Sports Medicine and Health Science 6 (2024) 159–166

Contents lists available at ScienceDirect

Sports Medicine and Health Science

journal homepage: www.keaipublishing.com/smhs

Original Article

Blood flow restriction training improves the efficacy of routine intervention in patients with chronic ankle instability

Shen Liu [a,b], Jiafu Tang [c], Guangjun Hu [c], Yinghong Xiong [a,b], Weixiu Ji [c,*], Daqi Xu [a,b,**]

[a] Department of Sports Medicine, Xiangya Hospital, Central South University, Changsha, China
[b] National Clinical Research Center for Geriatric Disorders, Xiangya Hospital, Central South University, Changsha, China
[c] Sports Health College, Tianjin University of Sport, Tianjin, China

ARTICLE INFO

Keywords:
Chronic ankle instability
Blood flow restriction training
Sports rehabilitation
Rehabilitation training

ABSTRACT

As a new means of rehabilitation, blood flow restriction training (BFRT) is widely used in the field of musculoskeletal rehabilitation. To observe whether BFRT can improve the efficacy of routine rehabilitation intervention in patients with chronic ankle instability (CAI). Twenty-three patients with CAI were randomly divided into a routine rehabilitation group (RR Group) and a routine rehabilitation + blood flow restriction training group (RR + BFRT Group) according to the Cumberland Ankle Instability Tool (CAIT) score. The RR Group was treated with routine rehabilitation means for intervention, and the RR + BFRT Group was treated with a tourniquet to restrict lower limb blood flow for rehabilitation training based on routine training. Before and after the intervention, the CAIT score on the affected side, standing time on one leg with eyes closed, comprehensive scores of the Y-balance test, and surface electromyography data of tibialis anterior (TA) and peroneus longus (PL) were collected to evaluate the recovery of the subjects. Patients were followed up 1 year after the intervention. After 4 weeks of intervention, the RR + BFRT Group CAIT score was significantly higher than the RR Group (19.33 VS 16.73, $p < 0.05$), the time of standing on one leg with eyes closed and the comprehensive score of Y-balance were improved, but there was no statistical difference between groups ($p > 0.05$). RR + BFRT Group increased the muscle activation of the TA with maximum exertion of the ankle dorsal extensor ($p < 0.05$) and had no significant change in the muscle activation of the PL with maximum exertion of the ankle valgus ($p > 0.05$). There was no significant difference in the incidence of resprains within 1 year between the groups (36.36% VS 16.67%, $p > 0.05$). The incidence of ankle pain in the RR + BFRT Group was lower than that in the RR Group (63.64% VS 9.09%, $p < 0.01$). Therefore, four-weeks BFRT improves the effect of the routine intervention, and BFRT-related interventions are recommended for CAI patients with severe ankle muscle mass impairment or severe pain.

1. Introduction

Residual symptoms from an initial lateral ankle sprain are identified as chronic ankle instability (CAI). In the United States, approximately 2 million acute ankle sprains occur each year,[1] and 70% of patients with acute lateral ankle sprains may develop CAI.[2] CAI patients are prone to suffering a cycle of sprain-instability-resprain, causing secondary damage to the cruciate ligament and meniscus.[2,3] If there is no effective rehabilitation intervention, it may lead to repeated wear and tear of the ankle joint cartilage, and even cause traumatic arthritis, which will seriously affect the daily life of patients.[2]

Studies have shown that CAI patients often have severe lower limb dysfunction, among which the reduction of balance ability, the weakening of ankle valgus muscle strength, and the prolongation of reaction time of the peroneus muscle are the main factors leading to CAI.[4] In addition, CAI patients also have defects in ankle proprioception,[5,6] accompanied by persistent symptoms, such as pain, limited ankle motion, reduced subjective sensation, etc.[4] As early as 2016, the International Ankle Consortium highlighted that in the treatment of ankle sprain, compared with other patients, CAI patients endured a longer recovery period, causing increased indirect costs.[2]

Blood flow restriction training (BFRT), also known as kaatsu training. When BFRT is performed, special device with pressure is placed on the proximal extremities (such as the forearms and thighs) in advance to restrict the flow of venous blood, so that the metabolic pressure below

* Corresponding author. Sports Health College, Tianjin University of Sport, Tianjin, 300381, China.
** Corresponding author. Xiangya Hospital of Central South University, Changsha, 410083, China.
E-mail addresses: jwx8918@163.com (W. Ji), Xudaqi96215@163.com (D. Xu).

https://doi.org/10.1016/j.smhs.2023.11.001
Received 13 May 2023; Received in revised form 18 October 2023; Accepted 7 November 2023
Available online 23 November 2023

List of abbreviations

BFRT	Blood flow restriction training
CAI	Chronic ankle instability
CAIT	Cumberland Ankle Instability Tool
RR	Routine rehabilitation
RR + BFRT	Routine rehabilitation + blood flow restriction training
RT	Resistance training
TA	Tibialis anterior
PL	Peroneus longus
sEMG	Surface electromyography
RMS	Root Mean Square
MVIC	Maximal voluntary isometric contraction

the restricted blood flow increases, thereby stimulating muscle growth and improving muscle activation.[7–9] It has been shown that combining BFRT with low-intensity resistance training (RT) can achieve similar results to high-intensity resistance training,[10] and that low-intensity BFRT used after anterior cruciate ligament reconstruction has been found to provide better relief of pain and effusion than high-intensity RT.[11] This pain-reducing effect was repeated in patients with patellar joint pain and knee arthritis.[12,13]

Due to its characteristics of low intensity and high stimulation, BFRT solves the problem that patients' limbs or joints cannot bear the heavy load.[14] In addition, BFRT can increase muscle strength and stimulate muscle activation,[8,9] suggesting that this training method may be suitable for CAI patients with reduced strength and poor neuromuscular control, plus its analgesic effect,[11–13] so we speculate that BFRT can accelerate the exercise rehabilitation of CAI patients. However, BFRT is rarely applied directly in the rehabilitation of CAI patients due to its potential safety problems such as limb numbness and abnormal coagulation, and the high cost of quantifiable BFRT devices.[15,16] Although some scholars have attempted to combine BFRT with RT and found that BFRT can reduce muscle atrophy in CAI subjects,[17,18] RT alone has been shown to be unable to completely cure CAI.[19] Multiple-mode exercise rehabilitation is supported by most studies.[20] Therefore, our study used non-quantified BFRT devices commonly used by healthy people to restrict venous blood flow in the lower limbs, combined with multi-mode exercise rehabilitation training, to verify the effect of BFRT on patients with CAI, and provide reference for clinical application.

