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Research article

Semi-Squat Exercises with Varying Levels of Arterial Occlusion Pressure during Blood Flow Restriction Training Induce a Post-Activation Performance Enhancement and Improve Vertical Height Jump in Female Football Players

Depeng Sun [1,2]✉ and Tieli Yang [1]
[1] Graduate department, Capital university of Physical Education and Sports, Beijing 100191, China; [2] Department of PE, Xi'an University of Finance and Economics, Xi'an 710100, China

Abstract

Low-load blood flow restriction training (BFRT) has been shown to induce a significant increase in muscle activation. However, low-load BFRT to augment the post-activation performance enhancement (PAPE) has not been previously examined. This study aimed to examine the PAPE of low-intensity semi-squat exercises with varying pressure BFRT on vertical height jump performance. Twelve elite athletes from the Shaanxi Province women's football team volunteered to participate in this study for 4 weeks. Participants completed four testing sessions that included one of the following at random: (1) non-BFRT, (2) 50% arterial occlusion pressure (AOP), (3) 60% AOP, or (4) 70% AOP. Muscle activity of the lower thigh muscles was recorded using electromyography (EMG). Jump height, peak power output (PPO), vertical ground reaction forces (vGRF), and rate of force development (RFD) were recorded for four trials. Two-factor repeated measures analysis of variance (ANOVA) showed that semi-squat with varying pressure BFRT had a significant impact on the measured muscle EMG amplitude and MF value of vastus medialis, vastus lateralis, rectus femoris, and biceps femoris ($P < 0.05$), and MF value decreased with increasing pressure. Muscle activation (EMG amplitude) did not change further. The EMG amplitude of the gluteus maximus was significantly decreased by semi-squat training with different pressures ($P < 0.05$), while that of the gluteus maximus muscle was gradually increased by non-BFR with semi-squat training ($P > 0.05$). The 50% and 60% AOP BFRTs significantly increased jump height, peak power, and force increase rate (RFD) after 5 min and 10 min of rest ($P < 0.05$). This study further confirmed that low-intensity BFRT can significantly increase lower limb muscle activation, induce PAPE, and improve vertical height jump in female footballers. In addition, 50% AOP continuous BFRT is recommended for warm-up activities.

Key words: BFR Training, Post-activation performance enhancement, Vertical jump performance, sporting performance, Temporal profile

Introduction

Football is a high-intensity 90-min game during which athletes perform a variety of explosive movements such as kicking, tackling, jumping, turning, and sprinting and experience tempo changes (Bangsbo et al., 2006). Therefore, skeletal muscle strength, power, and contraction speed are critical for changing direction, accelerating, and jumping during a football match (Reilly et al., 2000). Lower limb muscle strength is significantly associated with vertical jump height performance (Wisloff et al., 2004). In addition, some studies have confirmed that team success is significantly associated with the average jump height and lower limb power of football athletes (Arnason et al., 2001). Long-term training improves the athletic performance of football players, but warm-up activities can lead to short-term or acute improvements in athletic performance. Current football-related warm-up activities include static and dynamic stretching, neuromuscular activity, and acute heavy-resistance exercises, which may induce a post-activation performance enhancement (PAPE) (O'Grady et al., 2021; Wu et al., 2019).

Post-activation performance enhancement (PAPE) is a phenomenon through which muscle performance is acutely enhanced due to random muscle contraction stimuli under specific conditions (maximal or near maximal intensity) (O'Grady et al., 2021; Hodgson et al., 2005; Robbins, 2005), leading to improved athletic performance caused by muscular contractile patterns (Sale, 2002). The contraction stimulus that induces PAPE is called conditioning activity (CA) (Tillin and Bishop, 2009). The specific physiological mechanisms that induce PAPE are still unclear. However, the mechanism underpinning post-activation potentiation has been mainly explained by phosphorylation of myosin regulatory light chains (RLC), the recruitment of high threshold motor units and neural firing rates, and the alteration of the pinnation angle (Hodgson et al., 2005; Robbins, 2005; Liang et al., 2020; Liu, 2017). PAPE is probably associated with changes such as increased muscle temperature, fiber water content, and muscle excitation (Blazevich and Babault, 2019). However, the mechanisms underpinning post-activation potentiation cannot be ignored. In addition, muscle stiffness may contribute to PAPE (Krzysztofik et al., 2022), although evidence regarding this contribution is inconsistent. To maximize the PAPE, two crucial factors should be considered: the similarity in movement pattern between the CA and subsequent performance, and the balance between fatigue and potentiation. Neuromuscular fatigue and potentiation may co-exist after CA stimulation, and the balance between fatigue and potentiation will determine whether subsequent contractile performance is enhanced, weakened, or unchanged (Robbins, 2005). When potentiation exceeds fatigue and dominates, subsequent muscle contraction strength and power output increase, and vice versa (Hamada et al., 2003). Coaches and researchers use various training methods to achieve optimal subsequent contractile performance

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by reducing fatigue with simultaneous persistence in potentiation. High-intensity resistance training (≥80% of One Repetition Maximum, 1RM) is the most used method to induce PAPE (Seitz and Haff 2016). However, this method has the inconvenience of carrying heavy training equipment to the exercise yard. Recently, low load, short duration, and high efficiency blood flow resistance training (BFRT) has received increasing attention from coaches, athletes, and health enthusiasts. In addition, BFRT has been commonly promoted and applied in athletic training. Researchers have confirmed that BFRT can lead to similar effects as traditional high-intensity resistance training in muscle hypertrophy and strength (Wu et al., 2019). Another study confirmed that neuromuscular activity (assessed using surface electromyography [EMG]) was similar between low-intensity BFRT and traditional high-intensity resistance training, indicating that both training modalities have similar effects on the recruitment of type II muscle fibers (Pan et al., 2019; Moritani et al., 1992, Moore et al., 2004; Shinohara et al., 1997).

BFRT refers to the application of external pressure to the proximal root or "basement" of the extremities using an external compression device (such as a compression belt or tourniquet) to restrict the inflow of arterial blood and prevent the return of venous blood, creating a special and excellent environment for the exercising of muscles (Wei jia et al., 2019a). Blood flow is important for oxygen transport to the muscles during exercise (Andersen and Saltin, 1985). During exercise, when the force generated by muscle contraction exceeds 20% of maximal voluntary contractions (MVC), the pressure in the muscle increases, which limits the inflow of arterial blood and the return of venous blood and can increase accumulation of blood lactate and accelerate muscle fatigue (Bonde-Petersen et al., 1975). During BFRT, the restricted muscle is stimulated by both skeletal muscle contraction and external compression pressure, resulting in a significant increase in vascular pressure at the restricted site, which limits arterial blood flow to the distal limb and prevents venous blood return, leading to an increase in metabolic "overload" and hypoxia, and accelerating slow twitch fibers fatigue (Li et al., 2021). In addition, non-BFR muscle contraction (20-30% MVC) can reduce MVC and muscle activation, but low-intensity BFRT can gradually increase muscle activation. These studies confirm that BFRT can restrict oxygen supply to slow twitch fibers, accelerating slow muscle fiber fatigue, and can cause fast twitch fibers to be recruited earlier, resulting in increased muscle activation (Moritani et al., 1992). The recruitment of high threshold type II muscle fibers is an important mechanism for PAPE (Tillin and Bishop, 2009). Therefore, BFRT may induce PAPE. The main aim of this study was to examine whether different BFRT pressures can induce PAPE and to elucidate the mechanism through which different BFRT pressures influence the electromyography of skeletal muscles. This study also investigated the effect of different BFRT pressures with and without PAPE on the vertical jump height, peak power output (PPO), vertical ground reaction forces (vGRF), and rate of force development (peak power/time, RFD) using semi-squat exercises with BFRT. We hypothesized that BFRT with 50% AOP can induce PAPE and improve vertical jump height performance.

