Effect of Continuous and Intermittent Blood Flow Restriction Deep-squat Training on Thigh Muscle Activation and Fatigue Levels in Male Handball Players

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Abstract

Background: We aimed to investigate acute changes before and after low-intensity continuous and intermittent blood flow restriction deep-squat exercises on the thigh muscle activation characteristics and fatigue level under suitable individual arterial occlusion pressure (AOP) to provide a theoretical basis and practical reference for athletes undergoing blood flow restriction training.

Methods: Twelve elite male handball players were recruited. Continuous (Program 1) and intermittent (Program 2) blood flow restriction deep-squat exercises were performed with 30% one-repetition maximum intensity. Program 1 does not include decompression during the intervals, while Program 2 contains decompression during each interval. Electromyography (EMG) was performed before and after two blood flow restriction training programs in each period. EMG signals of the quadriceps femoris, posterior femoral muscles, and gluteus maximus, including the root mean square (RMS) and normalized RMS and median frequency (MF) values of each muscle under maximum voluntary contraction (MVC) before and after exercise were calculated.

Results: The RMS value under MVC (RMS_{MVC}) of the rectus femoris, vastus medialis, vastus lateralis, gluteus maximus decreased after continuous and intermittent blood flow restriction training programs, and those of the biceps femoris and semitendinosus increased; rectus femoris changed significantly after continuous exercise ($P<0.01$). RMS_{MVC} values of the biceps femoris and semitendinosus changed significantly after intermittent exercise ($P<0.01$). The RMS values of the vastus lateralis, biceps femoris, and semitendinosus were significantly increased after continuous and intermittent blood flow restriction training ($P<0.05$). The gluteus maximus RMS value significantly decreased after cuff binding ($P<0.05$); The MF values of rectus femoris, vastus medialis, vastus lateralis, and gluteus maximus decreased significantly after continuous blood flow restriction training ($P<0.05$).

Conclusion: Continuous blood flow restriction deep-squat training under 50%AOP is more effective than the intermittent training in removing pressure on the thigh muscle group. In the third and fourth sets of exercise, all muscle groups showed a significant increase except the medial femoral muscle. However, this may also cause fatigue that may be harder to eliminate than that after intermittent training.

Background

Resistance training can effectively promote muscle hypertrophy and increase strength in athletes [1]. Reducing intensity in training combined with blood flow restriction can cause the same adaptation effect [2–5]. Low-intensity blood flow restriction training, also known as blood flow restriction (BFR) training, can induce an increase in muscle volume and strength, and its force gain effect is similar to that of traditional high-intensity resistance training [6–8]. At the same time, blood flow restriction training can promote muscle activation to ensure a total power output similar to traditional training [9–11]. In addition, blood flow restriction training can enhance neural activation and promote the mobilization of type II motor units [12]. Therefore, the neuromuscular response generated by external pressure stimulation is also one of the main causes of muscle hypertrophy. Shinohara et al. concluded that the neuromuscular activity level generated by low-intensity blood flow restriction training is equivalent to that generated by traditional high-intensity resistance training, and both can promote the mobilization of type II motor units [13]. However, whether neuromuscular factors play a key role in blood flow restriction training induced muscular adaptation is unclear.

In studies on muscle hypertrophy induced by blood flow restriction training, different selection methods of external pressure resulted in different understandings of its physiological mechanism. Moore and Pierce used arbitrary, subjective pressure values to implement the blood flow restriction training program [14, 15], while Abe and Yasuda calculated external blood limit pressure based on brachial artery resting systolic pressure and applied it to their experimental design [16, 17]. Loenneke et al. pointed out that neither of the above two methods represents an effective strategy for controlling the blood pressure limit of the lower limbs [18]. Different girths experience different degrees of blood flow restriction under the same pressure condition and then produce completely different training stress responses. Laurentino et al. studied the pressure required to complete vascular occlusion in the upper thigh under static condition [19]. Therefore, the relative pressure calculated using the individual specific percentage of arterial occlusion pressure (%AOP) deserves widespread application and promotion.

In studies exploring the instantaneous changes in muscle activation caused by different external pressure stimuli before and after compression resistance training, the exercises were mainly single joint movements such as elbow flexion of the upper limb and isokinetic knee extension of the lower limb. Loenneke et al. found that knee stretching with 40–50%AOP to limit blood pressure may change the flesh instant response of the quadriceps femoris and improve the muscle activation level, while higher pressure does not cause these changes [20]. In the field of multi-joint sports, Li Zhiyuan et al. concluded that the application of 50% AOP can significantly improve the optimal activation degree of the quadriceps femoris and posterior femoris muscle groups of male handball players at the same time, resulting in the best training effect [21].

However, the effects of continuous and intermittent compression exercises on thigh muscle activation and fatigue during weight-bearing squats under the same external adaptive stress conditions have not been thoroughly investigated. Therefore, this study aimed to investigate the characteristics of the instantaneous changes in muscle group activation and fatigue of the lower limbs of male handball athletes before and after squat training with two modes of continuous pressure and depressure intervals under 50% AOP stimulation. This study provides a theoretical basis and reference for the scientific selection and rational utilization of the interval mode in blood flow restriction training. In this study, it was assumed that the activation of the anterior and posterior thigh muscle groups increased significantly during both continuous and intermittent pressure training programs. In contrast, the activation degree of the anterior thigh muscle group decreased, and that of the posterior thigh muscle group increased after pressure removal. However, continuous training leads to transient fatigue reactions in the anterior thigh muscle group.