2. Materials and methods

2.1. Subject

This trial is a randomized sham-controlled trial and was approved by the Ethics Committee of Tianjin University of Sport (TJUS-2022-025) in February 2022. This randomized controlled trial was registered with www.chictr.org.cn (ChiCTR2300067407). Enrollment begins on February 24, 2022, and 26 participants are expected to enroll. All subjects were required to sign informed consent to participate in the trial. Inclusion and exclusion criteria were defined as follows[21]: Inclusion criteria: (1) It conforms to the CAI evaluation standard given by the International Ankle Union[22]; (2) It should be more than 3 months since the last sprain; (3) Unilateral ankle sprain; (4) Ankle pain after sprain. Exclusion criteria: (1) Recurrence of an ankle sprain on the affected side during the rehabilitation intervention period; (2) Unable to train or present for examination at the required time; (3) Patients receiving other methods of ankle joint treatment during the intervention period; (4) Patients with contraindications to BFRT.

The 26 subjects recruited were numbered from 1 to 26 by the second author according to their CAIT score (from small to large). The odd group combined with BFRT was recorded as the RR + BFRT group, and the even group as the RR group.[23] Subjects with the same CAIT score drew lot to decide which group they would be assigned to. Before the intervention, one subject had a re-sprained ankle, one had a sprained knee, and one quit participating in the intervention. A total of 23 subjects were finally included in the study. After statistical analysis, no significant differences between the two groups in terms of height, age, weight, or BMI were identified. A summary of basic patient information is shown in Table 1. The participants selection process is shown in Fig. 1.

2.2. Sample size calculating

The sample size was obtained using G Power 3.0.18 software.[24] Based on previous studies, surface electromyography (sEMG) data – root mean square amplitude (*RMS*) was used as the primary outcome to calculate the required sample size. To achieve 95% power at the test level of 0.05, a total of 24 patients (12 per group) were required to detect meaningful changes in strength improvement between groups.[11] In consideration of subject loss, 26 subjects were initially recruited.

2.3. Blood flow restriction training

RR + BFRT Group placed tourniquets with a length of 90 cm and width of 5 cm at the root of the affected thigh to restrict lower limb blood flow and did not release the pressure of the tourniquet intermittently. RR Group's rehabilitation training involves wearing a non-pressure tourniquet. Since how the tourniquet restricted blood flow cannot objectively quantify the pressure of the tourniquet, a subjective quantification method of perceived pressure proposed by Wilson et al., namely, 7 levels of subjective pressure (10 levels in total) without discomfort and pain, was used as the pressure standard for blood flow restriction training in the BFR.[25] Patients were asked about their subjective feelings before each intervention. This method was used in this experiment, which has also proven to be effective in improving muscle quality and strength.[26]

2.4. Interventions

CAI's routine rehabilitation training mainly focuses on ankle proprioception,[6] lower limb strength,[27] and balance training.[28] In addition, a meta-analysis has indicated that joint mobilization more than 6 times has a significant effect on improving the dynamic and static balance ability of lower limbs,[19] and its mechanism may be related to stimulating the mechanoreceptors in the soft tissues around the ankle when sliding between bones, enhancing proprioceptive signal intake, and thus enhancing the control ability of the central nervous system over the ankle.[29] However, single rehabilitation intervention has been proven to have limited effect, while multi-mode rehabilitation intervention has a better effect.[28,30] In this study, two rehabilitation therapists made rehabilitation programs based on the latest meta-analysis on the effectiveness of CAI rehabilitation interventions,[19] and the multi-mode intervention proposed by Powden CJ was also referred to in our rehabilitation program.[20] One week before the formal intervention, the patients were trained in rehabilitation intervention through online means. Subjects in both groups received rehabilitation intervention for four weeks, three

Table 1
Basic information of subjects.

Group	RR + BFRT Group	RR Group
Number of cases	12	11
Sex(male/female)	4/8	2/9
Age (year)	20.67 ± 1.30	20.82 ± 1.47
Height (cm)	173.25 ± 14.42	181.36 ± 7.57
Weight (kg)	72.33 ± 15.48	74.09 ± 12.65
BMI (kg/m^2)	23.88 ± 2.81	22.49 ± 3.56

RR + BFRT = routine rehabilitation + blood flow restriction training , RR = routine rehabilitation , BMI = Body Mass Index.

