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Acute impact of blood flow restriction during resistance exercise – review

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Abstract

Introduction. Athletes, as well as recreationally trained individuals are increasingly looking for innovative techniques and methods of resistance training to provide an additional stimulus to break through plateaus, prevent monotony and achieve various training goals. Partial or total blood flow restriction (BFR) to the working muscles during resistance exercise has been used as a complementary training modality, aiming to further increase muscle mass and improve strength. BFR is usually used during low-load resistance exercise and has been shown to be effective in enhancing long-term hypertrophic and strength responses in both clinical and athletic populations. However, recently some attention has been focused on the acute effects of BFR on strength and power performance during high-load resistance exercise. Aim of Study. This article provides an overview of available scientific literature and describes how BFR affects the 1-repetition maximum (1RM), the number of repetitions performed, time under tension and kinematic variables such as power output and bar velocity. Material and Methods. Available scientific literature. Results. As a result, BFR could be an important tool in eliciting greater maximal load, power output and strength-endurance performance during resistance exercise. Conclusions. BFR as a training tool can be used as an additional factor to help athletes and coaches in programming varied resistance training protocols.

KEYWORDS: occlusion, cuff, ischemia, bar velocity, 1RM test, repetition.

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Introduction

Blood flow restriction (BFR) has received much attention and has been shown to be beneficial for clinical cohorts, athletes and active individuals in improving their physical performance [35, 51]. Exercise with BFR is a strategy that involves application of an inflatable cuff, tourniquet [35] or elastic wrap [22] around a limb, proximally to the muscles being trained, in order to reduce the arterial blood flow and to shut the venous blood flow [51]. BFR is applicable to any form of physical activity; however, most research is focused on resistance training [5, 10, 24]. The BFR during resistance exercise at low external loads is generally used for rehabilitation purposes as well as a tool to prevent sarcopenia in the elderly [22]. The resistance exercise under BFR performed at higher loads is used in order to maximize training adaptation [35], typically to increase hypertrophy responses [9, 17, 54]. The mechanical tension generated by the cuff increases metabolic stress and is the main physiological mechanism influencing muscle adaptation after resistance training under BFR. The increase of metabolic stress during resistance exercise under BFR results in cell swelling [24], enhances intramuscular signaling [19, 28], increases recruitment of fast-twitch muscle fibers [27, 40] and enhances responses of the endocrine system [36, 39]. Furthermore, the hyperemia following occlusion may play a significant role in nitric oxide production [37], increased phosphocreatine resynthesis, altered oxy-deoxyhemoglobin kinetics [3] and increased oxygen uptake [1]. In addition to physiological factors, recently also mechanical factors (mechanical energy accumulated and released by the cuff) have been indicated to influence acute kinematic changes following resistance training under BFR [32]. During resistance exercise under BFR the strain of the material, of which the cuff is made, may produce additional elastic energy, which is released from the cuff during the concentric contraction [50], increasing the value of the maximum external load lifted, power output and the maximum number of repetitions performed [48]. Despite countless scientific studies that focus on resistance exercise under BFR, only a select few have analyzed the acute effect of BFR during isotonic resistance exercise. BFR used during resistance exercise can influence acute exercise volume and in turn, the resultant chronic changes in maximum strength, power output and endurance performance [11, 32, 48, 50]. Therefore, the main focus of this review is to analyze the current state of knowledge concerning the influence of BFR during resistance exercise on mechanical responses to resistance training (Table 1).

Table 1. Summary of studies exploring the acute impact of blood flow restriction on power output, maximal strength and endurance performance during resistance exercises