Methods

Subjects

Twelve elite national athletes of the Beijing male handball team were recruited as subjects (age: 21.4±3.2 years, height: 190.0±8.7 cm, weight: 91.1±16.2 kg, training years 12.1±2.4 years). Before the experiment, the purpose, method, and possible risks were explained to the subjects, and written informed consent was obtained from all subjects. Before the test, the essentials of the tested action were explained to the subjects, and they were asked to train as usual 1 week before the beginning of the experiment.

Experimental instruments and equipment

A fully automatic KAATSU Master 2.0 Package (KAATSU Global, Inc., Japan) and 5 cm-wide pressure band were used to digitally display the limited blood pressure (inflation pressure) size. Other instruments included one Wave Plus Wireless surface electromyography (EMG) tester and surface electrodes (Cometa SRL, Italy), one Panasonic HC-V100 Review (Panasonic Global, Inc., Japan), one GymAware linear sensor device (Kinetic Performance Technology, Australia), one goniometer, one barbell rod and barbell piece, one set of Smith squat racks, one set of tape measures, one laptop, and one metronome.

Experimental Design

Test action

The subjects stood on the Smith squat rack with their eyes looking straight horizontally and their feet naturally apart. A squat-to-knee joint angle of 60–70º was achieved (with the thigh approximately parallel to the ground). The hip and knee were extended at the same time during squatting. The knee joint angle was measured and monitored in real-time using a goniometer, and the subjects were prompted verbally. The subjects controlled the timing and rhythm of each movement according to the metronome.

Testing method

The athletes’ thigh circumference was measured and evaluated 48 h before the experiment, and the relative value of 50%AOP cut-off blood pressure of each person was determined according to the right thigh circumference (Table 1) [20]. The athletes’ right thigh circumference was 62.9±6.1 cm, the binding pressure was uniformly selected as 40 mmHg [22], and the inflatable pressure was 150–180 mmHg. The inflatable pressure of the three athletes was 150 mmHg, and that of the other seven athletes was 180 mmHg. At the same time, the Gymaware linear sensor was used to measure the squat one-repetition maximum (1RM) for each athlete to determine the individualized load intensity (i.e., load weight) for the pressurized squat exercise.

Table 1
Thigh Circumstance and Relative AOP Value

Thigh circumference	Blood pressure limit(60%AOP)	Blood pressure limit(50%AOP)	Blood pressure limit(40%AOP)
< 45 cm ~ 50.9 cm	120 mmHg	100 mmHg	80 mmHg
51 cm-55.9 cm	150 mmHg	130 mmHg	100 mmHg
56 cm ~ 59.9 cm	180 mmHg	150 mmHg	120 mmHg
≥ 60 cm	210 mmHg	180 mmHg	140 mmHg

Each subject underwent weight-bearing squat exercises under the two intervention conditions of continuous compression intervals (Program 1) and decompression intervals (Program 2), with a load intensity of 30% 1RM and a relative blood pressure limit of 50% AOP. Automatic blood flow restriction training equipment was used to bind the pressure band to the middle and upper 1/3 of the subject's thigh, perpendicular to the thigh’s longitudinal axis. Before the pressure cuff was inflated to the target pressure, it was pressurized to 50, 75, and 100% of the target pressure, respectively, and then the pressure was removed immediately. Next, "keeping pressure-removing pressure" cyclic pressure adaptation preparation was performed. The cuff was inflated to the target pressure before the first session and removed after the last session. The total duration of each program did not exceed 10 min.

Testing procedure and collection of indicator data

Testing Schedule

Before the test, subjects underwent the following warm-up exercises: i) 6 min of no-load power cycling (60–70 rpm); ii) three sets of 30% 1RM weighted squat exercises (five repetitions per set). After the warm-up, practice and testing were carried out according to the following procedures (Fig. 1): i) maximum voluntary contraction (MVC) test of the thigh muscle group; ii) pre-test 1 (pre-1): three 30% 1RM deep-squat repetitions before fitting the pressure band; iii) pre-test 2 (pre-2): three 30% 1RM deep-squat repetitions after fitting the pressure band; iv) intermittent and continuous pressurized exercise with 30% 1RM. In both intermittent and continuous compression exercise, there were four sets of deep-squat with 30, 15, 15, and 15 repetitions intermittent at 30 s. Two types of rest were implemented: keeping pressure and removing pressure. The interval between two programs (keeping pressure and removing pressure) of exercises was set to 48 h; v) post-test 1 (post-1): after implementing the blood flow restriction training program, 30% 1RM squat exercises were performed three times; vi) post-test 2 (post-2): after removing the pressure band, three 30% 1RM deep-squat; vii) an MVC test of the thigh muscle group.

Test indicator data

Gymaware, a linear sensor, was used to test the 1RM of load-bearing squats using the increasing load test method [23]. In the testing procedure, the athletes’ maximum strength can be predicted by the linear regression equation: Load = M + B + Z (where M is speed, B is constant, and Z is the standard estimation error) owing to the highly negative correlation between the load and the speed [24]. In the first set, squatting speed should be more than 1 m/s, and in the last set, the squatting speed should be less than 0.5 m/s. The number of test sets was approximately 3–5, and the increasing load of each set was 20–30 kg, depending on the weight and strength of the athlete.