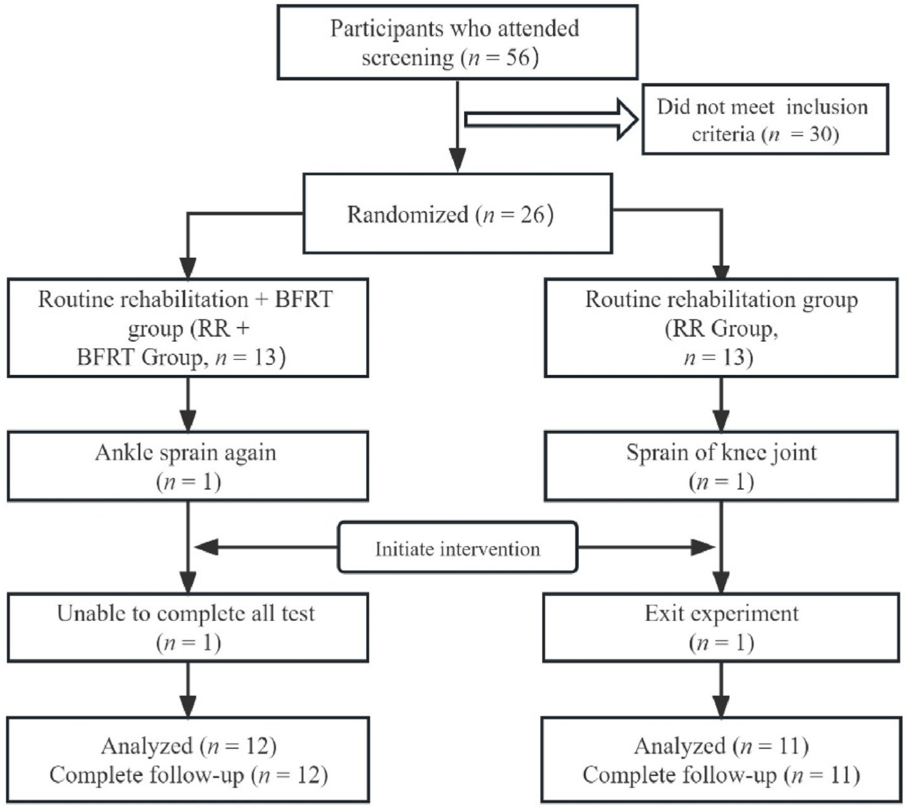

Fig. 1. Flow chart of the study design and participant follow-up during the trial. RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation.

times a week. The detailed rehabilitation plan of the RR + BFRT group is shown in Table 2.

2.5. Evaluation indicators

Testing was conducted in the laboratory of the Experimental Training Center of Tianjin University of Sports. Y-balance test measurements were performed in the morning and afternoon of the second day after intervention, with the main indicator-sEMG measured on the morning of the third day after intervention. Subjects avoided strenuous exercise and remained still before testing. The testing procedure was conducted by professional experimenters, with testing before and after intervention carried out by the same individual in the same environment. These experimenters did not know the groups beforehand. Subjects were followed up by telephone one year after the intervention.

Table 2
Intervention scheme.

Program	Training content	Time
Preparation	● Step on tennis balls and slant boards	5 min, 1–4 weeks
Strength Training (Do not remove tourniquet after completion)	➢ Resistance valgus ankle training ➢ Resistance varus ankle training ➢ Resistance Dorsiflexion Ankle Training ➢ Resistant plantar flexion ankle training	3 groups, 12 reps/group, 30 s rest, 1–4 weeks
Balance training (Remove tourniquet after completion)	■ Stand on a balance pad and eyes open ■ Stand on a balance pad and eyes close ■ Stand on the balance pad with the affected foot ■ Stand with one leg on the affected side of the balance pad, Anterior, posterior, lateral and posterior of the unaffected leg inside stretch	3 groups, 1 min/group, 30 s rest, 1–4 weeks 5 laps/set, 3 sets, stretch as far as you can, 30 s rest between sets, 3–4 weeks
Joint mobilization	◆ Therapist operates on the ankle	Level III, 30 s/group, 6 groups, 30 s rest between groups for 4 weeks

2.6. CAIT score

Questionnaires from which CAIT scores were calculated were delivered to participants using an online system, both before and after the interventions.

2.7. Surface electromyography test

Studies have shown that severe ankle valgus and dorsal extensor injury in CAI patients is one of the main causes of frequent ankle sprains,[31] so the activation of TA and PL was selected as the main observation index in this study.

TeleMyo&reg produced by Noraxon was used for sEMG acquisition. 2400T G2 sEMG telemetry system; Before the test, the subject is asked to stretch the local muscles, and then sit on the yoga mat with the lower limbs straightened. The test process is introduced to the subject for better cooperation with the test. Then the skin surface hair of the abdominal muscles of TA and PL was removed, mopped and peeled, and wiped with 75% alcohol. After air drying, the electrodes were pasted. The TA electrode was placed on one-third of the line distance between the fibula head and the medial malleolus, while the PL electrode was placed on the line between the fibula head and the lateral malleolus, about 4 cm from the fibula head.[32] After the test was ready, the patient was instructed to start the test. After hearing the "start" instruction, the patient was required to perform maximum exertion ankle dorsiflexion for 15 second (s), and the surface electromyography of maximum exertion ankle valgus was tested after 1 minute (min) of rest. Subjects underwent a practice maximum shrinkage test before the measurement test to ensure adequate performance and stability.

The sEMG test system was used to collect the electromyography signals during the maximum effort of the subjects during ankle dorsal extension and valgus. The obtained data were imported into MR-XP1.07 Master Edition software for filtering (signal filtering FIR, high frequency 10 Hz), rectification, and smoothing filtering (RMS algorithm, 50 ms window). RMS and maximum amplitudes of the subjects' muscles at 1–4 s, 5–8 s, and 9–12 s were then intercepted and recorded. Normalized mean and peak amplitudes were used for statistical comparison. The formula used to determine the normalized amplitude is expressed as a percentage maximal voluntary isometric contraction (MVIC),[33] as shown below: (mean amplitude [μV] / maximum amplitude [μV]) × 100% = normalized amplitude (%MVIC).

2.8. Standing on one leg with eyes closed

Static balance was assessed by standing on one leg with eyes closed.[34] The subjects took off their shoes and socks, stood on the wooden floor with their arms crossed in front of them, listened to the password, and closed their eyes. At the same time, they lowered their lower limbs to about 45° and bent their hips to about 30° on the healthy side, lifted their feet off the ground, and recorded the standing time on one foot. The test ends if the subject's healthy foot touches the ground, contacts the supporting lower limb, or is unable to maintain a standing position during the test. Measure three times and take the average.

2.9. Y-Balance test

The dynamic balance capability of the lower limbs of each subject was measured using Y-Balance test scores.[35] First, the distance from the anterior superior iliac spine to the medial malleolus was measured in the standing position, accurate to 0.5 cm, and recorded as leg length. Then The subjects stood barefoot on the foot on the affected side at a designated point, with the other foot actively extended forward, backward, then backward again, respectively. The maximum distance moved was recorded. This value was measured three times and the mean value was recorded. In the test, if the participant loses balance after standing on one leg, causing the standing foot to move significantly and the extended leg to touch the ground with the sole, preventing the extended leg from returning to the initial position, then the test was recorded as invalid. If the number of invalid tests was greater than 3, the test result in that direction was recorded as zero. The comprehensive score of the affected side = (forward distance + backward outward distance + backward inward distance) / (leg length × 3) × 100%.