Reference	Occlusion pressure (% AOP/mm Hg)/ BFR protocol	Subjects/cuff width	Protocol	Main findings
Dankel et al. [8]	70% AOP/ BFR applied at the completion of the first set for the duration of the rest interval and the second set	7 resistance-trained men, 3 resistance-trained women/ cuff width 50 mm	unilateral dumbbell elbow flexion (70% 1RM) part 1: 1 set × maximal number of reps to exhaustion without BFR part 2: 1 set × maximal number of reps to exhaustion with BFR	↓ maximal REP for BFR condition compared to control
Gepfert et al. [11]	100% AOP 150% AOP intermittent BFR	10 male judo athletes/ cuff width 100 mm	back squat (70% 1RM) 3 sets × 3 reps with maximal velocity of movement in concentric phase	↑ PP, MP, PV, MV for 150% AOP compared to control ↑ PP, MP, PV, MV for 150% AOP compared to 100% AOP ↔ PP, MP, PV, MV for 100% AOP compared to control
Loenneke et al. [21]	~50-100 mm Hg pressure/ BFR applied immediately before exercise, removed immediately after post-exercise whole blood lactate measurement	10 recreationally active men, 10 recreationally active women/knee wraps 76 mm wide	bilateral leg extension (30% 1RM) 1 set × maximal number of reps to exhaustion	↓ maximal REP for BFR condition compared to control
Rawska et al. [32]	80% AOP continuous BFR	4 resistance-trained women/ cuff width 100 mm	bench press 5 sets × maximal number of reps to exhaustion for 2/0/X/0 and 6/0/X/0 movement tempo	↑ maximal REP for BFR compared to control for 2/0/X/0 tempo in set 1, 2, 5 ↑ maximal REP for BFR compared to control for 6/0/X/0 tempo in set 1 ↑ total REP for BFR compared to control for both tempos

Wernbom et al. [41]	200 mm Hg pressure/ intermittent BFR	13 recreationally active men, 3 recreationally active women/cuff width 135 mm	unilateral knee extension 4 sets × maximal number of reps to exhaustion at 20, 30, 40, 50% 1RM	↓ maximal REP for BFR compared to control at 20, 30, 40% 1RM ↔ maximal REP for BFR compared to control at 50% 1RM
Wernbom et al. [42]	100 mm Hg/ continuous BFR	8 resistance-trained men, 3 resistance-trained women/cuff width 135 mm	unilateral knee extension 3 sets × maximal number of reps to exhaustion at 30% 1RM	↓ maximal REP for BFR compared to control for each of 3 sets and for all 3 sets combined
Wilk et al. [44]	70% AOP/ intermittent and continuous BFR	11 resistance-trained men/cuff width 40 mm	bench press 8 sets × 2 reps (20 to 90% 1RM with 10% steps) with maximal velocity in concentric phase	↑ PV for intermittent and continuous BFR conditions at 20, 30, 40, 50% 1RM compared to control ↔ PV for intermittent and continuous BFR conditions at 60, 70, 80, 90% 1RM compared to control ↔ MV in all conditions
Wilk et al. [48]	100% AOP and 150% AOP/ intermittent BFR	12 resistance-trained men/cuff width 100 mm	bench press part 1: 1RM test, part 2: 3 sets (60% 1RM) × × maximal number of reps to exhaustion at maximal velocity of movement	part 1: ↑ 1RM for 150% AOP compared to control part 2: ↑ maximal REP, TUT for 150% AOP compared to control ↑ maximal REP, TUT for the 150% AOP compared to control 100% AOP
Wilk et al. [49]	90% AOP/ intermittent BFR	10 resistance-trained men/cuff width 100 mm	bench press 3 sets × 3 reps (70% 1RM) at maximal velocity of movement	↑ PP, MP, PV, MV for BFR condition compared to control
Wilk et al. [50]	90% AOP/ intermittent BFR	14 resistance-trained men/cuff width 40 mm (narrow cuff) and 100 mm (wide cuff)	bench press 1 set × 3 reps (70% 1RM) at maximal velocity of movement	↑ PP, MP, PV, MV for wide cuff BFR compared to narrow cuff BFR ↑ PP, MP, PV, MV for wide cuff BFR compared to control ↔ PP, MP, PV, MV for narrow cuff BFR compared to control

Note: AOP – arterial occlusion pressure; BFR – blood flow restriction; 1RM – 1 repetition maximum; PP – peak power output; MP – mean power output; PV – peak bar velocity; MV – mean bar velocity; TUT – time under tension; REP – number of performed repetitions; tempo of movement (2/0/X/0) – eccentric/isometric/concentric/isometric; ↑ denotes significant increases; ↔ denotes non-significant differences; ↓ denotes significant decreases

Factors affecting acute performance during BFR resistance exercise

Several factors regarding the acute impact of BFR resistance training on various adaptive changes have been distinguished; however, their exact impact still remains insufficiently examined and described. The current literature analyzes the influence of individual variables such as cuff width, cuff pressure, scheme of BFR use (continuous and intermittent) and type of movement, which can significantly affect the acute and long-term adaptive changes following resistance exercises under BFR conditions.

