obtained 2 d before initiating the training period and then after the last strength training session. All tests were performed in the same order and by the same investigators at both time points.

BFR. To restrict blood flow to the thighs, narrow cuffs (5 cm wide; Kaatsu Master; Sato Sports Plaza, Tokyo, Japan) were wrapped around the most proximal portion of the thigh. The cuff pressure for the leg receiving BFR exercise was set to 80% of arterial occlusion, which was estimated from the thigh circumference. Thigh circumference was measured with a tape measure positioned at one-third of the distance between the most proximal portion of the thigh and the top of the patella (knee cap) (35). According to the athletes' thigh circumferences, the cuff pressure was set between 200 and 250 mm Hg (35).

Training protocol. The training protocol was designed by the coaches of the China National Paralympic alpine ski team and was planned as part of the para-alpine ski racers annual periodization. There were 12 sessions per week (from Monday to Saturday) and two sessions per day (morning and afternoon sessions). The training protocol included high-load (HL), local muscle endurance (LME), and aerobic endurance (AE) sessions (Table 1). All exercises were familiar to athletes and were used in daily training. The HL sessions included machine leg extension, hip adduction and abduction, leg curl and leg press (three sets, six repetitions, 85% of 1RM, four sessions/wk). Circuit resistance training was used for the LME sessions (3 sets, 20–25 repetitions, 40% of 1RM, 4 sessions per week). The exercises of circuit resistance training were the same as those of HL exercises. In the AE sessions, skiers performed two sets of cycling exercises for 30 min each set at 80%–85% of maximum heart rate (four sessions per week). The BFR and no-BFR legs performed the same training protocol; the only difference was that the BFR legs were restricted with cuffs during LME and AE sessions. All exercises were designed as bilateral exercises. Before exercise, pressure cuffs were wrapped around the most proximal portion of the thigh receiving BFR and inflated to the target pressure. The cuff pressure was sustained throughout the exercise but was released between sets.

TABLE 1. Training protocol of HL, LME, and AE exercises.

	Exercises	Intensity	Volume and Frequency	BFR Leg	No-BFR Leg
HL	Machine leg extension, hip adduction and abduction, leg curl and leg press	85% 1RM	3 sets 6 reps 4 sessions per week	Exercising without BFR	Exercising without BFR
LME	Circuit resistance training: machine leg extension, hip adduction and abduction, leg curl and leg press	40% 1RM	3 sets 20–25 reps 4 sessions per week	Exercising with BFR	Exercising without BFR
AE	Cycling	80%–85% HRmax	2 sets 30 min 4 sessions per week	Exercising with BFR	Exercising without BFR

HRmax, maximal heart rate.

MVIC test. Participants were given a 10-min warm-up on a cycle ergometer. After light dynamic stretching for the lower body muscles, participants were seated on a dynamometer (IsoMed 2000; D & R Ferstl GmbH, Hemau, Germany) and strapped to the dynamometer with belts. The knee joint angle was set at 70° of flexion (0° flexion was defined as full extension). The knee joint angular velocity was set at 0°·s⁻¹. While grasping the handle, participants performed three knee extension MVICs for both the BFR and no-BFR lower limbs in a random order. A 60-s rest interval separated each repetition. Participants were instructed to perform the contractions as forcefully as possible and maintain the contraction for 3 s. Visual feedback was provided using a computer monitor, along with verbal encouragement. The trial with the highest maximal torque was defined as the MVIC and was recorded for analysis (36).

Muscle work ability test. The muscle work ability test was performed using the same dynamometer as for the MVIC test. After a 10-min warm-up on a cycle ergometer and light dynamic stretching for the lower body muscles, participants were seated on the dynamometer and were strapped to it with belts. Participants performed 35 repetitions of maximal isokinetic quadriceps muscle eccentric and concentric contractions using the lower limb in a random order. The range of the knee joint was set from 30° to 90°. The angular velocity of eccentric contraction was set to 30°·s⁻¹, and the angular velocity of concentric contraction was set to 40°·s⁻¹ (2,14). Participants were instructed to perform the contractions as forcefully as possible. Participants were provided with real-time visual feedback allowing them to know the torque produced during each maximal contraction. Verbal encouragement was provided throughout. The total work (TW) completed during the test was recorded and used for analyzing muscle work ability.