2.10. Follow-up visit

Subjects in the two groups were followed up one year after the end of the experiment. 12 subjects were followed up in the RR + BFRT group, and 11 subjects were followed up in the RR group. Follow-up time: 2022.04.20-2023.4.21. Follow-up questions: Did you have another severe ankle sprain (requiring rest for more than one day) after the intervention? Did you experience ankle pain after the intervention?

2.11. Statistical analysis

Statistical analysis was conducted using SPSS 25.0 software. Following normality testing, measurement data conforming to a normal distribution were expressed as mean ± standard deviation ($\overline{X} \pm SD$), while differences between groups were tested using an independent samples *t*-test. Differences within groups were tested using a paired-samples *t*-test. A Mann-Whitney *U* test was used for a comparison of groups of the measurement data that did not conform to a normal distribution, while a Wilcoxon (*W*) test was used for comparisons within each group. A Fisher's Exact Probability Test was used to compare the rate of respiration. $p < 0.05$ represent statistically significant differences.

3. Results

3.1. Comparison of CAIT scores before and after intervention

Available Y-balance data was obtained in the RR + BFRT group of 12 people and the RR group of 11 people. There was no significant difference between the pre-intervention groups. After the intervention, the RR + BFRT group was significantly higher than the RR group. For intra-group comparison, the CAIT scores of subjects in both groups were significantly improved, with a mean increase of 3.91 points in the RR group and 2.82 points in the RR group, as shown in Table 3.

3.2. Comparison of balance capability indicators before and after intervention

Finally, 12 people in the RR + BFRT group and 11 people in the RR group be statistically analyzed. Before the intervention, there was no difference in standing time with eyes closed between the two groups ($t = -2.46$, $p = 0.808$). After 4 weeks of intervention, subjects in both groups had long standing time with eyes closed after the intervention, but there was no statistical significance between groups ($t = 0.749$, $p = 0.462$), as shown in Fig. 2.

Available Y-balance data was obtained in the RR + BFRT group of 12 people and the RR group of 11 people. Before the intervention, there was no difference in Y-balance scores between the two groups ($t = -1.865$, $p = 0.076$). After the intervention, the comparison of Y-balance scores between the two groups was not statistically significant ($t = -1.103$, $p = 0.284$), as shown in Fig. 3.

3.3. Comparison of sEMG before and after intervention

There were 12 people in the RR + BFRT group and 10 people in the RR group. Before the intervention, there was no significant difference in the activation degree of the malleolus dorsal extensor TA between the two groups ($t = -3.95$, $p = 0.724$). After the intervention, the degree of activation in the RR + BFRT group was significantly higher than that in the RR group by comparison between groups ($t = 2.125$, $p = 0.047$), as shown in Fig. 4.

PL surface EMG data was available for the RR + BFRT group of 11 and the RR group of 10. Before the intervention, there was no significant difference between the two groups in the degree of activation of PL malleolus valgus ($t = 0.462$, $p = 0.650$). After the intervention, the comparison between groups was not statistically significant ($t = -0.584$, $p = 0.566$), as shown in Fig. 5.

Table 3
Comparison of CAIT scores.

Group	Before intervention	After intervention	Mean difference	*p* value
RR + BFRT Group	15.42 ± 4.14	19.33 ± 4.29 **	3.91	0.004
RR Group	13.91 ± 4.30	16.73 ± 3.55 *#	2.82	0.020
p value	0.40	0.009		

Values are mean ± *SD*, **p* < 0.05 compared with prior to intervention, ***p* < 0.01 compared with prior to intervention, #*p* < 0.01 comparison between the two groups, CAIT = Cumberland Ankle Instability Tool, RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation.

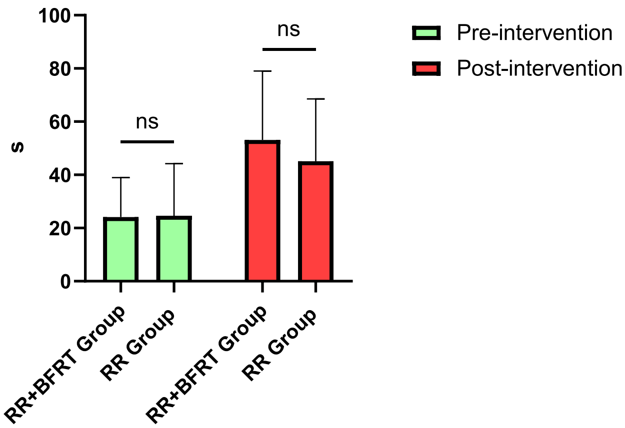

Fig. 2. Comparison of standing time on one leg with eyes closed on affected side before and after intervention. RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation, ns = not significant.

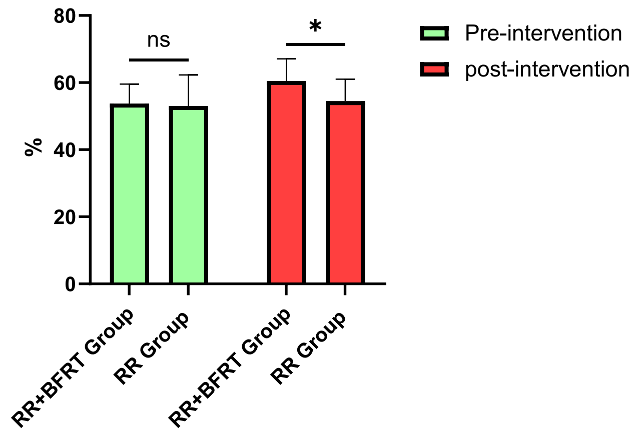

Fig. 4. Comparison of activation of ankle dorsalis extensor anterior tibial muscle. *$p < 0.05$ for comparison between groups, RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation, ns = not significant.