Methods

Subjects

The participants were 12 elite soccer players from the Shaanxi Province women's football team who had undergone more than 3 years of lower limb resistance training, were cleared of any lower extremity injury for at least six months, had not undergone strenuous exercise 48 h before the experiment, and had not consumed caffeine within 3 h before the test. Basic information of the subjects given in Table 1. The participants were informed of the risks involved in performing the experiment and filled out an informed consent before the formal test. The study design and procedures were in accordance with ethical standards and the Declaration of Helsinki. Therefore, this study meets the ethical standards of the Journal of Sports Science and Medicine. Data collection commenced after receiving approval from Capital University of Physical Education and Sport.

Experimental approach to the problem

A two-factor repeated-measures experimental design with pressure (between-group factor) and time (within-group factor) was used to investigate whether different BFRT pressures could improve the PAPE during vertical jump. Participants underwent one familiarization session and four trial sessions. Three trial sessions served as the experimental phase (50% AOP & 60% AOP or 70% AOP; experimental group) and one session served as the control phase (non-BFR; control group). The participants randomly selected sessions at the beginning of the experiment and were subsequently removed to prevent duplicate testing. Participants completed three Counter Movement Jump (CMJ) and Squat Jump (SJ) prior to each trial (PRE), rested for10 min, and then performed four additional CMJs and SJs after (POST) the participants had rested for 15 sec, 5 min, 10 min, and 15 min (POST1, POST2, POST3, and POST4). EMG amplitude and MF value were collected during semi-squat, and vertical jump height, peak power output (PPO), vertical ground reaction forces (vGRF), and rate of force development (RFD) for PRE, POST1, POST2, POST3, and POST4 were averaged for each participant and then used for statistical analysis. To account for fatigue and allow full recovery, the trial interval between sessions was 72 h. All trials were performed at the same time of the day to minimize the effect of circadian rhythms.

Table 1. Basic information of participants (n = 12).

Age, year	Height, m	Weight, /kg	BMI	1RM, kg	30%1RM	Binding pressure, mmHg
18.34 ± 1.88	1.67 ± 0.04	58.37 ± 7.41	21.93 ± 1.03	99.54 ± 10.77	33.18 ± 3.59	40

BMI: body mass index.

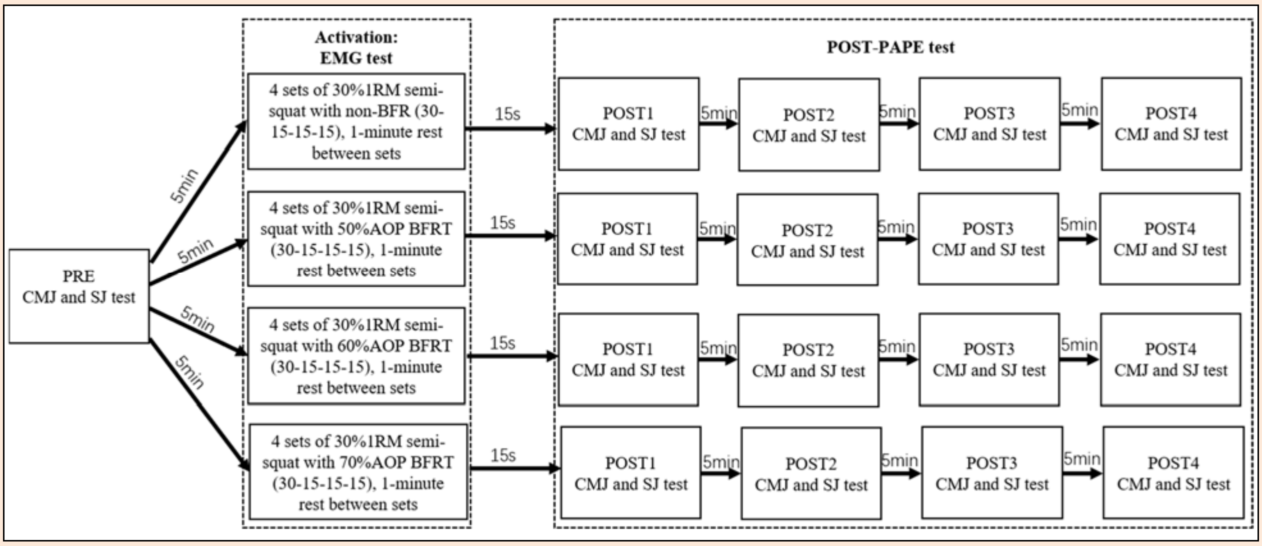

Figure 1. Experimental design of the study. BFRT: Low-load with blood flow restriction training; RM: Repetition maximum; AOP: Arterial occlusion pressure; CMJ: Countermovement jump; SJ: Squat jump.

Training procedure

A total of five visits were completed by each participant. The first visit was familiarization with each experimental protocol. The participants completed three experimental groups (50% AOP & 60% AOP or 70% AOP) and one non-BFR (Figure 1), respectively. The group used a portable intelligent pressurized training device (KAATSU SMART) from Beijing Yijia Yuan Sports Technology Development Co., Ltd. The width of the cuff was 5 cm, the cuff was bound to the upper-middle third of the thigh with a binding pressure of 40 mmHg and perpendicular to the longitudinal axis of the thigh. Arterial Occlusion Pressure (AOP) was determined in participants according to the following formula: AOP (mmHg) = {5.893 x right thigh circumference (cm) + 0.734 x diastolic blood pressure (DBP) + 0.912 x systolic blood pressure (SBP) - 220.046}. Muscle fatigue was highly correlated with relative pressures including 40%, 60%, and 80% AOP during knee extension exercises. In addition, a higher pressure (80% AOP) can induce greater muscle fatigue and rate of perceived exertion, and a lower pressure (40% AOP) cannot induce significant muscle activation (Fatela et al., 2016). According to the literature, lower or moderate pressures (50% AOP) were more effective than higher pressures (at or near arterial obstruction), which shows pressure had an "inverted U" relationship with the effect of BFRT (Loenneke et al., 2014). Therefore, this study used 50% AOP, 60% AOP, and 70% AOP for the experimental groups. Brachial systolic (bSBP) and diastolic (bDBP) blood pressure were measured using a KANGKANG blood pressure measuring device (Beijing Kangkang Shengshi Information Technology Co., LTD). Blood pressure was taken in duplicate, which were averaged for analysis. With the participant standing, the pressure was set to 50 mmHg for 30 sec, and then released for 10 sec. This cycle was repeated with an additional 20 mmHg on each inflation until the final pressure was attained for 50% AOP, 60% AOP, or 70% AOP. According to Patterson et al. (2019), this study used a 30% 1RM load and 4 sets/75 reps (30 - 15 - 15 - 15) with a 60-sec interval time. The cuff pressure was maintained continuously throughout the semi-squats, including inter-set rest periods, but was released and removed immediately following the final set of semi-squats. The non-BFR group used 30% 1RM semi-squats and 4 sets/75 reps (30 - 15 -15 - 15), with 60-sec intervals between sets and no pressure during the semi-squats.

Maximum strength test (1RM)

The 1RM for back squat was determined by a standardized protocol. Prior to the test, each participant completed a warm-up involving 10 min of self-selected cycling on a cycle ergometer (ergoselect 4, ergoline GmbH, German). After resting for 5 min, each participant completed 5 to10 repetitions at the 40% - 70% estimated 1RM, with 2 min of rest between each load. The participants subsequently rested for 3 min and performed 1 repetition at a 90% estimated 1RM. If this stage was successful, the investigators increased the load based on the participant's perception of the previous attempt. If this attempt with increased load was unsuccessful, the last successful attempt defined the participant's 1RM (Jo et al., 2009). During all the attempts, each participant was required to squat to a depth at which a 90° knee angle is achieved. The participants were allowed three days resting between the 1RM procedure and the first data collection session.