Blood perfusion test. The blood perfusion test was performed before and after the 2 wk of exercise training. The blood perfusion test and quadriceps muscle work ability test were carried out at the same time. The local microcirculatory blood perfusion (MBP) of the muscle was measured by using a laser Doppler blood flow detector (PeriFlux 5000 system; Perimed, Jakobsberg, Sweden). The instrument emits a beam of laser light through a fiber-optic probe that is scattered by the tissue to be tested. Part of the laser beam is reflected by moving red blood cells. The degree of any wavelength change and frequency distribution of the reflection are related to the number and speed of red blood cells in motion. A change in MBP is related to a change in the concentration of moving blood cells and the average velocity of blood cells. The unit for MBP is PU, and 1 PU means 1 perfusion unit.

The test site was the middle of the thigh. Before the test, the test site was wiped with alcohol and shaved. After the alcohol had evaporated, the probe was fixed on the test site. The test site was a half of the distance between the most proximal portion of the thigh and the top of the patella (knee cap). While resting on the dynamometer for 5 min, the participant's MBP data were recorded as the baseline value. The participant's MBP data were also recorded during the test for analysis.

Statistical analysis. Data analyses were performed using SPSS software, version 22. The variables followed a normal (Gaussian) distribution. Independent-samples *t* tests were used to determine statistical differences between the BFR and no-BFR exercise groups. Statistical differences between preintervention and postintervention measurements were assessed by a paired-samples *t* test. Results are presented as means with 95% confidence intervals (95%CI). The statistical significance level was set at $P \leq 0.05$. Descriptive data are presented as the mean \pm SD.

RESULTS

All nine para-alpine skiers performed the same training protocol and completed 24 exercise sessions, which included 16 BFR exercise sessions. No significant differences between groups were observed for any measure at baseline (Table 2). All the athletes, except the skier in sport class LW2, performed bilateral exercises.

Maximal strength. After training, both the leg with BFR exercise and the leg without BFR exercise showed significantly increased MVIC from the baseline (with BFR, 35.88 [95%CI, 23.50–48.27] N·m, $P < 0.001$; without BFR, 16.71 [95%CI, 0.26–33.17] N·m; $P = 0.047$; Fig. 1A). The leg with BFR exercise also showed a significant increase in relative MVIC (0.55 [95%CI, 0.32–0.76] N·m·kg⁻¹, $P = 0.001$; Fig. 1B). No significant group differences were observed in the MVIC and relative MVIC (Table 3), but the change in MVIC was significantly greater in the BFR condition than in the no-BFR condition (BFR vs no-BFR, 35.88 16.71 N·m; 95%CI, 0.98–37.34 N·m; $P = 0.040$; Fig. 2).

Blood perfusion. There were no differences between groups in postintervention blood perfusion (BFR, 22.79 \pm 7.72 PU; no-BFR, 19.14 \pm 6.74 PU; $P > 0.05$) or in the change in MBP (BFR, 302.02% \pm 72.45%; no-BFR, 330.15% \pm 110.42%; $P > 0.05$) from rest to exercise. The muscles in the legs with BFR showed a significant increase in MBP (7.78 [95%CI, 2.41–13.14] PU; $P = 0.011$; Fig. 3A) and in the change in MBP from rest to exercise ($\Delta\%$, 82.32 [95%CI, 29.63–135.00]; $P = 0.008$; Fig. 3B), whereas no significant differences were observed for these measures before and after training in the no-BFR condition (Fig. 3).

TABLE 2. Baseline measurements in participants stratified by BFR condition.

Measure	BFR Condition (<i>n</i> = 8)	No-BFR Condition (<i>n</i> = 7)	Condition Differences at Baseline (<i>P</i>)
Muscle strength			
MVIC (N·m)	198.75 \pm 55.17	223.71 \pm 62.81	0.427
Relative MVIC (N·m·kg ⁻¹)	3.19 \pm 0.78	3.65 \pm 0.96	0.315
Muscle work ability			
TW (J)	5525 \pm 1194	5911 \pm 1703	0.616
Relative TW (J·kg ⁻¹)	89.86 \pm 21.98	95.73 \pm 21.66	0.612
Blood perfusion			
MBP (PU)	15.01 \pm 3.58	15.31 \pm 3.30	0.869
Change in MBP during exercise (%)	219.70 \pm 72.28	229.54 \pm 60.33	0.781

Values are presented as means \pm SD. No significant differences were observed between the two conditions at baseline (means \pm SD).