Thigh circumference was measured with the participants' feet shoulder-width apart, placing a tape measure at the line below their hips and horizontally measuring their thigh circumference. The left and right thighs were measured three times, and the mean was calculated. The blood pressure limit at each stage was set according to the right thigh circumference.

Collection and processing of surface EMG data

Electrode placement and requirements

The rectus femoris, vastus medialis, vastus lateralis, biceps femoralis, semitendinosus, and gluteus of right thigh maximus were selected for testing. The electrodes were placed according to the requirements in EMG manual [25]; the skin was cleaned before placement, hair was shaved, the skin was smoothed with sandpaper, and then wiped with 75% medical alcohol to remove any oil on the skin's surface. The surface electrode was placed on the most elevated part of the muscle and fixed along the direction of the muscle fiber to avoid any vibration-induced interference.

MVC test and root mean square (RMS) value collection

After placing the surface electrodes, the electrode wires were connected to test the thigh muscles' MVC, and the corresponding muscle surface EMG signals were recorded. Specific testing methods are outlined in the EMG manual [25] (Fig. 4). We collected and recorded surface EMG values, which were used as RMS values under MVC (RMS_{MVC}) after processing.

Surface EMG data collection and processing

Before each squatting test, the camera and Waveplus wireless EMG acquisition system were set up. After the subjects began to move, the acquisition system was turned on to collect the EMG data. All EMG signals from 1 to 4 sets of exercise were selected according to the synchronous video of the experiment. The original EMG data were cleaned, filtered, smoothed, and their amplitude standardized using the matching analysis software of the Emgserver instrument, and the selected index was the RMS amplitude. The range of muscle exertion was selected from the original EMG, and the mean RMS was determined. The EMG RMS of each muscle obtained during MVC testing was defined as 100%MVC. The standardized EMG data processing system automatically divided the EMG RMS value obtained in each set by the EMG of maximum voluntary contraction (EMG_{MVC}) value for standardized processing; the RMS standardized processing unit is %.

Statistical Analysis

Two-way analysis of variance (ANOVA; operation period × intermittent method) and the Mauchly sphericity test were used to evaluate the lower limb muscle groups' RMS and median frequency (MF) values during the weight-bearing squat in the pre-1, pre-2, post-1, and post-2 periods. If the test P-value was > 0.05, the sphericity test was not satisfied, and the test result of the one-way ANOVA prevailed. If the test P-value was < 0.05, the sphericity test could be satisfied, and two-way ANOVA test results were used. Using the Bonferroni method, multiple comparisons were made between the four operation periods before and after blood flow restriction training to test for significant between-condition differences. The RMS_{MVC} was evaluated before and after implementing the two training programs of continuous pressure interval and depressure interval by repeated measurement two-factor analysis (time×interval method). The significance level was set at $\alpha = 0.05$; $P < 0.05$ indicates a significant difference, and $P < 0.01$ indicates a highly significant difference.

Results

Variation characteristics of maximum activation of thigh muscle groups before and after compression squat exercises

As shown in Table 2, the main effects of time on the rectus femoris, biceps femoralis, semitendinosus, and gluteus maximus RMS_{MVC} values were significantly different ($P < 0.05$). The time and interval mode interaction was significantly different in the rectus femoris, biceps femoralis, semitendinosus, and gluteus maximus RMS_{MVC} values ($P < 0.05$). The rectus femoris, vastus medialis, vastus lateralis, and gluteus maximus RMS_{MVC} values decreased after removing pressure at the end of the compression squat program. The rectus femoris and gluteus maximus RMS_{MVC} values changed significantly ($P < 0.05$), while the biceps femoralis and semitendinosus RMS_{MVC} values increased. There were significant changes in interval training ($P < 0.05$).

Table 2
Change in Thigh Muscle Group RMS_{MVC} Value of Before and After Resistance Deep-squat Exercise

Muscle	Intermittent mode	Pre-test RMS_{MVC}	Post-test RMS_{MVC}	Rate of change(%)	P-value (Interaction effect)	P-value (Time main effect)
Rectus femoris	Continuously	616.32±146.35	548.39±102.37**↓	-12.39	0.035	0.014
	Intermittently	599.53±107.69	574.37±156.59	-4.38		
Vastus medialis	Continuously	480.94±207.22	444.15±189.95	-7.65	0.078	0.124
	Intermittently	502.31±147.38	486.39±102.37	-3.32		
Vastus lateralis	Continuously	395.68±117.20	369.57±117.56	-6.60	0.096	0.135
	Intermittently	403.14±123.58	397.23±177.58	-1.47		
Biceps femoralis	Continuously	534.05±153.01	591.64±125.03	10.78	0.037	0.039
	Intermittently	514.23±211.58	621.24±255.32**↑	20.81		
Semitendinosus	Continuously	440.58±159.49	449.63±85.21	2.05	0.026	0.034
	Intermittently	476.59±174.53	543.19±97.45**↑	13.97		
Gluteus maximus	Continuously	422.39±174.41	360.77±213.77**↓	-5.45	0.047	0.036
	Intermittently	436.15±144.51	412.36±101.25	-14.59		

Changes in the relative activation degree of thigh muscle groups before and after compression squat exercises