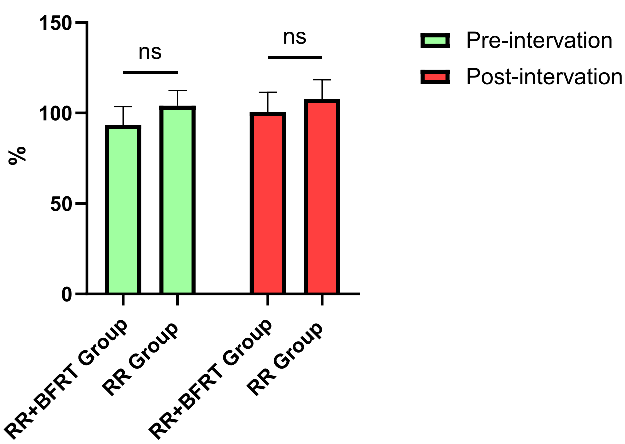

Fig. 3. Comparison of Y-balance comprehensive scores on the affected side before and after intervention. RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation, ns = not significant.

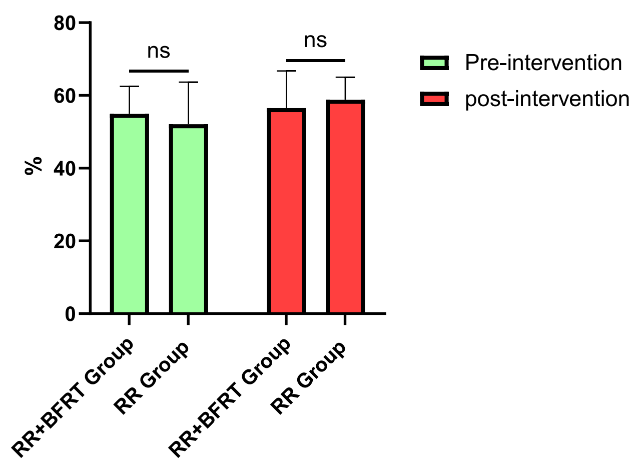

Fig. 5. Comparison of activation degree of peroneus longus of ankle valgus. RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation, ns = not significant.

3.4. Follow-up results

After the intervention, the incidence of resprains was 36.36% in the RR Group and 16.67% in the RR + BFRT Group. Although the incidence of resprains was higher in the RR Group, there was no statistical difference between the groups, as shown in Table 4.

After the intervention, the incidence of pain in the RR Group was 63.64%, and that in the RR + BFRT Group was 9.09%, significantly lower than that in the RR Group, as shown in Table 5.

4. Discussion

In this study, the combination of BFRT and multi-mode rehabilitation intervention was adopted, which is closer to the clinic. In addition, we observed the effects of BFRT on pain and resprain rates in CAI patients after one year for the first time, proving the long-term effects of BFRT on CAI patients and providing a theoretical basis for clinical application.

Firstly, the CAIT self-assessment questionnaire can evaluate the pain and stability of ankle joints in functional activities, and it can be used to screen the CAI population. The higher the score, the better the lower limb function of patients. The International Ankle Consortium recommended CAIT < 24 points to identify Chinese CAI individuals,[36] and a score less than 24 points represented ankle joint instability. When the CAIT score was increased by more than 3 points, it indicated clinical significance.[37,38] Some scholars have found that four-week supervised multi-modal exercise rehabilitation training can significantly improve CAI patients' CAIT scores.[39] However, the observation of BFRT on CAIT score of CAI patients has not been reported in the literature. Our study first studied the effect of BFRT on CAIT of subjects and found that the RR Group CAIT score increased by 2.82 on average after 4 weeks. The mean value of the RR + BFRT group was increased by 3.91. From clinical perspective, the efficacy of the RR + BFRT group was superior to that of the RR group, which proved that BFRT was beneficial to the lower limb functional rehabilitation of CAI patients. However, when evaluating the efficacy, relying solely on the subjective scale may not be reliable enough. Other objective indicators, such as muscle activation and lower limb balance, should also be referred to.[40]

In CAI patients, the ankle joint valgus and dorsi extensor muscles were severely damaged.[31] In response to this problem, Yin L et al.[41] observed the effects of Kinesiology Tape on muscle activation in CAI patients and found that Kinesiology Tape had little effect on muscle

Table 4
Ankle sprains after 1 year.

Group	Re-sprained	No-sprained	Total	Rate	*p* value
RR Group	4	7	11	36.36%	0.370
RR + BFRT Group	2	10	12	16.67%	
Total	6	17	23		

RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation.

Table 5
Ankle pain after 1 year.

Group	Pain	No pain	Total	Rate	*p* value
RR Group	7	4	11	63.64%	0.009
RR + BFRT group	1	11	12	9.09%	
Total	8	15	23		

RR + BFRT = routine rehabilitation + blood flow restriction training, RR = routine rehabilitation.

activation of the PL and TA muscles in CAI patients. Burkhardt M et al.[42] found that CAI patients showed increased activation of the vastus lateralis and soleus when using BFRT for dynamic balance exercises, but had no effect on the activation of the PL and TA. However, subsequent studies have proved that when combined with BFRT, resistance valgus and dorsal exercise increased the activation degree of PL and TA in subjects.[17] Therefore, there is controversy about the effect of BFRT on the muscle activation of TA and PL in CAI patients.

In CAI patients, increasing TA activation during exercise is a coping strategy that can help CAI patients regain normal gait.[43] The research results of Rachel M et al.[44] support the previous theory. In our study, the RR + BFRT group significantly increased TA activity in dorsiflexion after a 4-week rehabilitation intervention, and the improvement was better than that in the routine group, which is consistent with the main effect of BFRT, namely better muscle activation compared with traditional resistance exercise.[8] However, the degree of PL activation does not change significantly during valgus, and the authors have no good explanation for this reason. It is worth noting that in the intervention process of the experiment, although the subjects had received valgus intervention training one week before the intervention, the activation degree of PL was still small in CAI patients when they performed maximum exertion ankle varus, and TA was accompanied by different degrees of activation, which proved that CAI subjects had abnormal ankle valgus action pattern. This may be the reason why PL improved activation is not obvious. Overall, the authors suggest that BFRT has a positive effect on lower limb muscle activation in CAI subjects.