Change in MBP during exercise = (MBP during exercise/MBP during rest) \times 100; relative MVIC = MVIC/body weight; TW, TW derived from the muscle work ability test; relative TW = TW/body weight.

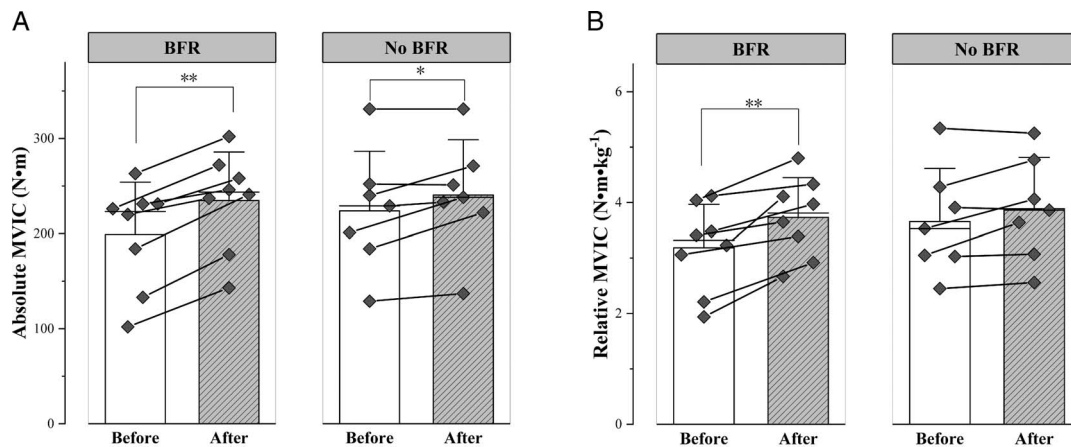


FIGURE 1—Maximal muscle strength before and after 2 wk of exercise training with or without BFR. Changes in absolute MVIC (A) and relative MVIC (B). Bars represent means; horizontal lines, medians; error bars, SD; and diamonds, individual data points. * $P < 0.05$ and ** $P < 0.01$ for the indicated comparisons.

Muscle work ability. After the 2-wk muscle endurance and AE training intervention, the muscles in the legs with BFR showed increased TW ($1269.88 [_{95\%CI}, 491.78\text{--}2047.97]$ J; $P = 0.006$; Fig. 4A) and relative TW ($19.22 [_{95\%CI}, 7.13\text{--}31.32]$ J·kg⁻¹; $P = 0.007$; Fig. 4B), whereas no significant differences were observed in the no-BFR condition (Fig. 4). Although after the intervention, the TW (6795 ± 1508 J) and the relative TW (109.08 ± 27.18 J·kg⁻¹) values for the muscles in the legs with BFR seemed modestly higher than those for the legs without BFR (TW, 6418 ± 1721 J; relative TW, 103.08 ± 24.57 J·kg⁻¹), these differences were not statistically significant ($P > 0.05$).

DISCUSSION

The present study investigated the effects of 2 wk of local muscular endurance and AE training with or without BFR on torque, local muscular endurance, and blood flow perfusion in the knee extensors of paralympic alpine skiers in the standing category. The main findings were that under the same training conditions, the BFR condition displayed significant increases in TW and MBP in the short term, whereas no significant increases were observed in the no-BFR condition for these measures. Both the no-BFR and BFR conditions displayed significant increases in MVIC. Although the increases in MVIC of the quadriceps muscles in the BFR condition were larger than in the no-BFR condition (BFR vs no-BFR, 35.88 ± 14.83 vs 16.71 ± 17.79 N·m), no significant group differences were observed in the MVIC. Moreover, to our knowledge, this is first

report that BFR improved muscular blood perfusion during exercise in elite para-alpine skiers.