As shown in Table 3, there was a significant difference ($P < 0.05$) in the main effect of operation time on the RMS standard values of the vastus medialis, vastus lateralis, biceps femoralis, semitendinosus, and gluteus maximus. There were significant differences in the RMS standard values of the vastus medialis, biceps femoralis, semitendinosus, and gluteus maximus between the two modes ($P < 0.05$). According to multiple comparison results in Table 3, the standard RMS value of the anterior thigh muscle group increased in the pre2, post-1, and post-2 periods during continuous and interval training compared with pre-1. Vastus lateralis RMS showed significant changes in post-1 ($P < 0.05$), and vastus medialis and vastus lateralis RMS had significant changes in post-1 ($P < 0.05$) during interval practice. The RMS standard values of the posterior thigh muscle group were increased in the pre2, post-1, and post-2 periods, and the biceps femoralis and semitendinosus RMS standard values were significantly changed in the post-1 period ($P < 0.05$). The semitendinosus RMS standard value changed significantly compared to the pre-2 period ($P < 0.05$). During continuous and interval training, the standard value of the gluteus maximus RMS decreased significantly in pre-2 compared with pre-1 ($P < 0.05$), while the standard value of the gluteus maximus RMS increased significantly in post-2 compared with pre-2 ($P < 0.05$).

Table 3
Change in Thigh Muscle Group RMS (%MVC) Before and After Resistance Deep-squat Exercise

Muscle	Intermittent mode	Period				P-value (Interaction effect)	P-value (Time main effect)
		Pre test-1	Pre test-2	Post test-1	Post test-2		
Rectus femoris	Continuously	38.10±9.68	46.32±18.32	44.33±17.30	43.31±7.93	0.855	0.074
	Intermittently	40.10±7.38	44.32±14.35	46.33±7.75	45.31±14.44		
Vastus medialis	Continuously	49.62±2.74	50.28±6.52	57.31±7.81	55.68±8.91	0.042	0.031
	Intermittently	52.62±4.66	53.32±12.35	58.31±10.58*	57.82±12.60		
Vastus lateralis	Continuously	46.25±2.56	50.28±6.52	56.25±2.83*	50.63±5.70	0.769	0.014
	Intermittently	49.31±5.77	52.14±9.09	57.87±11.47*	54.41±15.50		
Biceps femoralis	Continuously	20.48±7.82	23.52±3.41	26.80±4.51*	24.11±3.50	0.025	0.048
	Intermittently	18.55±9.24	22.52±13.72	28.38±9.63*	26.39±9.87		
Semitendinosus	Continuously	19.09±4.75	20.31±5.57	28.20±4.26*$^{\Delta}$	24.53±7.11	0.031	0.036
	Intermittently	21.56±8.59	21.93±9.81	25.97±7.37*$^{\Delta}$	23.37±11.85		
Gluteus maximus	Continuously	31.04±8.75	27.34±8.74*	29.73±14.56	32.29±14.33$^{\#}$	0.027	0.022
	Intermittently	34.88±2.90	29.04±4.70*	28.53±13.29	30.30±4.40$^{\#}$		

Note: * indicates that pre-2, post-1, and post-2 are significantly different from PRE-1; △ indicates a significant difference between post-1 and post-2 compared with pre-2; #Indicates that post-2 is significantly different from post-1.

Comparative analysis of fatigue of the thigh muscle group before and after the compression squat exercise

As shown in Table 4, the main effect of the operation period on MF values of the anterior thigh muscle group and gluteus maximus were significantly different ($P < 0.05$). In contrast, the interaction between the operation period and intermittent mode showed a significant difference in MF values of the anterior thigh muscle group and gluteus maximus ($P < 0.05$). The multiple comparison results (Table 4) show that, compared with pre-1, the MF values at pre-2, post-1, and post-2 show a trend of intial increase followed by a decrease in the two schedules of continuous compression and decompression intervals. The MF values of the rectus femoris, vastus medialis, and vastus lateralis decreased significantly during the post-1 period ($P < 0.05$). However, in post-2 period, the MF values of the rectus femoris and vastus medialis returned to levels of pre-1 period. There were no significant changes in the biceps femoralis and semitendinosus MF values in the pre-2, post-1, and post-2 periods ($P > 0.05$). During continuous exercise, the MF value decreased significantly in post-1 compared to pre-1 ($P < 0.05$).

Table 4
Change in Thigh Muscle Group Median Frequency Value Before and After Resistance Deep-squat Exercise

Muscle	Intermittent mode	Period				P-value (Interaction effect)	P-value (Time main effect)
		Pre test-1	Pre test-2	Post test-1	Post test-2		
Rectus femoris	Continuously	66.21±11.47	65.17±11.07	57.13±6.43*Δ	65.00±7.94#	0.011	0.028
	Intermittently	65.15±11.22	64.13±11.40	60.10±8.28	63.90±7.50		
Vastus medialis	Continuously	58.22±5.96	59.50±5.70	52.11±5.22*Δ	58.83±5.80#	0.037	0.040
	Intermittently	56.74±6.70	57.47±5.66	52.07±6.27	55.61±6.07		
Vastus lateralis	Continuously	60.92±6.45	61.17±6.46	56.03±5.07*Δ	59.58±7.23	0.035	0.047
	Intermittently	58.88±4.62	59.04±6.45	57.07±4.53	59.58±7.23		
Biceps femoralis	Continuously	62.97±10.13	60.75±9.80	64.68±12.24	63.36±9.59	0.748	0.102
	Intermittently	64.92±8.18	62.25±7.17	66.68±11.44	63.36±9.59		
Semitendinosus	Continuously	65.67±13.22	65.31±9.75	69.54±8.58	67.30±11.11	0.804	0.097
	Intermittently	67.73±13.02	66.20±9.25	69.51±9.60	67.17±7.89		
Gluteus maximus	Continuously	42.62±4.65	41.16±3.71	37.31±3.98*	40.99±4.69	0.043	0.019
	Intermittently	44.52±3.96	43.12±3.28	45.27±5.62	44.97±7.25		