Vertical jump test

Vertical jump (CMJ and SJ) was used to assess lower limb performance, which is one of the effective and reliable indicators to evaluate the lower limb power of football players and an important guarantee for football players to compete for heading (Stolen et al., 2005). The success of the football game is significantly correlated with the average jumping height of players and the power of lower limb extension (Arnason et al., 2001). A force plate was used for the kinetic analysis of the vertical jump. The kinetic system included a 3D force platform (Kistler 9287C, Switzerland), an instrument amplifier, and a personal computer using customized software sampling at 1,000 Hz. The participants followed the tester's command to "get on the force platform," return the force platform to the "0" setting, and complete the data "de-weighting." To minimize the effect of upper limb swing on the test results, the participants were required to keep their hands at their waist during the test. For the SJ test, the participants were instructed to squat with thighs parallel to the ground, maintaining the position for 3 sec, and then jump up quickly. For the CMJ test, the participants were instructed to squat quickly to the lowest possible level and then jump up quickly. Participants were instructed to place their feet shoulder width apart at the center of the Kistler 3D force platform for each trial. From the vertical force trace during each jump, variables including vertical height (VH), vGRF, PPO, and RFD were calculated. The vertical jump height is calculated as the time the body stays in the air. Time is calculated as the difference between the moment of takeoff and moment of landing. Jump height is then obtained using the equation: $VH = 1/2g(t/2)^2$, where t is the time during which the body is in the air and $g = 9.81m/s^2$ (Aragón, 2000). The vertical jump test was performed 3 times each at PRE, POST1, POST2, POST3, and POST4 (Figure 1), the best one was used for statistical analysis.

Surface electromyography (EMG) test

Electrodes were placed based on Li (2015) recommendations, followed by continuous recording from the right Rectus Femoris (RF), Vastus Medialis (VMO), Vastus Lateralis (VLO), Biceps Femoris (BF), Gluteus Medius (Gmeds), and Gluteus Maximus (GM) throughout the semi-squats, using preamplified electrodes with a gain of 300 times and with band-pass filtered between 12 and 3,200 Hz. Before electrodes were placed, the skin was cleaned and wiped with 75% medical alcohol to minimize skin impedance. The electrodes sheet was pasted on the most protuberant part of the abdominal muscle and fixed with bandages. All electrodes were taped down to prevent movement of the electrodes. The EMG signals were selected by Cometa Wave Plus (Cometa Wave/Wave Plus Italy) for each group during the semi-squat based on the simultaneous video recording of the test. The raw EMG data were rectified, filtered, smoothened, and normalized using an Emgserver software. The root mean square (RMS) standard value and median frequency (MF) values were used for statistical analysis.

Statistical analyses

Descriptive statistics (mean ± SD) were calculated for all participants. All data were analyzed using the SPSS software version 21 (SPSS Inc., Chicago, IL, USA). Two-way repeated-measures ANOVA (pressure × time) was used to analyze the participants' baseline, 15 sec, 5 min, 10 min, and 15 min rest values for the potentiation% (vertical jump height at each time/baseline), the height, vGRF, PPO, RFD, RMS standard values, and MF values of the four groups obtained during the semi-squat. The Mauchly's sphericity test was performed, and if the test showed $P > 0.05$, the Huynh-Feldt condition was met, the sphericity hypothesis test result was accepted, and the one-dimensional ANOVA result was determined; if the test showed $P < 0.05$, the sphericity hypothesis was violated, and the Greenhouse-Geisser correction factor for degrees of freedom was used. The presence of interaction effects between between-group factors (pressure) and within-group factors (time) was also tested. In addition, the test data of different groups at the same time were tested using one-way ANOVA. Statistical significance was set a priori at $p < 0.05$.

Results

Two-way repeated measures ANOVA revealed significant pressure × time interaction for CMJ-potentiation% ($F(6.12, 57.14) = 2.98$, $p = 0.0.013 < 0.05$, $\eta^2 = 0.24$). The main effect for time was significant for CMJ-potentiation% t ($F = 123.74$, $p = 0.000 < 0.05$, $\eta^2 = 0.82$) and SJ-potentiation% ($F = 3.83$, $p = 0.047$, $\eta^2 = 0.12$). The main effect for pressure was significant for CMJ-potentiation% ($F = 4.47$, $p = 0.011$, $\eta^2 = 0.32$) and SJ-potentiation% ($F = 3.83$, $p = 0.047$, $\eta^2 = 0.12$; $F = 1.16$, $p = 0.04$, $\eta^2 = 0.11$) (Figure 2).

Two-way repeated measures ANOVA revealed significant pressure × time interaction for the RMS standard values of VMO, VLO, and GM ($p < 0.05$) and the MF values of VLO, BF, and GM ($p < 0.05$). The main effect for time was significant ($p < 0.05$) for the RMS standard values of VMO, VLO, RF, BF, and GM. The main effect for pressure was significant for the RMS standard values of BF ($p < 0.05$) and the MF values of RF, VMO, VLO, and BF ($p < 0.05$). The results of the one-way ANOVA showed that, except for the non-BFR group, the RMS standard values of VMO, VLO, RF, and BF increased significantly compared to Set1 ($p < 0.05$). MF values for VMO, VLO, RF, and BF decreased significantly ($p < 0.05$) in the Set4 semi-squat compared to Set1 during semi-squat with BFRT; the RMS standard values of GM decreased significantly ($p < 0.05$) in the BFR, but tended to increase in the non-BFR group ($p > 0.05$), and MF values for GM was decreased significantly ($p < 0.05$) in Set4 for the 70% AOP intervention. One-way ANOVA showed that standard values of VL, RF, and BF during the 50%, 60%, and 70% AOP pressure semi-squats were significantly different in Set4 compared to the non-BFR group ($p < 0.05$); compared to the 50% AOP, the RMS standard values of RF, VMO, VLO, and BF were significantly decreased during the 70% AOP ($p < 0.05$). Additionally, the MF values of VMO, VLO, RF, and BF was significantly different in Set4 ($p < 0.05$) compared to the 50% AOP (Table 2 and Table 3).

When comparing vertical jump performance measures between time points (i.e., PRE to POST4) and between 50% AOP, 60% AOP, and 70% AOP non-BFR conditions, a significant pressure × time interaction was found for CMJ height ($F(8.06, 75.21) = 3.27$, $p < 0.05$, $\eta^2 = 0.26$), CMJ-PPO ($F(6.94, 64.80) = 2.31$, $p = 0.04$, $\eta^2 = 0.20$), CMJ-RFD ($F(7.35, 68.63) = 4.17$, $p = 0.001$, partial $\eta^2 = 0.31$), and SJ-RFD ($F(5.99, 55.88) = 5.52$, $p < 0.05$), while there was no interaction effect for SJ height, SJ-PPO, CMJ-vGRF, and SJ-vGRF (Figure 3, 4, 5 and 6). Specifically, the 50% AOP condition exhibited significantly greater values for CMJ height (6.69%), SJ height (6.35%), CMJ-PPO (6.33%), SI-PPO (3.21), CMJ-RFD (2.35%), and SJ-RFD (2.31%) at 5 min resting compared to the non-BFR condition ($p < 0.05$). During the 50% AOP and 60% AOP conditions, CMJ height, SJ height, CMJ-PPO, SI-PPO, CMJ-RFD, and SJ-RFD were significantly greater at 5 min and 10 min resting compared to PRE. There were no significant differences across time points for these measures within the 70% AOP and non-BFR condition ($p > 0.05$; Figure 3, 4 and 5).