Muscle strength. It is generally accepted that high-intensity resistance training ($\geq 70\%$ of 1RM) can stimulate gains in muscle strength (22). However, previous studies have shown that low-load BFR resistance and endurance exercises performed with BFR can increase maximal strength (28,31,37–40). The results of the present study are consistent with previous research in that the leg with BFR exercise showed increased muscle strength. However, the leg without BFR exercise also showed an increase in muscle strength. In our training protocol, in addition to LME and AE training sessions, participants also performed unrestricted HL strength training (85% of 1RM, four training sessions per week). It is generally believed that conventional low-load resistance exercise and endurance exercise cannot effectively stimulate muscle strength gains in athletes (22,41). In addition, although a combination of resistance and endurance training (concurrent training) was employed in this study, these resistance and endurance training were done in separate sessions, and the endurance training modality was cycling. It is believed that when resistance and endurance training are performed separately (> 2 h) (42) and endurance training modality is cycling (43), the concurrent training will not result in significant decrements in both hypertrophy and strength. Therefore, the observed increase in muscle strength of the legs without BFR may have been induced by the HL strength training, and that might be the reason why there were no significant group differences.

Although no significant group differences were observed in maximal strength (Fig. 1), BFR exercises induced larger

TABLE 3. Maximal muscle strength before and after 2 wk of exercise training with or without BFR.

Measure	Before			After		
	BFR Condition (n = 8)	No-BFR Condition (n = 7)	P	BFR Condition (n = 8)	No-BFR Condition (n = 7)	P
MVIC (N·m)	198.75 ± 55.17	223.71 ± 62.81	0.427	234.63 ± 51.07	240.42 ± 58.23	0.842
Relative MVIC (N·m·kg ⁻¹)	3.19 ± 0.78	3.65 ± 0.96	0.315	3.73 ± 0.72	3.89 ± 0.93	0.719

Values are presented as means ± SD. No significant group differences were observed in the in MVIC and relative MVIC. Relative MVIC = MVIC/body weight.

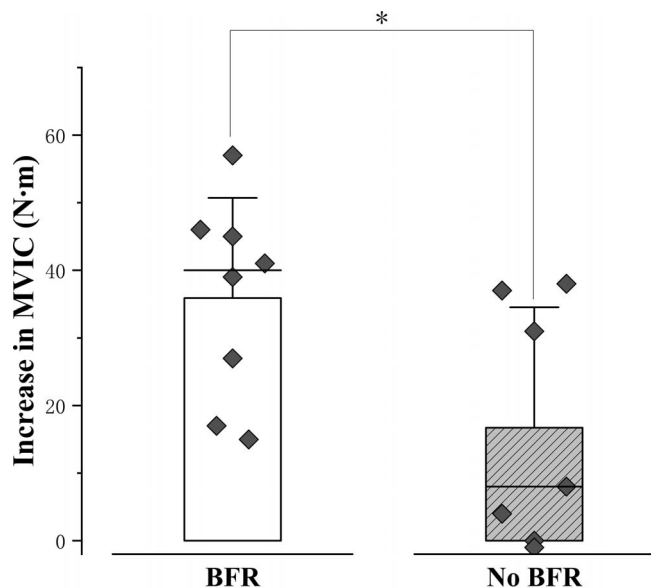


FIGURE 2—Muscle strength gains as assessed by increases in MVIC after 2 wk of training with vs without BFR. Bars represent means; horizontal lines, medians; error bars, SD; and diamonds, individual data points. * $P < 0.05$.

increases in muscle strength than in the absence of BFR (Fig. 2). Bjørnsen and coworkers (26) recently reported that two 1-wk blocks with low-load BFR resistance training induced a significant increase in maximal isokinetic strength in elite powerlifters. Walking and cycling with BFR can also positively influence maximal strength (28,31,40,44) According to recent meta-analysis, training with BFR can more effectively improve strength and hypertrophy than low-load training performed with unrestricted blood flow (45). Furthermore, previous findings suggest that significant muscle development is possible in athletes after low-load training with BFR (37–39). Although evidence suggests that high-intensity exercise without BFR provides a more neurological stimulus than low-intensity resistance exercise with BFR (46,47), well-trained athletes show limited potential for further neural adaptations (48). However, because of the anabolic environment resulting from localized

hypoxia during BFR, research has established that low-intensity resistance training with BFR can facilitate greater muscular gains than equivalent training without BFR (49). In addition, there were similar muscle hypertrophy effects between HL and low-load BFR resistance training (50). Thus, for well-trained athletes, low-load BFR exercise in combination with conventional HL resistance training may provide an additional stimulus for muscular development (51). In the present study, greater muscle strength increase in the leg with BFR may be related to the dual effects of HL resistance exercise and the BFR intervention. Our finding provides further supporting evidence for the application of BFR in strength training for athletes.