Note: * indicates that pre-2, post-1, and post-2 are significantly different from pre-1; △ indicates a significant difference between post-1 and post-2 compared with pre-2; # indicates that post-2 is significantly different from post-1.

Characteristics of changes in activation of lower limb muscle groups by compression weight-bearing squat exercises

As shown in Fig. 2, under the intermittent modes of continuous pressure and depressure, in sets 1–4, the activation of the rectus femoris, vastus medialis, vastus lateralis, biceps femoralis, semitendinosus, and gluteus maximus increased compared with the initial stage (pre-2); additionally the activation of the rectus femoris, biceps femoralis, and semitendinosus increased significantly in the third and fourth sets ($P < 0.05$). Vastus lateralis activation increased significantly only in the fourth set ($P < 0.05$), while vastus medialis activation increased significantly in the fourth set of continuous practice and the third set of intermittent practice ($P < 0.05$). The activity of the gluteus maximus did not change significantly between the first and fourth sets in either continuous compression or intermittent compression ($P > 0.05$).

Discussion

Analysis of the change characteristics of the thigh muscle groups' maximum activation before and after the compression squat exercise

The results in Table 2 show that the RMS_{MVC} values of the rectus femoris, vastus medialis, and vastus lateralis decreased after compression removal. The RMS_{MVC} values of the rectus femoris changed significantly after continuous compression ($P < 0.05$), while those of the vastus medialis and vastus lateralis showed no significant change ($P > 0.05$). Most previous studies showed that after the implementation of blood flow restriction training, the maximum activation of active muscles restricted by blood flow had a downward trend. Loenneke et al. [18] performed compression and non-compression one-knee stretching exercises with the quadriceps as the main active muscle group in 16 healthy adult males and found that the MVC value of the quadriceps muscle decreased after the compression and non-compression leg exercises. Umbel et al. [26] found that the MVC value of centripetal contraction decreased by 9.8%, and the MVC value of centrifugal contraction decreased by 3.4% after 24 h of unilateral compression knee stretching exercise and returned to normal after 96 h, which may be related to delayed onset muscle soreness. Fatela et al. [27] performed compression knee stretching exercises with different blood pressure limits in 14 adult males and found that the vastus medialis and vastus lateralis' RMS_{MVC} values decreased significantly after exercise under 60 and 80% BFR relative blood pressure limits. This study found that compared with knee stretch exercise, the pressurized squats exercise can lead to reduced quadriceps activation; additionally, compared with the intermittent exercise continuous pressurized squats exercise it led to more reduction, which may be linked to activity of the muscle cell metabolites caused by excessive accumulation of acidosis.

In addition, the results in Table 2 also showed that the RMS_{MVC} values of the biceps femoralis and semitendinosus increased after the compression squatting program, and there was a significant change after the interval training. However, the RMS_{MVC} value of the gluteus maximus decreased and significantly changed after continuous pressure interval exercise. The results showed that the RMS_{MVC} of the posterior thigh muscle showed an increasing trend after compression squat exercises. Yasuda et al. [28] also found that the activation contribution rate of the triceps brachii as an antagonistic muscle increased from 40–60% after 30%-1RM multi-joint compression bench press exercise, suggesting that compression exercise can improve the maximum independent activation rate of antagonistic muscles and thus effectively develop the strength of antagonistic muscle group compared with non-compression multi-joint exercise. The results also showed that RMS_{MVC} values of the biceps femoralis and semitendinosus increased significantly after blood flow restriction training. This indicated that blood flow restriction training can provide an optimal acidic environment to activate fast muscle fibers in the posterior thigh muscle group and induce more muscle fibers to activate.

Analysis of changes in the activation degree of thigh muscle groups before and after compression squat exercises

Many studies have confirmed that the RMS value of active muscles increases during low-intensity compression exercises. After the exercises, the RMS values of the anterior and posterior thigh muscle groups were higher than those before compression exercises. During continuous compression exercises, vastus lateralis, biceps femoralis, and semitendinosus were significantly improved. After the compression band was removed, the RMS values of the anterior and posterior thigh muscle groups decreased compared with the RMS values of the period before the compression at the end of the implementation of the compression program but were higher than the RMS values before compression.