The evaluation of the static balance ability of CAI patients mainly uses the force plate.[45] Compared with healthy individuals, CAI patients had poor postural control and showed more forward and lateral pressure centers in a single-limb static balance standing on a force plate.[46] However, due to the limitation of experimental conditions, our experiment selected the standing time with eyes closed as an evaluation indicator. The time of standing on one foot with eyes closed can reflect the static balance of CAI patients, and to some extent, the proprioception of the ankle joint.[47] We found that the standing time of subjects in both groups was significantly extended after four-week multi-modal intervention. This is consistent with the findings of Hale SA et al., who found that a four-week comprehensive rehabilitation program resulted in benign improvements in postural control in patients with chronic ankle instability.[48] Although the balance ability improved more in the RR + BFRT group, the comparison between groups after the intervention was not statistically significant. It suggests that BFRT does not enhance the static balance improvement effect of conventional rehabilitation training.

Standing time on one leg with eyes closed can only evaluate the static balance ability of the ankle joint, and ankle instability mostly occurs in the control of dynamic balance. In order to further observe the effect of BFRT on the balance ability of CAI patients, the Y-balance test was also used in this study to evaluate the dynamic postural control ability, which can effectively detect the function loss of CAI patients.[49] Studies have shown that BFRT can effectively improve knee active position perception and Y-balance performance.[50] Some scholars have also suggested that BFRT can enhance muscle activity during exercise and improve Y-balance test results.[42] In our experiment, after 4 weeks of intervention, Y-balance scores and time of standing on one foot with eyes closed were improved in the RR + BFRT group, but there was no significant difference compared with the RR group. This is consistent with the research results of Werasirirat P et al.,[18] who also found that no significant difference was observed in homeostasis between groups after four weeks of rehabilitation intervention, with or without combined BFRT. In addition, some scholars have pointed out that CAI patients will feel greater postural instability and fatigue after dynamic balance exercises with restricted blood flow,[42] This may also be one reason why the difference in Y-balance scores is not significant.

A major characteristic of CAI is repeated sprains.[51] One year after the intervention, we followed up with the patients and found that the rate of respiration in the RR + BFRT Group was lower than that in the RR Group, with 2 patients in the RR + BFRT group and 4 patients in the RR Group, although there was no statistical difference in the probability of ankle resprians between the two groups. This may be related to the small sample size included in the test, resulting in false positives.

Pain is a major concern for CAI patients,[4] Previous studies have shown that BFRT can improve short-term pain in patients with anterior fork surgery and knee joints after intervention.[11,13] This is similar to our results. We found that the recurrence probability of pain in the RR + BFRT group was significantly lower than that in the RR group within one year after intervention, indicating that BFRT could not only improve the degree of pain immediately after intervention, but also have long-term effects.

There are some limitations in this experiment. It has been pointed out that CAI patients have muscle weakness with muscle groups fixed in the hips and ankles.[52] However, our intervention program is limited to the muscle groups around the ankle and does not pre-do the hip muscle groups. Due to the limitations of the experimental conditions, conducting sEMG tests in the sitting position was selected for the present study. However, ankle sprains mostly occur during sports activities and so observing changes in sEMG in a sitting position is somewhat limited in scope, preventing an explanation of muscle mobilization during ankle joint motion.[53] Future studies suggest expanding the sample size, extending the intervention time, and focusing on observing the surface electromyography data of the periankle muscles during exercise to better reflect the effect of intervention.

Submission statement

All authors agree with manuscript content. The manuscript is only communicated to the Journal, the manuscript will not be submitted elsewhere for review and publication.

Ethical approval statement

Ethics approval was obtained from the Ethics Committee of Tianjin University of Sport in March 2022 (Ethics No. TJUS-2022-025). Informed consent was obtained from each participant. This randomized controlled trial was registered with www.chictr.org.cn (ChiCTR2300067407).

Authors' contributions

Shen Liu: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Jiafu Tang:** Data curation, Writing – review & editing. **Guangjun Hu:** Data curation. **Yinghong Xiong:** Data curation. **Weixiu Ji:** Funding acquisition, Methodology, Writing – review & editing. **Daqi Xu:** Methodology, Writing – review & editing.

Conflict of interest

The authors declare that they have no competing interests.

Acknowledgement

The authors would like to thank Professor Huang Liping, Teacher Wang Lei and Teacher Liu Ning of Experiment Training Center of Tianjin University of Sport for providing the experiment guidance and experiment platform, and thanks to all the participants of this experiment.