Muscle work ability. Although no significant differences in the work ability of the muscle from baseline to after exercise training were observed in the no-BFR condition, BFR significantly increased the amount of work completed during the test and the relative value. An increase in maximal muscle strength and its influencing factors may affect strength endurance (52–54). Østerås et al. (54) reported that a relatively small change in maximal strength has a substantial effect on endurance in cross-country skiers. However, TW did not increase with the gain in muscle strength in the no-BFR condition. Two points should be highlighted. First, the lower limbs in no-BFR increased in muscle strength, but the gains were smaller than for those in the lower limbs with BFR. Second, an increase in MBP in the local muscles indicates a greater supply of oxygen and energy and more efficient removal of metabolites, all of which are beneficial to resisting fatigue. Although the absolute gains in strength were not different between groups, we thus argue that the higher relative strength gains and the improved MBP in the BFR condition may be responsible for strength endurance gains. By contrast, a relatively small MVIC increase was not enough to increase TW.

Limitations. There are some limitations associated with the present study. First, we did not use a random grouping method in the athletes who are in sport classes LW5–8 because before the experiment, we thought that it might increase the risk of injury for the athletes with disabilities. Both asymmetry of muscle strength between limbs (55) and leg dominance

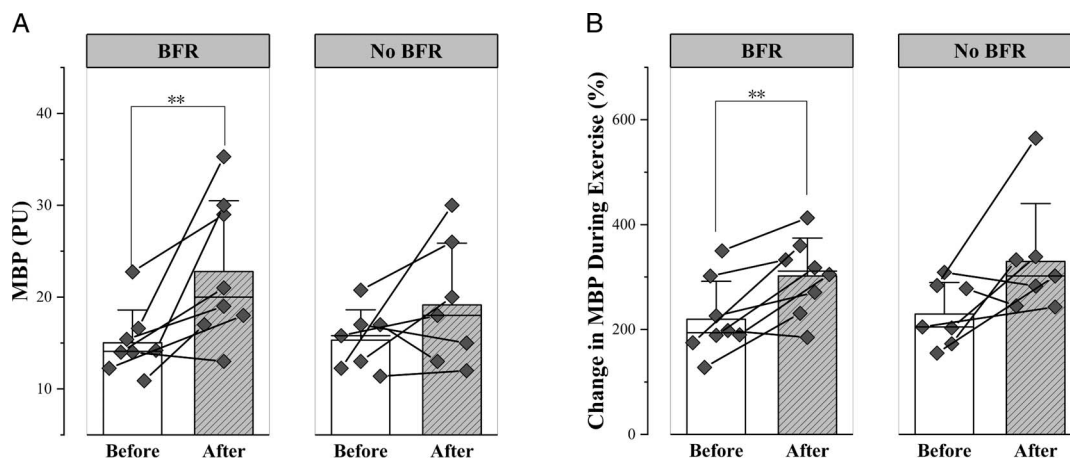


FIGURE 3—MBP before and after 2 wk of training with or without BFR. Absolute MBP (A) and the change in MBP from rest to exercise (B) with or without BFR. Bars represent means; horizontal lines, medians; error bars, SD; and diamonds, individual data points. ** $P < 0.01$ for the indicated comparisons.