The above results show that after the implementation of the compression program, the activation of the thigh's anterior and posterior muscle groups increased. It is mainly caused by the acidic environment resulting from the accumulation of metabolites in the muscle, which can generate more type II muscle fibers, thus increasing the average amplitude of the electromyographic signal on the surface [29]. Fatela et al. [27] also found that rectus femoris and vastus medialis activation changed with external blood pressure limitation during compression knee stretching exercises. Acute external pressure stimulation increased the RMS values of the rectus femoris and vastus medialis; nevertheless, the vastus medioris and rectus femoris responded differently to different external pressure stimulations. Vastus medialis activation was significantly increased in 60 and 80% BFR external pressure restriction conditions before blood flow restriction training (post-1) compared to pre-2. The activity of the rectus femoris increased significantly only under 80% RFR, suggesting that higher blood pressure restriction can induce a reflex increase in vastus medialis and rectus femoris activation. The results also showed that the vastus lateralis, biceps femoralis, and semitendinosus had similar characteristics of change before and after compression with continuous and intermittent practice under constant external pressure limits and that the vastus lateralis, biceps femoralis, and semitendinosus, interval exercises significantly increased vastus medialis activation. In addition, the results in Table 3 show that the activation of the gluteus maximus was significantly reduced after bandaging. It was comparable to that after bandaging at the end of the treatment and did not return to pre-compression levels after intermittent depressurization. Sun et al. [30] concluded that low-intensity compression and hard pull exercises can increase the activation degree of the distal muscles with limited blood flow and the proximal muscles with no limited synergistic function. This study showed that low-intensity compression squats reduced the activation of the gluteus maximus, suggesting that different compression exercises had different effects on the activation of unrestricted proximal coordination muscles.

Analysis of changes in fatigue degree of thigh muscle groups before and after compression squat exercises

Indicators reflecting muscle fatigue are usually expressed by the MF, and the decrease in the MF value is strongly correlated with the decrease in the swing rate of the muscle bridge [31]. Place et al. [32] confirmed that the degree of intramuscular acidity and the reduction of Ca^{2+} absorption by the sarcoplasmic reticulum are the main factors affecting the decline in muscle contraction function. The results in Table 4 show that the MF values of the rectus femoris, vastus medialis, and vastus lateralis decreased before the end of compression training in both continuous compression mode and intermittent compression mode, and there were significant differences after continuous compression mode. It is suggested that the primary muscle in the front group of the thigh is the main force-generating muscle group, which leads to excessive accumulation of metabolites such as lactic acid in the muscle during the weight-bearing exercise in the continuous pressure mode. This results in acidity changes, reduced Ca^{2+} absorption by the sarcoplasmic reticulum, and ultimately, accelerated muscle fatigue.

After a short rest of 1 min after decompression, the MF values of the three muscles in the front thigh group have recovered to the pre-compression level. This indicates that the functional decline of the muscle caused by the two programs at 50% AOP level is temporary, and it can be restored to the level before compression after a short rest with decompression. In addition, Pierce et al. [15] pointed out that 60%AOP of continuous compression knee extension exercise can cause a significant reduction in the vastus lateralis and rectus femoris' MF values. Neto et al. [33] also performed a set of 80%1RM high-intensity compression squats with 60%AOP blood pressure limitation, and the results showed that the MF values of the vastus medialis and vastus lateralis decreased by 18.5 and 18.2%, respectively. Previous studies have shown that blood flow restriction training induces fatigue mainly by stimulating protein synthesis of the Akt/mTOR signaling pathway, and the decrease in MF values is sensitive to biochemical changes in type II muscle fibers [34].

Combined with the above results, it can be concluded that neuromuscular fatigue is affected by the intermittent mode and the external pressure-limiting intensity. A higher pressure-limiting intensity will cause greater fatigue and slower recovery speed. In addition, Table 4 shows that the MF values of the biceps femoralis and semitendinosus increased before pressure removal at the end of pressure training in both modes and returned to the level before pressure removal 1 min later. This also suggests that both continuous and intermittent modes of load-bearing compression squat exercise can largely promote the activation of the posterior thigh muscle group, ensure that the neuromuscular component is at a suitable level of excitement, ensure the high synchronization of motor neuron discharge, and then promotes the reflex improvement of contraction force. In addition, the two modes of weight-bearing compression exercise had different effects on muscle fatigue in the unrestricted area. The gluteus maximus MF decreased significantly after continuous compression exercise but recovered shortly after decompression, while intermittent compression exercise had less effect on the gluteus maximus MF. It does not cause fatigue in the gluteus maximus.

Analysis of the change characteristics of the activation degree of lower limb muscle groups in each set of compressive weight-bearing squat exercises

As shown in Fig. 2, anterior thigh muscle group activation was higher during all four sets of compression squats than before the experiment, suggesting that the rectus femoris, vastus medialis, and vastus lateralis were activated to varying degrees during each set of compression. The acidic environment created after the application of pressure stimulation can attract more fast muscle fibers to participate in the activity so that the discharge frequency of fast muscle motor units gradually increases. The RMS value of the rectus femoris in the third and fourth sets was significantly higher than that in the initial set. Vastus medialis RMS values were significantly higher in the second set of continuous mode practice and the third set of intermittent mode practice than at the initial stage ($P < 0.05$), and the vastus lateralis values were significantly higher in the fourth set of both modes of practice than at the initial stage ($P < 0.05$). Counts et al. [35] found that the degree of activation of the biceps brachii during an elbow flexion exercise was not affected by external limit blood pressure. High-and low-limit blood pressure had similar adaptive effects on muscle hypertrophy, strength, endurance, and other aspects, but high-limit blood pressure would produce higher discomfort. In addition, Dandel et al. [36] found that adding BFR to interval of high-intensity elbow flexion training could not promote the activation of the biceps brachii and cause muscle hypertrophy. It has been suggested that blood flow restriction during low-intensity squat exercises can promote muscle activation and cause a hypertrophic response. The results of this study, similarly to previous studies, showed that continuous and intermittent exercises of the upper and lower extremities with moderate intensity blood pressure limitation could effectively improve the activation degree of the prime muscle and reduce discomfort.