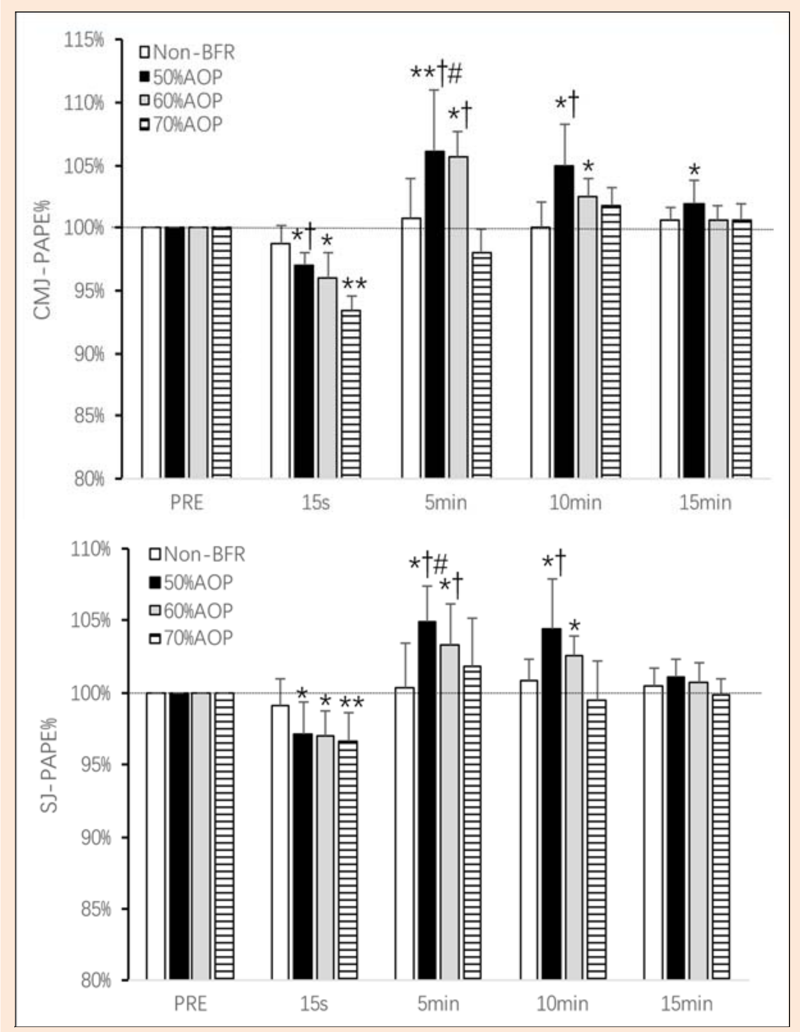

Figure 2. The potentiation time domain of different blood flow restricted training pressures. * significant difference compred to baseline at each time point, P < 0.05, ** denotes very significant difference, P < 0.01; # significant difference compared to the non-BFR group, P < 0.05; † significant difference compared to the 70% AOP group, P < 0.05. CMJ: Countermovement jump; SJ: Squat jump; PAPE: post-activation performance enhancement.

Discussion

PAPE depends on muscle activation induced by CA stimulation, which may further induce a reduction or an enhancement in subsequent performance (Wallace et al., 2019). Skeletal muscle shows opposing effects of fatigue and enhancement after CA, and both mechanisms coexist (Table 2 and Table 3) (Rassier and Macintosh, 2000). When enhancement after CA stimulation exceeds fatigue and predominates, muscle force and output power can be increased, and vice versa (Hamada et al., 2003). In addition, the time interval is an important factor in the generation of PAPE by CA stimulation. A rest interval that is too short may cause fatigue to exceed enhancement, and a rest interval that is too long may cause the enhancement to disappear, both of which are usually detrimental to the optimal PAPE. So far, studies on the interval duration that induces optimal PAPE after CA remain inconsistent. In general, short intervals (5 min), medium intervals (8-12 min), and long intervals (18.5 min) can induce PAPE after CA (Smith and Fry, 2007). Wilson et al. (2013) confirmed in a meta-analysis that the optimal interval duration may be related to the load of the CA protocol but results of most studies have suggested that medium interval (7-10 min) after CA may be the optimal interval for increased power output. The characteristics of participants may also be an important factor influencing PAPE. According to the literature, stronger athletes demonstrate a higher PAPE earlier during higher levels of training, and the different characteristics of the participants indicate rest interval (Seitz et al., 2014). This explanation is consistent with the findings of this study. The current study compared the PAPE of semi-squat between 50% AOP, 60% AOP, 70% AOP, and non-BFR conditions. The improvement in vertical jump measures during the 50% AOP or 60% AOP condition shows that the BFRT with 50% AOP or 60% AOP of the lower limb, compared to the 70% AOP or non-BFR condition, can induce a substantial PAPE stimulus despite equal workload. BFRT causes muscle hypoxia and requires more anaerobic metabolism, which leads to increased production of lactic acid, acceleration fatigue of slow fibers, and earlier recruitment of fast muscle fibers (Wei et al., 2019b; Moritani et al., 1992; Takarada et al., 2000; Liang et al., 2020). Recruitment of higher threshold fast fibers has been shown to be one of the underpinning mechanisms of PAPE (11). This study showed (Figure 2) that the BFRT with 50% AOP and 60% AOP (30% 1RM) can induce PAPE during 5 min and 10 min of rest (50% AOP > 60% AOP). This is consistent with the findings of Doma et al. (2020) that lower limb BFRT with 130% bSBP induced PAPE during 6-15 min of rest, which significantly improved jump height, flight time, and power. However, 70% AOP did not induce PAPE due to increasing fatigue by overpressure (Table 3 and Table 4). Another study showed no significant difference in acute vertical jump performance between BFR and non-BFR isometric squats combined with vibration conditions but showed a significant increase in power during isometric contraction under BFR conditions, which may be due to differences between the mode of intervention (static isometric contraction) and the deep jump (dynamic contraction) (Miller et al., 2018). This study suggests that the kinematic characteristics of CA are similar to those of the subsequent exercise mode to induce PAPE (Doma et al., 2016). To achieve optimal induction of PAPE during subsequent performance, the dynamic mode of CA intervention should be fully considered. Therefore, BFRT with 50% AOP is a more accessible and practical alternative to the traditional high-intensity (80% 1RM) semi-squat for inducing PAPE and enhancing acute dynamic performance. In addition, several studies have indicated that BFRT or high-intensity training can have parallel effects on the cross-sectional area of the patella tendon and on tendon stiffness. According to previous literature, high-intensity back squats could increase Achilles stiffness (Pozarowszczyk et al., 2018). However, several studies have indicated that CAs could decrease Achilles stiffness, which might be related to the changes in pennation angle and could explain performance enhancement (Wang et al., 2017). Achilles stiffness may contribute to PAPE, but it was not discussed in the study. Therefore, further studies on how BFRT influences Achilles stiffness are needed.