References

1. Waterman BR, Owens BD, Davey S, Zacchilli MA, Belmont PJ. The epidemiology of ankle sprains in the United States. *J Bone Joint Surg Am*. 2010;92(13):2279–2284. https://doi.org/10.2106/JBJS.I.01537.
2. Gribble PA, Bleakley CM, Caulfield BM, et al. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *Br J Sports Med*. 2016;50(24): 1496–1505. https://doi.org/10.1136/bjsports-2016-096189.
3. Xu Y, Song B, Ming A, Zhang C, Ni G. Chronic ankle instability modifies proximal lower extremity biomechanics during sports maneuvers that may increase the risk of ACL injury: a systematic review. *Front Physiol*. 2022;13:1036267. https://doi.org/10.3389/fphys.2022.1036267.
4. Thompson C, Schabrun S, Romero R, Bialocerkowski A, van Dieen J, Marshall P. Factors contributing to chronic ankle instability: a systematic review and meta-analysis of systematic reviews. *Sports Med*. 2018;48(1):189–205. https://doi.org/10.1007/s40279-017-0781-4.
5. Hagen M, Lemke M, Lahner M. Deficits in subtalar pronation and supination proprioception in subjects with chronic ankle instability. *Hum Mov Sci*. 2018;57: 324–331. https://doi.org/10.1016/j.humov.2017.09.010.
6. Xue X, Ma T, Li Q, Song Y, Hua Y. Chronic ankle instability is associated with proprioception deficits: a systematic review and meta-analysis. *J Sport Health Sci*. 2021;10(2):182–191. https://doi.org/10.1016/j.jshs.2020.09.014.
7. Wortman RJ, Brown SM, Savage-Elliott I, Finley ZJ, Mulcahey MK. Blood flow restriction training for athletes: a systematic review. *Am J Sports Med*. 2021;49(7): 1938–1944. https://doi.org/10.1177/0363546520964454.
8. Sousa J, Neto GR, Santos HH, Araujo JP, Silva HG, Cirilo-Sousa MS. Effects of strength training with blood flow restriction on torque, muscle activation and local muscular endurance in healthy subjects. *Biol Sport*. 2017;34(1):83–90. https://doi.org/10.5114/biolsport.2017.63738.
9. Amani-Shalamzari S, Farhani F, Rajabi H, et al. Blood flow restriction during futsal training increases muscle activation and strength. *Front Physiol*. 2019;10:614. https://doi.org/10.3389/fphys.2019.00614.
10. Lixandrao ME, Ugrinowitsch C, Berton R, et al. Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: a systematic review and meta-analysis. *Sports Med*. 2018;48(2):361–378. https://doi.org/10.1007/s40279-017-0795-y.
11. Hughes L, Rosenblatt B, Haddad F, et al. Comparing the effectiveness of blood flow restriction and traditional heavy load resistance training in the post-surgery rehabilitation of anterior cruciate ligament reconstruction patients: a UK national health service randomised controlled trial. *Sports Med*. 2019;49(11):1787–1805. https://doi.org/10.1007/s40279-019-01137-2.
12. Wang HN, Chen Y, Cheng L, Cai YH, Li W, Ni GX. Efficacy and safety of blood flow restriction training in patients with knee osteoarthritis: a systematic review and meta-analysis. *Arthritis Care Res*. 2022;74(1):89–98. https://doi.org/10.1002/acr.24787.
13. Li S, Shaharudin S, Abdul KM. Effects of blood flow restriction training on muscle strength and pain in patients with knee injuries: a meta-analysis. *Am J Phys Med Rehabil*. 2021;100(4):337–344. https://doi.org/10.1097/PHM.0000000000001567.
14. Hughes L, Paton B, Rosenblatt B, Gissane C, Patterson SD. Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. *Br J Sports Med*. 2017;51(13):1003–1011. https://doi.org/10.1136/bjsports-2016-097071.
15. Loenneke JP, Wilson JM, Wilson GJ, Pujol TJ, Bemben MG. Potential safety issues with blood flow restriction training. *Scand J Med Sci Sports*. 2011;21(4):510–518. https://doi.org/10.1111/j.1600-0838.2010.01290.x.
16. Patterson SD, Brandner CR. The role of blood flow restriction training for applied practitioners: a questionnaire-based survey. *J Sports Sci*. 2018;36(2):123–130. https://doi.org/10.1080/02640414.2017.1284341.
17. Killinger B, Lauver JD, Donovan L, Goetschius J. The effects of blood flow restriction on muscle activation and hypoxia in individuals with chronic ankle instability. *J Sport Rehabil*. 2020;29:633–639. https://doi.org/10.1123/jsr.2018-0416.
18. Werasirirat P, Yimlamai T. Effect of supervised rehabilitation combined with blood flow restriction training in athletes with chronic ankle instability: a randomized placebo-controlled trial. *J Exerc Rehabil*. 2022;18(5):123–132. https://doi.org/10.12965/jer.2244018.009.
19. Shi XJ, Rong JF, Cai B, Liu Y, Han J. Effect of physical therapy on neuromuscular control dysfunction for chronic ankle instability: a systematic review [in Chinese]. *Chin J Rehabil Theory Pract*. 2022;28(2):132–143. https://doi.org/10.3969/j.issn.1006-9771.2022.02.002.
20. Powden CJ, Hoch JM, Jamali BE, Hoch MC. A 4-week multimodal intervention for individuals with chronic ankle instability: examination of disease-oriented and patient-oriented outcomes. *J Athl Train*. 2019;54(4):384–396. https://doi.org/10.4085/1062-6050-344-17.
21. Gribble PA, Delahunt E, Bleakley C, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *J Orthop Sports Phys Ther*. 2013;43(8):585–591. https://doi.org/10.2519/jospt.2013.0303.
22. Gribble PA, Delahunt E, Bleakley C, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *Br J Sports Med*. 2014;48(13):1014–1018. https://doi.org/10.1136/bjsports-2013-093175.
23. Werasirirat P, Yimlamai T. Effect of supervised rehabilitation combined with blood flow restriction training in athletes with chronic ankle instability: a randomized placebo-controlled trial. *J Exerc Rehabil*. 2022;18(2):123–132. https://doi.org/10.12965/jer.2244018.009.
24. Faul F, Erdfelder E, Lang AG, Buchner AG. *Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191. https://doi.org/10.3758/bf03193146.
25. Wilson JM, Lowery RP, Joy JM, Loenneke JP, Naimo MA. Practical blood flow restriction training increases acute determinants of hypertrophy without increasing indices of muscle damage. *J Strength Condit Res*. 2013;27(11):3068–3075. https://doi.org/10.1519/JSC.0b013e31828a1ffa.
26. Luebbers PE, Witte EV, Oshel JQ, Butler MS. Effects of practical blood flow restriction training on adolescent lower-body strength. *J Strength Condit Res*. 2019; 33(10):2674–2683. https://doi.org/10.1519/JSC.0000000000002302.
27. Hall EA, Chomistek AK, Kingma JJ, Docherty CL. Balance-and strength-training protocols to Improve chronic ankle instability deficits, part I: assessing clinical outcome measures. *J Athl Train*. 2018;53(6):568–577. https://doi.org/10.4085/1062-6050-385-16.
28. Kosik KB, McCann RS, Terada M, Gribble PA. Therapeutic interventions for improving self-reported function in patients with chronic ankle instability: a systematic review. *Br J Sports Med*. 2017;51(2):105–112. https://doi.org/10.1136/bjsports-2016-096534.
29. Roijezon U, Clark NC, Treleaven J. Proprioception in musculoskeletal rehabilitation. Part 1: basic science and principles of assessment and clinical interventions. *Man Ther*. 2015;20(3):368–377. https://doi.org/10.1016/j.math.2015.01.008.
30. Tsikopoulos K, Mavridis D, Georgiannos D, Vasiliadis HS. Does multimodal rehabilitation for ankle instability improve patients'self-assessed functional outcomes? a network meta-analysis. *Clin Orthop Relat Res*. 2018;476(6):1295–1310. https://doi.org/10.1097/01.blo.0000534691.24149.a2.
31. Khalaj N, Vicenzino B, Heales LJ, Smith MD. Is chronic ankle instability associated with impaired muscle strength? Ankle, knee and hip muscle strength in individuals with chronic ankle instability: a systematic review with meta-analysis. *Br J Sports Med*. 2020;54(14):839–847. https://doi.org/10.1136/bjsports-2018-100070.
32. Jaber H, Lohman E, Daher N, et al. Neuromuscular control of ankle and hip during performance of the star excursion balance test in subjects with and without chronic ankle instability. *PLoS One*. 2018;13(8):e201479. https://doi.org/10.1371/journal.pone.0201479.
33. Bordessa JM, Hearn MC, Reinfeldt AE, et al. Comparison of blood flow restriction devices and their effect on quadriceps muscle activation. *Phys Ther Sport*. 2021;49: 90–97. https://doi.org/10.1016/j.ptsp.2021.02.005.
34. Woon EL, Low J, Sng YL, Hor AB, Pua YH. Feasibility, correlates, and validity of the one-leg sit-to-stand test in individuals following anterior cruciate ligament reconstruction. *Phys Ther Sport*. 2021;52:280–286. https://doi.org/10.1016/j.ptsp.2021.10.007.
35. Khalaj N, Vicenzino B, Smith MD. Hip and knee muscle torque and its relationship with dynamic balance in chronic ankle instability, copers and controls. *J Sci Med Sport*. 2021;24(7):647–652. https://doi.org/10.1016/j.jsams.2021.01.009.
36. Li Y, Tsang RC, Liu D, Ruan B, Yu Y, Gao Q. Applicability of cutoff scores of Chinese Cumberland Ankle Instability Tool and Foot and Ankle Ability Measure as inclusion criteria for study of chronic ankle instability in Chinese individuals. *Phys Ther Sport*. 2021;48:116–120. https://doi.org/10.1016/j.ptsp.2020.12.021.
37. Donahue M, Simon J, Docherty CL. Critical review of self-reported functional ankle instability measures. *Foot Ankle Int*. 2011;32(12):1140–1146. https://doi.org/10.3113/FAI.2011.1140.
38. Wright CJ, Linens SW, Cain MS. Establishing the minimal clinical important difference and minimal detectable change for the cumberland ankle instability tool. *Arch Phys Med Rehabil*. 2017;98(9):1806–1811. https://doi.org/10.1016/j.apmr.2017.01.003.
39. Tsikopoulos K, Mavridis D, Georgiannos D, Vasiliadis HS. Does multimodal rehabilitation for ankle instability improve patients' self-assessed functional outcomes? a network meta-analysis. *Clin Orthop Relat Res*. 2018;476(6):1295–1310. https://doi.org/10.1097/01.blo.0000534691.24149.a2.
40. Shi XJ, Han J, Liu Y, et al. Research progress on pathological mechanism and evaluation diagnosis of chronic ankle instability [in Chinese]. *Chin J Sports Med*. 2019;38(9):816–824. https://doi.org/10.16038/J.1000-6710.2019.09.015.
41. Yin L, Liu K, Liu C, Feng X, Wang L. Effect of kinesiology tape on muscle activation of lower extremity and ankle kinesthesia in individuals with unilateral chronic ankle instability. *Front Physiol*. 2021;12:786584. https://doi.org/10.3389/fphys.2021.786584.
42. Burkhardt M, Burkholder E, Goetschius J. Effects of blood flow restriction on muscle activation during dynamic balance exercises in individuals with chronic ankle instability. *J Sport Rehabil*. 2021;30(6):870–875. https://doi.org/10.1123/jsr.2020-0334.