Figure 2 shows that biceps femoralis and semitendinosus activation was significantly higher in the third and fourth sets than at the beginning of the weight-bearing exercises. However, activation of the gluteus maximus increased in the first set. Activation in the second, third, and fourth sets gradually declined, indicating that both continuous and intermittent blood flow restriction training will not only improve the thigh before the group of the original dynamic degree of muscle activation, but also improve the state of no pressure and rarely participate in and mobilization of the stocks after the muscle group, such as antagonist muscle activation degree. This can improve the thigh muscle group compared to flexion and extension and help prevent sports injuries. In addition, Abe et al. used 20% 1RM for compression squats, believing that, due to the low training intensity and the unrestricted position of the gluteus maximus, such load would not cause gluteus maximus hypertrophy [37]. However, there may be synergies between the thigh and buttocks in squat exercises. This study showed that the gluteus maximus was complementary, and its activation increased significantly when the anterior thigh group was relatively low during pressure exercise. In the second, third, and fourth exercise sets, the activity of the anterior thigh muscles gradually increased, while the activity of the gluteus maximus gradually decreased. This may be because the gluteus maximus extends the hip while the quadriceps muscle mainly extends the knee. The two muscles may be complementary in function to some extent as the adjacent active muscles of the important lower limb motor chain and the gluteus maximus may recruit more motion units to supplement the quadriceps deficit. This demonstrates that 50% AOP compression during weight-bearing squat training can induce more significant muscle group activation in the front and back of the legs, while gluteus maximus stimulation was not significant for hip extension. The authors believe that the main reason is that the compression site mainly plays a major role in lower limb blood flow occlusion but has little effect on the gluteal muscle. At the same time, lightweight squatting exercises may not significantly affect the gluteus maximus, and further extensive hip extension or increased weight-bearing strength to 85% or more may induce greater gluteus maximus activation.

Limitations

Due to the limitations of research conditions, considering the daily training of sports teams, the accumulated effects of the athletes' other physical and technical training may have interfered with the subsequent tests to a certain extent and affected the accuracy of the acquired EMG data. In addition, the study did not measure the blood concentrations of lactic acid, creatine phosphate, or other blood metabolites or the participants' subjective physical effort level. To meet the need for training practice, future studies should combine the methods of electric index blood physiological and biochemical indicators and subjective indicators, which could comprehensively evaluate the mechanism and effect of blood flow restriction training .

Conclusions

In 50% AOP compression squats under 30% 1RM, the acute activation of thigh muscle groups was different between continuous compression interval training and decompression interval training. The degree of of thigh muscle groups activation induced was greater in continuous compression interval training than in decompression interval training. RMS values of all muscle groups except the vastus medialis increased significantly after training in the third and fourth sets, but fatigue also occurred. In contrast, although the intermittent mode of pressure removal produces fatigue, recovery is faster. Therefore, the use of a continuous pressure training mode is recommended for trained athletes and an intermittent pressure training mode for beginners.

Abbreviations

1RM, one-repetition maximum; %AOP, percentage of arterial occlusion pressure; ANOVA, analysis of variance; BFR, blood flow restriction; EMG, electromyography; MF, median frequency: MVC, maximum voluntary contraction; RMS, root mean square; RMS_{MVC}, RMS value under MVC.

Declarations

Ethics approval and consent to participate

The study was approved by Fuzhou University Human Research Ethics Committee (LLWYH20200269) and all aspects of the study were conducted in agreement with the Declaration of Helsinki. All of the participants were fully informed about the purpose and experimental procedures of the study. Informed consent was obtained prior written from each participant. The participants were informed that all data collected would be processed anonymously.

Consent for publication

All participants were informed about the experimental nature of the study and gave their written informed consent for the publication of relevant data.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YW, ZL, and TC conceived and designed research. TC and ZL conducted experiments and facilitated the data collection. YW undertook the data analysis and drafted the manuscript. YW completed the writing of the manuscript. YW, ZL, and TC reviewed and provided comments on the manuscript. All authors read and approved the final manuscript.