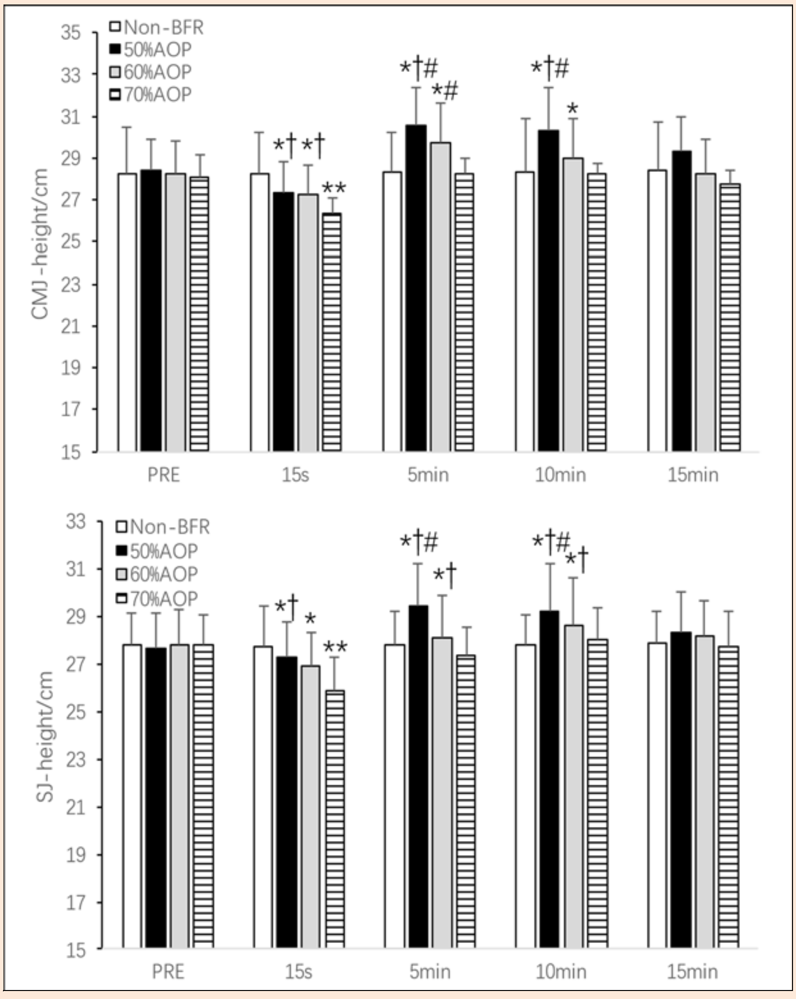

Figure 3. The flight height time domain of different blood flow restricted training pressures. * significant difference compared to baseline at each time point, P < 0.05, ** denotes very significant difference, P < 0.01; # significant difference compared to the non-BFR group, P < 0.05; † significant difference compared to the 70% AOP group, P < 0.05. CMJ: Countermovement jump; SJ: Squat jump.

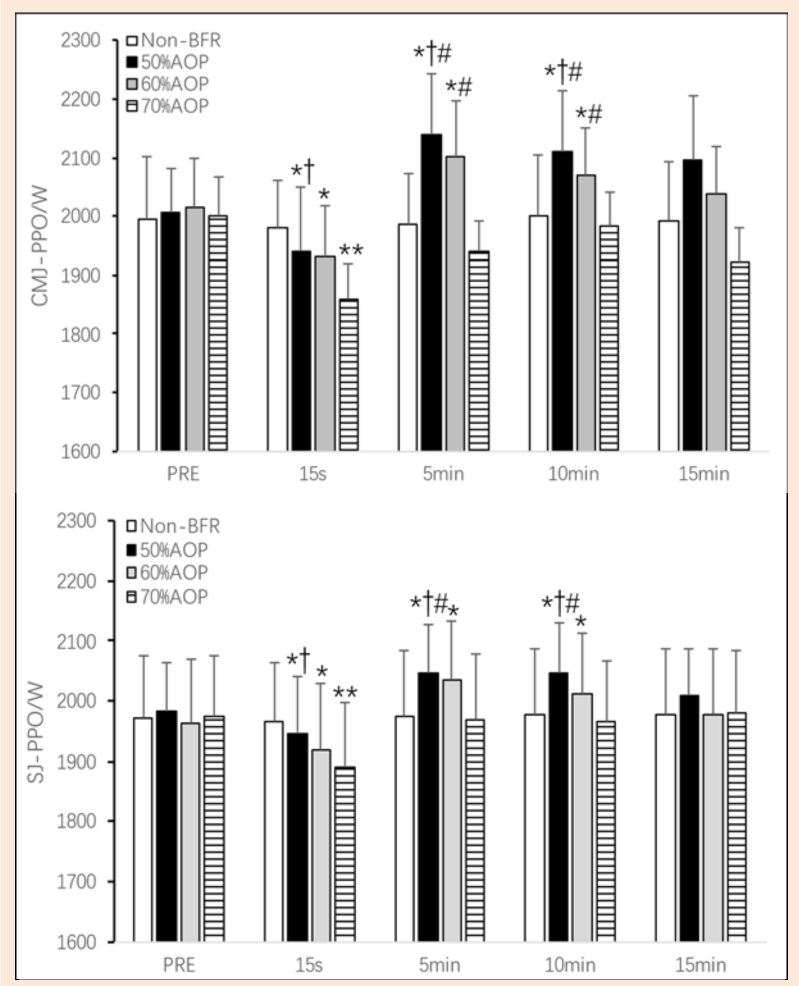

Figure 4. The peak power output time domain of different blood flow restricted training pressure. * significant difference compared to baseline at each time point, P < 0.05, ** denotes very significant difference, P < 0.01; # significant difference compared to the non-BFR group, P < 0.05; † significant difference compared to the 70% AOP group, P < 0.05. CMJ: Countermovement jump; SJ: Squat jump; PPO: peak power output.

The semi-squat movement is a multi-joint activity that involves the hip, knee, and ankle joints. The semi-squat movement requires the coordination and cooperation of the knee flexors and hip flexors and extensors for a rapid transition between concentric and eccentric contraction. Previous studies have confirmed that semi-squat movement can activate and improve the muscle activity of the major muscle groups of the lower limb (Caterisano et al., 2002). According to the EMG amplitude analysis, activation (RMS standard values) of the agonist and antagonist muscles of the lower limb using different occlusion pressure was similar. The RMS standard values of muscle (i.e., VM, VLO, RF, and BF) increased significantly in set4 compared to set1. Compared to the non-BFRT condition, the RMS standard values of the muscles in the lower limb during the semi-squat with BFRT were significantly higher, and the values increased as the sets progressed. This implies that the amount of oxygen delivered to the slow fibers of the lower limb muscles was insufficient, and the muscle was "overloaded" with metabolites (e.g., depletion of phosphocreatine stores and lower pH), which altered the relationship between energy supply and demand during muscle contraction, accelerating slow fiber fatigue and requiring the recruitment of more and larger threshold motor units to maintain the original muscle strength (Moritani et al., 1992; Takarada et al., 2000; Kilduff et al., 2007). There was no difference in RMS standard values of the lower limb muscles during the semi-squat in the 60% AOP and 70% AOP conditions, which shows that the muscle activation did not increase further with increasing external pressure. This result is consistent with that of Loenneke et al. (2015a) who reported a significant increase in muscle RMS standard values when BFRT was applied to the lower limb muscles (lateral femoral muscles) and the pressure was increased from 40% AOP to 50% AOP. However, the RSM standard values did not increase with a further increase in pressure from 50% AOP to 60% AOP. Our study result is not consistent with that of Counts et al. who reported that muscle activation continued to increase with increasing pressure (80%, 100%, and 120% bSBP) in upper limb muscles, where 120% bSBP caused greater muscle activation with the same exercise load. The reason for the inconsistency between the results may be related to the different occlusion pressures used during testing. Counts et al. determined pressure based on arm systolic pressure, whereas the present study determined pressure based on lower limb thigh circumference and systolic and diastolic pressures. The differences may also be related to the different intrinsic structure of upper and lower limb muscles. In addition, as the number of sets increased, the RMS standard values of the GM gradually decreased in the BFR conditions, and the activation of the GM was significantly smaller in Set4 compared to Set1. However, in the non-BFR condition, the activation of the GM gradually increased as the number of sets increased. This may be because the hip joint is the main source of force and the GM is the main force-generating muscle during semi-squat exercises, and synergistic effects may occur between the knee and hip joint during the exercise. As the number of exercises sets increases, the GM fatigue gradually increases, and the greater the pressure, the greater the GM fatigue, resulting in a significant decrease in the RMS standard value during BFRT. Furthermore, as the GM fatigue increases, other muscles around the hip joint are gradually activated, and the muscles around the hip joint compensate significantly for the shortage of GM function.