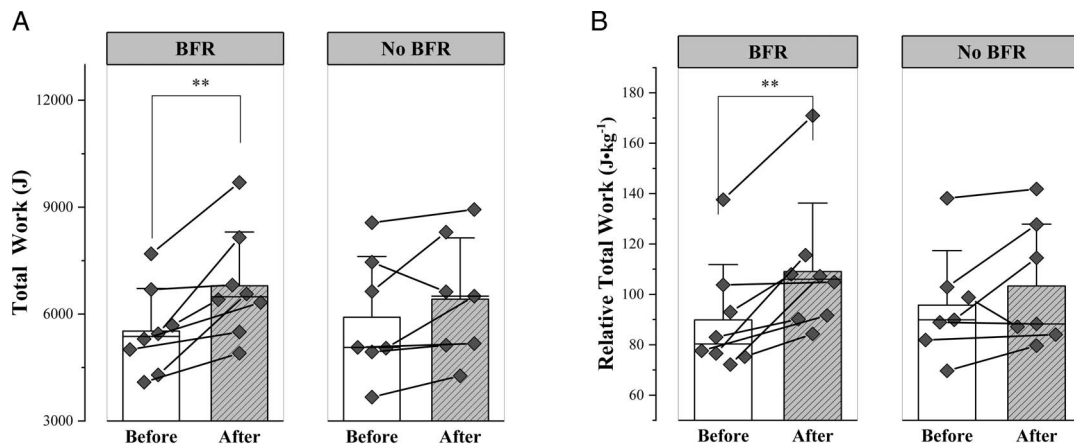


FIGURE 4—TW before and after 2 wk of training with or without BFR. Changes in absolute TW (A) and relative TW (B). Bars represent means; horizontal lines, medians; error bars, SD; and diamonds, individual data points. ****** $P < 0.01$ for the indicated comparisons.

(injuries occurred more often in the nondominant leg) (56–58) are risk factors for injuries in skiers. Previous studies reported that the enhancing metabolic stimuli produced by high-frequency BFR training may promote muscle hypertrophy in a very short term (26,38,59,60). In addition, it is suggested that optimal hypertrophy may comprise maximizing the combination of mechanical and metabolic stimuli (22). Recently, Cook et al. (61) reported that the combination of HL resistance training and BFR training (3 times per week for 3 wk) could produce greater strength gains than HL training alone in rugby athletes. During designing this study, because of using a higher-frequency (8 times per week) BFR exercise, we believed that our intervention program might induce greater strength gains in BFR legs than in no-BFR legs. Therefore, if a random grouping method was used in the current study, it would be possible to put these two risk factors together (i.e., the dominant leg became significantly stronger than the nondominant leg) and increase the risk of injury during subsequent ski training. Second, in the current study, we chose a very short training duration (2 wk). The purpose of this study is to find an effective training regimen for skier with disabilities. As mentioned previously, based on the previous studies, we hypothesized that the traditional training combined with BFR would more effectively increase the physical fitness of the athletes with disabilities. Referring to the study of Cook et al. (61), we chose the 2-wk training period to examine our hypothesis. Third, the sample size of the present study was relatively small. However, considering that the subjects were elite paralympic alpine skiers, we had recruited all the participants that was possible. Fourth, we compared the lower limbs of the same athlete; thus, blood samples could not be used to analyze the impact of the different interventions. Finally, we did not obtain muscle biopsy specimens because the subjects

rejected muscle biopsy test. According to the requirements of the Ethics Committee, this test could not be performed without permission.

CONCLUSIONS

This is the first study, to our knowledge, to compare the effects of BFR on skeletal muscle strength, local muscle blood perfusion, and specific strength endurance in elite standing alpine skiers with disabilities. We concluded herein that short-term (2 wk) BFR exercise induced a significant increase in MVIC, TW, and MBP in this population. Thus, the BFR strategies (low-load and endurance BFR exercises combined with conventional HL strength training) used in this study may be applied to physical training of alpine ski racers with or without disabilities, especially during the ski season, or to other athletes who need to improve muscle strength and strength endurance in the short-term. Future studies should investigate whether BFR combined with specific exercises promotes sport-specific muscle function, such as the rate of force development in the initial phase of muscle contraction.

Author Contributions: Y. G. and X. P. conceived the study and performed experiments; Y. G., X. P., and L. Z. analyzed data; Y. G. drafted the manuscript; Y. G., X. P., and L. Z. critically evaluated and contributed to the manuscript. All authors have approved the final version of the manuscript

The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation, and the results of the present study do not constitute endorsement by the American College of Sports Medicine.

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