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Figures

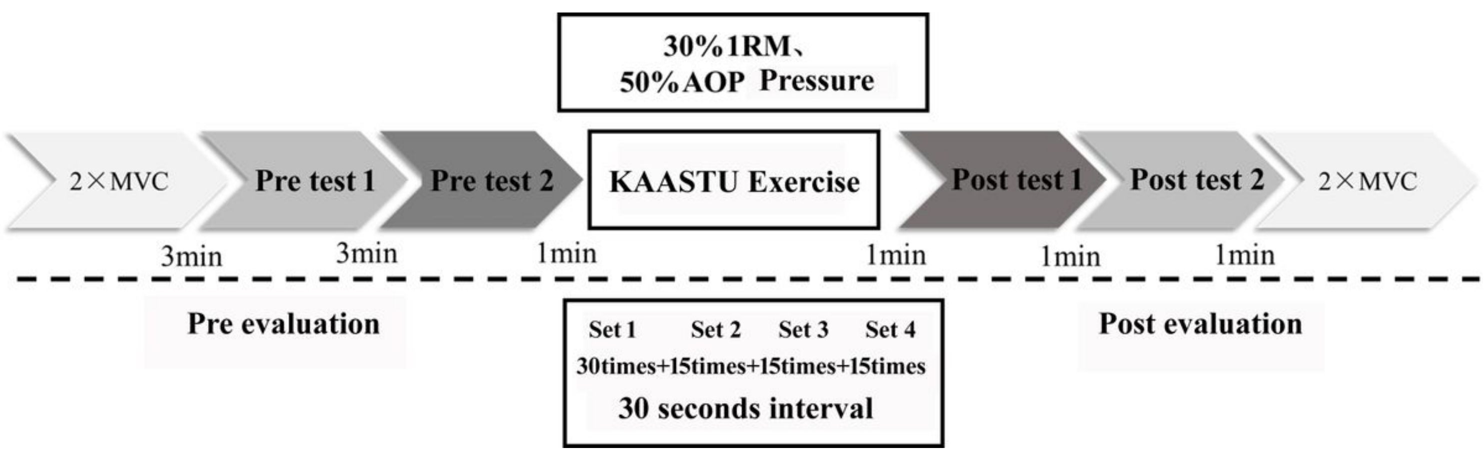

Figure 1

Study flow chart

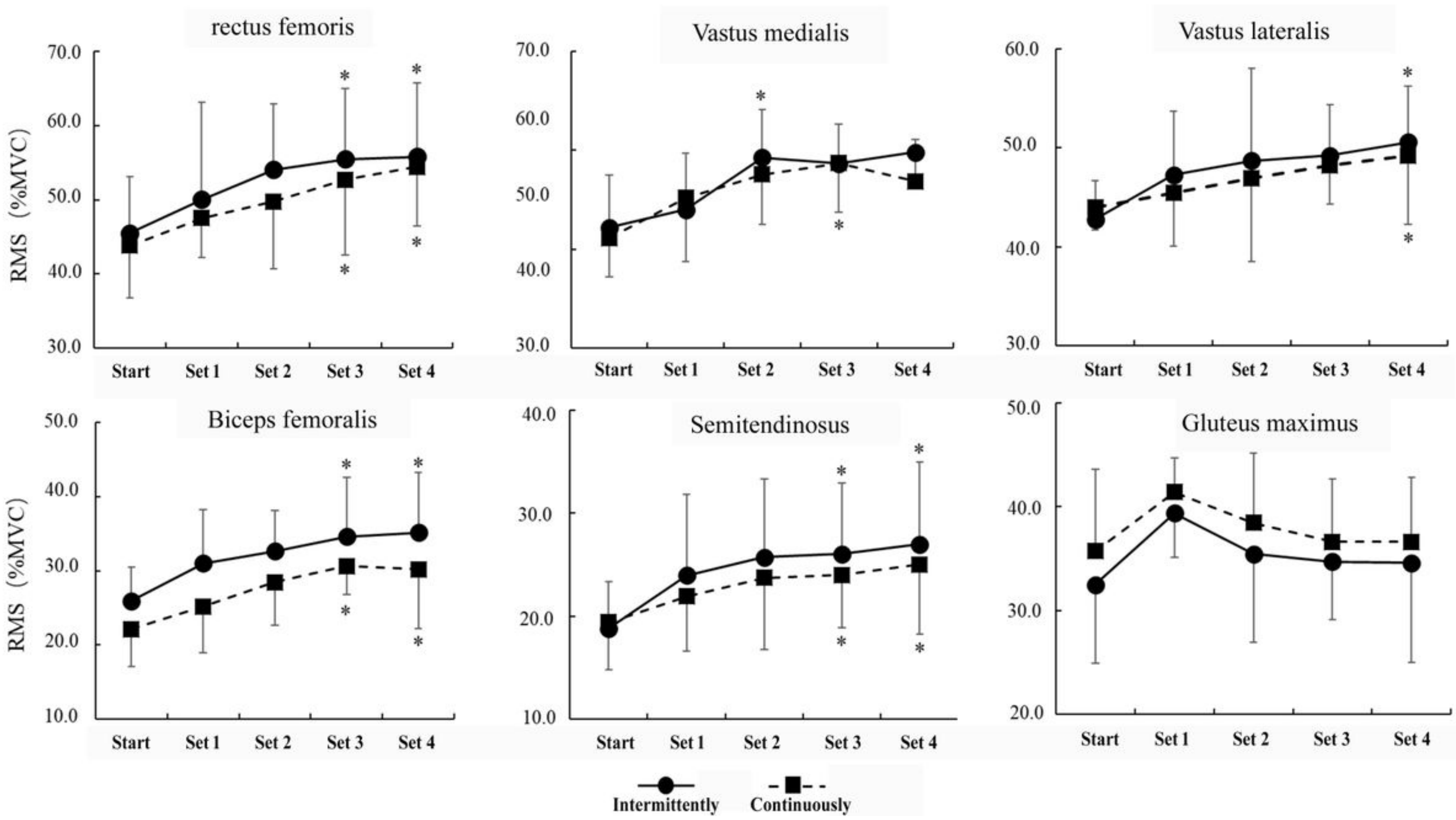

Figure 2

Thigh muscle group change in RMS (%MVC) during the Resistance deep-squat exercise. * indicates significant differences between sets 1, 2, 3, and 4 compared with the beginning period.