The MF values of the muscles of the lower limb during the BFRT were similar. As the number of sets increased, the MF values of the VMO, VLO, RF, and BF decreased significantly in set4 compared to set1. The MF values of the VMO, VLO, RF, and BF in the same semi-squats set were significantly lower than those of the non-BFR condition. Therefore, BFRT is a very effective movement to induce significant changes in neuromuscular function, although the exact mechanism of this change remains unclear. However, most studies have shown that the decrease in MF values is highly correlated with the synchronization of motor units (Bigland-Ritchie et al., 1981), and during BFRT, the intramuscular H^+ concentration increases, the pH decreases, and the sensitivity of the sarcoplasmic reticulum to Ca^{2+} is lost or reduced, resulting in a decrease in the conduction velocity of muscle fibers and fatigue. The current study showed that the MF values of the lower limb muscle decreased with increasing occlusion pressure (Table 3). These data suggest that neuromuscular fatigue increases with increasing occlusion pressure during BFRT. As pressure increases, the acidic environment changes, leading to an increase in the neuromuscular disorder, a change in the relationship between energy supply and demand, and accumulation of lactic acid in the muscle, which cause significant changes in EMG signals. In addition, Fatela et al. found that higher pressures caused a reduction in the sensitivity of type II muscle fibers and changes in intramuscular biochemical characteristics, which result in greater muscle fatigue (Fatela et al., 2016). Therefore, participants required longer rest duration for recovery of the neuromuscular system from fatigue. BFRT may affect the generation of PAPE and the improvement of acute exercise performance.

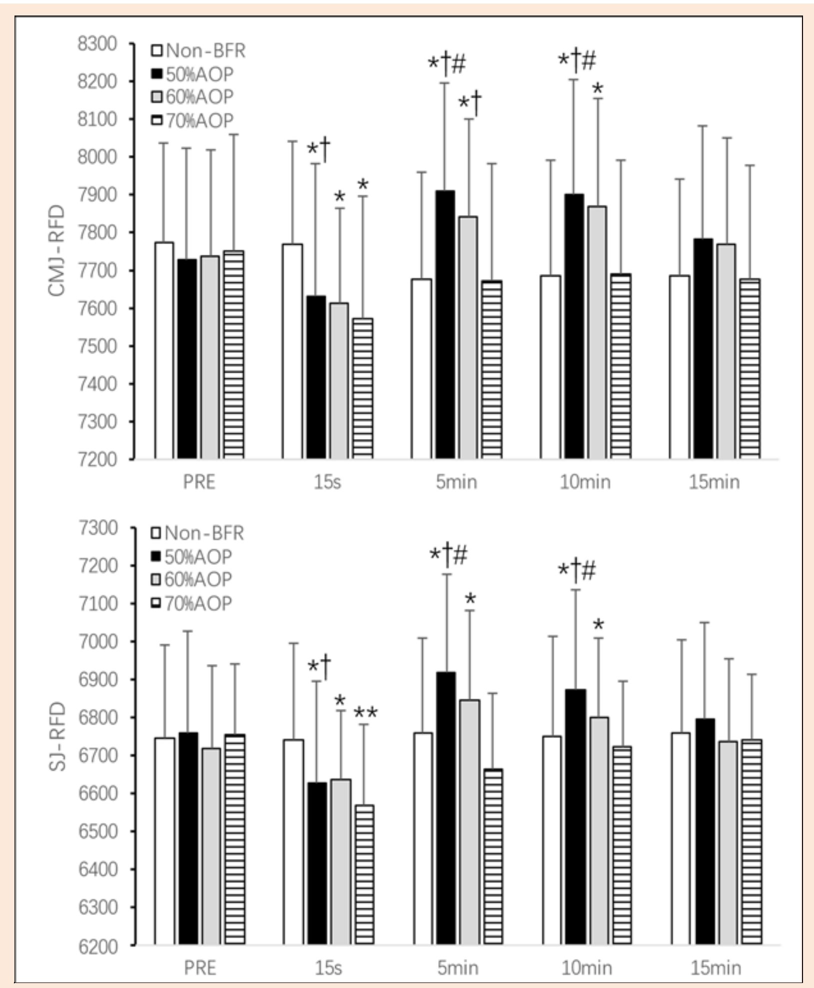

Figure 5. The rate of force development time domain of different blood flow restricted training pressure. * significant difference compared to baseline at each time point, $P < 0.05$, ** denotes very significant difference, $P < 0.01$; # significant difference compared to the non-BFR group, $P < 0.05$; † significant difference compared to the 70% AOP group, $P < 0.05$. CMJ: Countermovement jump; SJ: Squat jump; RFD: rate of force development.

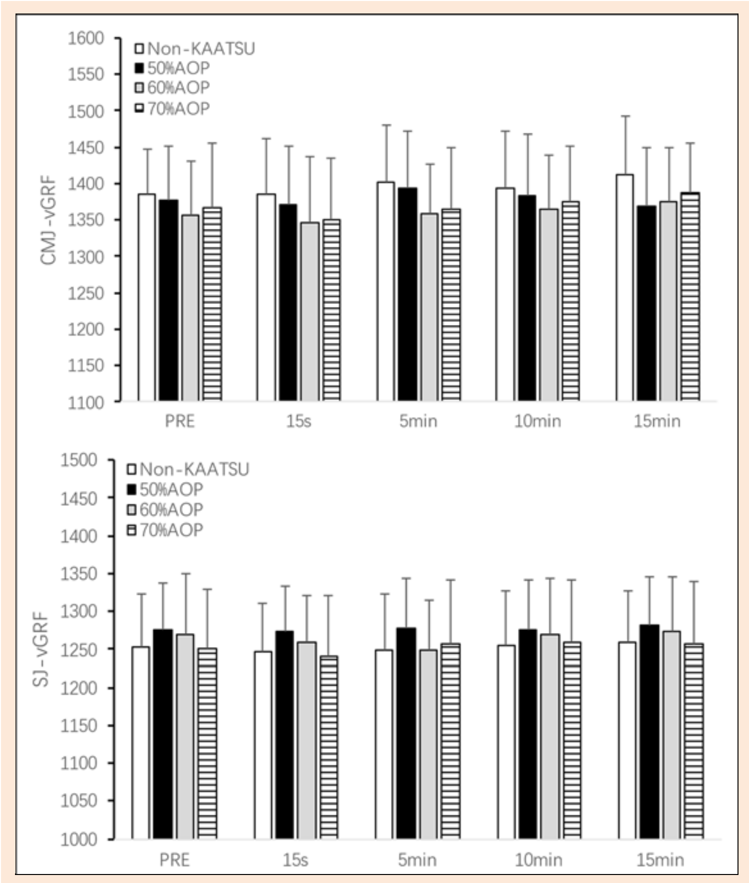

Figure 6. The vertical ground reaction forces time domain of different blood flow restricted training pressures.
CMJ: Countermovement jump; SJ: Squat jump; vGRF: vertical ground reaction forces.

Table 2. Changes of RMS standard values of each muscle in semi-squat.