43. Feger MA, Donovan L, Hart JM, Hertel J. Lower extremity muscle activation in patients with or without chronic ankle instability during walking. *J Athl Train*. 2015; 50(4):350–357. https://doi.org/10.4085/1062-6050-50.2.06.
44. Koldenhoven RM, Feger MA, Fraser JJ, Saliba S, Hertel J. Surface electromyography and plantar pressure during walking in young adults with chronic ankle instability. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(4):1060–1070. https://doi.org/10.1007/s00167-016-4015-3.
45. Hou ZC, Ao YF, Hu YL, et al. Analysis of plantar pressure characteristics and related factors in patients with chronic ankle instability [in Chinese]. *J Peking Univ (Heal Sci)*. 2021;53(2):279–285. https://doi.org/10.19723/j.issn.1671-167X.2021.02.008.
46. Mettler A, Chinn L, Saliba SA, McKeon PO, Hertel J. Balance training and center-of-pressure location in participants with chronic ankle instability. *J Athl Train*. 2015; 50(4):343–349. https://doi.org/10.4085/1062-6050-49.3.94.
47. Zhang QX, Hua XQ, Shi YJ. Development and application of measurement methods for ankle proprioception [in Chinese]. *Chinese J Tissue Eng Res*. 2011;15(35): 6619–6623. https://doi.org/10.3969/j.issn.1673-8225.2011.35.038.
48. Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther*. 2007;37(6): 303–311. https://doi.org/10.2519/jospt.2007.2322.
49. McKeon PO, Hertel J. Spatiotemporal postural control deficits are present in those with chronic ankle instability. *BMC Muscoskel Disord*. 2008;9:76. https://doi.org/10.1186/1471-2474-9-76.
50. Wei X. *Effect of Different Blood Flow Restriction Training Regiments on Lower Limb Function in Athletes with Knee Injury [in Chinese]*. Dissertation. Guangzhou Sport University; 2021. https://doi.org/10.27042/d.cnki.ggztc.2021.000156.
51. Doherty C, Bleakley C, Delahunt E, Holden S. Treatment and prevention of acute and recurrent ankle sprain: an overview of systematic reviews with meta-analysis. *Br J Sports Med*. 2017;51(2):113–125. https://doi.org/10.1136/bjsports-2016-096178.
52. Labanca L, Mosca M, Ghislieri M, Agostini V, Knaflitz M, Benedetti MG. Muscle activations during functional tasks in individuals with chronic ankle instability: a systematic review of electromyographicalstudies. *Gait Posture*. 2021;90:340–373. https://doi.org/10.1016/j.gaitpost.2021.09.182.
53. Bleakley C, Wagemans J, Netterstrom-Wedin F. Understanding chronic ankle instability: model rich, data poor. *Br J Sports Med*. 2021;55(9):463–464. https://doi.org/10.1136/bjsports-2020-103311.