Muscle	Different pressure	Semi-squat intervention				Interac-tion	Time main	
		Set1	Set2	Set3	Set4		Within-subject	Inter-subject
Vastus Medialis VMO)	Non-BFR	218.00 ± 33.95	221.61 ± 35.07	222.30 ± 36.77	223.57 ± 35.86	2.48#	3.53#	4.54#
	50%AOP	241.10 ± 38.36△	242.47 ± 39.84△	245.82 ± 37.01*△	247.75 ± 38.39 *△			
	60%AOP	241.19 ± 30.20△	245.97 ± 29.86△	248.85 ± 31.34*△	250.56 ± 29.77*△			
	70%AOP	248.49 ± 33.74△	251.45 ± 33.82△†	254.69±31.92*△†	257.61±33.03*△†			
Vastus Lateralis (VLO)	Non-BFR	228.19 ± 31.63	229.57 ± 34.60	230.24 ± 35.02	231.27 ± 35.41	5.98#	12.36#	1.65#
	50%AOP	237.29 ± 35.57△	239.30 ± 33.80△	242.84 ± 33.66△	244.33 ± 31.01*△			
	60%AOP	236.91 ± 36.28△	240.36 ± 36.69△	244.72 ± 29.26*△	247.28 ± 33.17*△			
	70%AOP	240.37 ± 37.32△	243.34 ± 34.31△	247.70 ± 36.50*△	253.27±34.01*△†			
Rectus Femoris (RF)	Non-BFR	191.71 ± 26.08	192.91 ± 29.87	195.52 ± 24.60	201.93 ± 25.10*	1.08	2.55#	3.17#
	50%AOP	207.22 ± 29.11△	208.32 ± 27.26△	210.05 ± 27.18△	213.89 ± 29.96*△			
	60%AOP	210.09 ± 22.03△	214.91 ± 21.60△	217.83 ± 22.91*△	222.45±22.08*△†			
	70%AOP	214.87 ± 22.06△	217.87 ± 28.12△†	221.12±31.67*△†	225.42±25.09*△†			
Biceps Femoris (BF)	Non-BFR	63.26 ± 11.79	64.84 ± 16.42	66.65 ± 17.10	70.04 ± 14.61*	1.07	11.45#	3.09#
	50%AOP	70.53 ± 12.18△	72.29 ± 10.12△	73.29 ± 19.92△	76.77 ± 22.17*△			
	60%AOP	72.16 ± 18.26△	75.17 ± 17.90△	77.18 ± 15.28△	79.91 ± 16.33*△			
	70%AOP	77.64 ± 17.16△	80.41 ± 15.02△	84.80±16.04*△†	87.81±17.32*△†			
Gluteus Maximus (GM)	Non-BFR	68.42 ± 11.33	68.49 ± 12.92	69.82 ± 9.99	70.52 ± 10.56	2.67#	4.56#	4.88
	50%AOP	70.76 ± 14.01	71.25 ± 24.00	68.30 ± 12.43	67.32 ± 13.31*			
	60%AOP	71.57 ± 14.15	70.99 ± 17.39	69.25 ± 18.86	66.89 ± 15.38*			
	70%AOP	73.10 ± 10.61△	71.75 ± 13.54	69.07 ± 10.91	68.27 ± 13.27*			
Gluteus Medius (Gmeds)	Non-BFR	61.72 ± 7.79	62.18 ± 7.26	62.03 ± 9.67	63.67 ± 10.15	1.95	4.39	1.71
	50%AOP	64.66 ± 4.76	64.84 ± 5.12	62.75 ± 4.61	62.49 ± 4.85			
	60%AOP	63.88 ± 12.77	62.75 ± 10.91	64.04 ± 10.46	65.37 ± 12.65			
	70%AOP	65.24 ± 13.64	64.23 ± 13.28	66.28 ± 12.59	66.66 ± 13.27			

Data are presented as mean±SD. * significant difference compared to the first group, △ significant difference compared to the non-BFR, † significant difference compared to the 50% AOP, # significant difference in the pressure, time, and interaction on the standard values of RMS for each muscle during the semi-squat. $p < 0.05$.

Table 3. Changes in MF values of each muscle in semi-squat.

Muscle	Different pressure	Semi-squat intervention				Interaction	Time main	
		Set1	Set2	Set3	Set4		Within-subject	Inter-subject
Vastus Medialis VMO)	Non-BFR	75.54 ± 7.23	73.55 ± 7.09	72.92 ± 7.49	72.29 ± 7.44	1.74	6.36#	1.15#
	50%AOP	69.92 ± 5.45	67.91 ± 5.65△	66.61 ± 5.94△	65.05 ± 6.13*△			
	60%AOP	69.71 ± 8.57	67.33 ± 8.07△	65.30 ± 7.53*△	63.13 ± 8.00*△			
	70%AOP	67.43 ± 7.85	63.46 ± 6.26△	62.18 ± 6.34*△	59.74 ± 7.14*△†			
Vastus Lateralis (VLO)	Non-BFR	74.71 ± 11.22	73.56 ± 11.44	72.18 ± 11.38	71.64 ± 11.30	1.91	4.87#	0.87#
	50%AOP	69.92 ± 5.45	67.91 ± 5.65△	66.61 ± 5.94△	65.06 ± 6.13*△			
	60%AOP	68.73 ± 6.05	67.43 ± 6.89△	64.99 ± 6.92*△	62.21 ± 7.37*△†			
	70%AOP	66.30 ± 10.90	63.02 ± 10.34△	61.28 ± 10.56*△†	60.94±10.73*△†			
Rectus Femoris (RF)	Non-BFR	80.48 ± 8.67	78.81 ± 8.61	78.81 ± 8.61	76.10 ± 8.68*	2.02#	9.91#	1.91#
	50%AOP	77.62 ± 5.72	76.84 ± 4.55	75.56 ± 4.42	73.06 ± 5.58*△			
	60%AOP	75.48 ± 5.33△	73.18 ± 6.10△	72.44 ± 5.51*△	70.50 ± 5.33*△†			
	70%AOP	74.29±11.81△	71.60 ± 11.78△†	69.09 ± 11.81*△†	67.01±11.65*△†			
Biceps Femoris (BF)	Non-BFR	79.31 ± 9.61	78.54 ± 9.67	77.95 ± 9.53	76.51 ± 9.69*	2.52#	7.56#	1.56#
	50%AOP	74.87 ± 9.56△	72.97 ± 9.16△	71.54 ± 9.68△	69.46 ± 8.95*△			
	60%AOP	73.63 ± 8.83△	71.31 ± 8.33△	68.79 ± 9.00*△	66.39 ± 8.46*△†			
	70%AOP	71.67±12.29△	67.32 ± 11.80*△	64.61 ± 12.22*△†	62.08±12.03*△†			
Gluteus Maxi-mus (GM)	Non-BFR	55.96 ± 4.71	55.73 ± 4.78	56.92 ± 4.72	56.10 ± 4.13	2.05#	6.65#	1.49
	50%AOP	53.98 ± 7.48	53.46 ± 7.92	53.70 ± 8.66	54.01 ± 8.38			
	60%AOP	51.26 ± 8.96△	52.50 ± 10.09	52.71 ± 11.15	53.06 ± 11.57			
	70%AOP	50.01 ± 8.16△	51.53 ± 7.83	52.14 ± 7.48	53.90 ± 7.30*			
Gluteus Medius (Gmeds)	Non-BFR	68.44 ± 5.84	67.68 ± 5.63	66.34 ± 5.95	66.04 ± 6.37	0.77	4.31#	1.70#
	50%AOP	65.20 ± 4.60	63.77 ± 3.69	63.46 ± 3.21	62.85 ± 3.41△			
	60%AOP	66.24 ± 6.38	65.90 ± 4.74	64.76 ± 4.18	63.29 ± 4.59△			
	70%AOP	65.10 ± 7.16	64.16 ± 7.37	63.02 ± 7.54	62.21 ± 7.09△			

Data are presented as mean±SD. * significant difference compared to the first group, △ significant difference compared to the non-BFR, † significant difference compared to the 50% AOP, # significant difference from the pressure, time, and interaction on the standard values of RMS for each muscle during the semi-squat, $p < 0.05$.

Table 4. Rating of Perceived Exertion in semi-squat.

Intervention mode	PRE	Set1	Set2	Set3	Set4
Non-KAATSU	3.45±0.38	5.31±0.61	5.99±0.74	6.51±0.57	7.01±0.40
50%AOP	3.48±0.34	7.15±0.84*	7.61±0.68*	8.04±0.75*	8.65±0.82*
60%AOP	3.42±0.37	7.48±0.91*	8.12±1.01*	8.68±1.20*	9.01±1.24*
70%AOP	3.44±0.33	8.01±1.05*#	8.54±1.32*#	9.04±1.45*#	9.47±1.67*#

Data are presented as mean ±SD. * significant difference from non-KAATSU group, # significant difference from 50% AOP.

In football, athletes play using mainly high-intensity intermittent movements. In an official match, athletes need to perform approximately 1,000-1,400 different short bursts of maximum intensity or near-maximum intensity activities such as sprints, accelerations, decelerations, jumps, tackles, kicks, turns, and tempo changes. Athletes perform a maximum intensity exercise every 90 sec or a high-intensity sprint every 30 sec (Stolen et al., 2005). These intermittent activities enable athletes to recover in a short time, which enhance their athletic performance. Alternatively, fatigue is eliminated more quickly than enhancement (Sale, 2002); therefore, PAPE may more likely be induced in football players. In addition, the vertical jump (explosive) ability of athletes in the penalty area is very important for attackers and defenders because many goals are scored by athletes who jump and head the ball (Requena et al., 2011). The vertical jump is relatively simple and similar to several movement patterns, which is one of the valid and reliable indicators for evaluating the explosive power of the lower limbs of football players (Stolen et al., 2005; Yu et al., 2020). Previous studies have shown that team success was significantly correlated with average jump height and power, which indicates that explosive strength is important for the athletic performance of football players (Arnason et al., 2001). Therefore, PPO or RFD in the lower limbs plays a very important role during football games. Muscle activation and vertical jump performance are linked through GRF, and the interaction between muscle activation and GRF determines vertical jump performance. To investigate the effect of PAPE on vertical jump performance, it is essential to analyze GRF variables (e.g., peak force, RFD, and PPO). The temporal profile characteristics of the GRF variables during the vertical jump induced by different BFRT PAPE were as follows: 1) The effect of semi-squat training-induced PAPE on PPO was consistent in the 50% AOP or 60% AOP condition, and the PPO was significantly higher during 5- and 10-min rest than the baseline. PPO was higher during 5-min rest in the 50% AOP condition than non-BFR (Figure 4); 2) RFD was significantly lower during 15-sec rest than the baseline after BFR conditions, and the CMJ-RFD reduced significantly in the 70% AOP condition. The effect of semi-squat on RFD was consistent in the 50% AOP and 60% AOP conditions, RFD was significantly higher after the 5-10-min rest than the baseline, and the RFD was higher after 5-min rest in the 50% AOP condition than non-BFR (Figure

5); and 3) The relative vGRF did not differ significantly at different time points within the conditions. These results indicated that semi-squat with 50% AOP or 60% AOP BFRT could induce PAPE, and the 50% AOP may be more effective than the 60% AOP (Figure 6).

Wilk et al. (2020) investigated the changes in PAPE using successive multiple sets of 70% 1RM with and without BFR (90% AOP) bench press training and its effect on participants' output power and velocity. Their results showed that under BFR condition, at 5 min rest intervals per set, peak power and barbell bar velocity increased significantly in the second set compared with the first set, and decreased significantly in the third set compared with the second set. The explanation for this result may be that the BFR conditions made the second set to have an increased PAPE, while the third group counteracted the increase in PAPE due to muscle fatigue. BFR bench press training may increase bench press power and speed, although these improvements in performance may have led to greater fatigue, affecting power and related parameters during multiple consecutive sets. Cleary and Cook (2020) showed that the squats with high intensity BFRT did not elicit PAPE in a 3-min interval between sets, and the vertical jump height decreased with an increase in the number of sets. These studies suggest that occlusion pressures and exercise load place extensive pressure on the muscles, which increases fatigue with increasing number of sets. Furthermore, participants may require a longer recovery time to reduce PAPE; thus, recovery time is an important factor. The optimal recovery time window should ensure an optimal balance between fatigue and enhancement (Wilk et al., 2020). To exclude the effect of fatigue on PAPE as much as possible, Wilson et al. (2013) showed in a meta-analysis that the optimal recovery time for PAPE-induced output power was 5-10 min, and reported that the ATP-CP energy supply system was resynthesized within 5 min. Therefore, the 5-min time interval was used in this study to induce PAPE. The results showed that semi-squat with 50% AOP and 60% AOP BFRT can induce PAPE after 5 min and 10 min of rest, and that vertical jump height, PPO, and RFD increased significantly, and the 50% AOP condition was superior to the 60% and 70% AOP. This is consistent with the findings by Doma et al. (2020) in which 3 sets of 8 reps (8 reps for each left and right leg) of lunge squat with BFRT elicited PAPE after 6-15 min of rest, which significantly improved jump height, flight time, and the power of the deep jump. In summary, BFRT induces PAPE, and the size and duration of the PAP is highly dependent on the balance between fatigue and potentiation; as pressure increases, the fatigue becomes greater, and the induction of PAPE is more affected.

Functionally, the ability of muscle contraction to generate rapid force is more important than the muscle maximal force because most functional movements are completed within a limited time (0-200 ms), whereas peak muscle force usually generates muscle contraction in 300-600 ms (Baudry and Duchateau, 2007). Compared with maximal force, the RFD provides a better assessment of exercise performance. Previous literature has shown that traditional high-intensity training can cause an increase in efferent nerve impulses, which can be confirmed by changes in EMG amplitude (the rate of EMG signal development in early muscle contraction is similar to changes in RFD) (Aagaard et al., 2020; Liu and Guo, 2019). Guellich and Schmidtbleicher (1996) suggested that neuromuscular activation is the main factor affecting peak RFD and muscle strength. Compared with non-BFR, BFRT can recruit more and larger threshold motor units and increase the RMS standard values (Kilduff et al., 2007), thereby impacting on RFD. The results showed that RFD was significantly higher after 5- and 10-min rest than baseline values in 50% and 60% AOP BFR conditions, and significantly higher in the 50% AOP than in the 70% AOP after 5 min of rest (Figure 5). This is consistent with the findings of Baudry and Duchateau et al. who showed that PAPE was induced by 6-sec isometric contractions, followed by a significant increase in RFD during maximal voluntary contractions and brief high frequency stimulation. This may optimize the mechanism of stretch-shortening cycle due to myosin light chain phosphorylation, leading to an increase in RFD (Doma et al., 2020).

Conclusion

Our results demonstrated that semi-squats with 50% or 60% AOP induced PAPE, and the 50% AOP condition showed better effects in 5 - 10 min after the semi-squat intervention than the 60% AOP condition. The different BFRT pressures used in this study activated the muscles differently, as muscle activation was enhanced with increasing pressure, and neuromuscular fatigue increased with increasing pressure. BFRT with 50% AOP can significantly improve vertical jump performance. Therefore, moderate pressure BFRT is a feasible and effective daily warm-up activity to improve anaerobic power in female football players.

Acknowledgements

The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated and analyzed during the current study are not publicly available, but are available from the corresponding author who was an organizer of the study.

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Key points

- The improvement in vertical jump shows that the BFRT with 50% AOP or 60% AOP of the lower limb can induce a substantial PAPE stimulus despite equal workload.
- Compared to the non-BFRT condition, the RMS standard values of the muscles in the lower limb during the semi-squat with BFRT were significantly higher, and the values increased as the sets progressed.
- Semi-squats with 50% or 60% AOP induced PAPE, and the 50% AOP condition showed better effects in 5 - 10 min after the semi-squat intervention than the 60% AOP condition.
- The different BFRT pressures used in this study activated the muscles differently, as muscle activation was enhanced with increasing pressure, and neuromuscular fatigue increased with increasing pressure.

AUTHOR BIOGRAPHY

Depeng SUN
Employment
Graduate department, Capital university of Physical Education and Sports, Beijing, China
Degree
PhD candidate
Research interests
theory and practice of sports training, adolescent body motor function training and pressure training
E-mail: zhuimeng_209@163.com

Tieli YANG
Employment
Department of PE, Xi'an University of Finance and Economics, Xi'an, China
Degree
PhD
Research interests
sports humanities and sociology, sports industry and leisure sports
E-mail: yangtieli@cu-pes.edu.cn

✉ **Depeng SUN**
Graduate department, Capital university of Physical Education and Sports, Beijing 100191, China