Cuff width

There is no uniformly adopted and standard cuff width for BFR training. However, previous studies confirmed that cuff width is a significant factor that should be taken into account during resistance exercise under BFR [13, 21, 33]. There is a wide range of cuff widths (3-18.5 cm) presented in the BFR literature [31, 35, 51]. The cuff width and its impact on acute and chronic changes following BFR resistance exercise are directly related to the pressure value applied to the limb. The use of a wide (13.5-cm) cuff results in arterial blood flow restriction at a lower pressure compared to the narrow (5-cm) cuff [6, 21]. Furthermore, greater cardiovascular (heart rate and blood pressure) and perceptual (rate of perceived physical effort) responses are obtained when a wide cuff (13.5-cm) is used compared to a narrow (5-cm) cuff with equal pressure [33]. Similarly, Loenneke et al. [21] demonstrated that when constant pressure is applied, the use of a wider cuff results in different physiological adaptive responses compared to the use of a narrow cuff. Therefore, a wider cuff provides the same effect at a lower absolute pressure.

Wilk et al. [50] suggested that the effect of cuff width on the level of performance is related not only to physiological responses, but also affects the value of mechanical energy generated by the cuff. As suggested by Rawska et al. [32] and Wilk et al. [48], mechanical factors (mechanical energy accumulated and released by the cuff during the concentric phase of the movement) may impact acute performance changes under BFR condition; however, such a potential effect is proportional to cuff width [50]. A cuff is a passive element, but during movement, especially in the eccentric phase of the movement, the strain of the material, of which the cuff is made, may produce additional elastic energy. The mechanical energy accumulated in the cuff is probably proportional to its width [50]. A wider cuff has a larger surface area for mechanical work, thus the strain of a wider cuff may potentially produce more elastic energy when compared with a narrow cuff. A wide cuff may also act similarly to compressive gear used in powerlifting, supporting the athlete during the eccentric phase and giving a “rebound” effect during the concentric phase of the lift, which allows a greater load to be lifted [46]. However, the use of extremely wide cuffs may limit the range of movement during exercise [31, 50].

Cuff pressure

Cuff pressure has been recognized as a relevant factor that affects the effectiveness of resistance exercise under BFR [33, 48]. Arterial occlusion pressure (AOP) is the amount of pressure required to cease blood flow to a limb and is related to individual limb characteristics, shape and width of the cuff [31]. It can be accomplished by inflating the cuff being used during an exercise up to the point, where blood flow is completely cut off (100% AOP) and then a percentage of that AOP is used for BFR during exercise [31, 50]. Although in some studies pressures relative to brachial systolic blood pressure have been applied, because of a wide variety of cuffs setting pressure according to the individual value of AOP is recommended [31, 50]. Moreover, cuff pressure is related to individual characteristics such as the circumference of the occluded limb and composition of the body, as well as the width, shape and material, of which the cuff is made [13, 21, 30, 51].

According to Loenneke et al. [23], BFR may follow the hormesis theory, meaning that low or moderate pressures produce beneficial effects, while higher pressures (at or near arterial occlusion) may decrease the exercise benefits and increase health risks, thus moderate (about 50% AOP) pressure values are recommended. On the other hand, a wider range (40-80% AOP) of pressures to be applied has been suggested by Patterson et al. [31], while the use of high (80-90%) or extremely-high (100--150% AOP) pressure values has also been reported in the scientific literature [11, 32, 48, 49, 50]. However, it should be noted that only few studies investigated cuff pressure above 100% AOP [11, 48].

Type of exercise

The differences in BFR impact on the upper and lower body need to be taken into account. According to studies by Crenshaw et al. [6] and Loenneke et al. [24], the absolute value of pressure depends largely on the circumference of the limb, to which compression is applied. Thus, it should be noted that due to the larger circumference of the lower limb compared to the upper limb, for the lower body a higher absolute pressure and a wider cuff may be required to produce similar results as in the upper body [30]. Moreover, as suggested by Gepfert et al. [11], also the length of the occluded limb may impact performance changes under BFR conditions.

Scientific studies regarding the acute impact of BFR resistance training on various adaptive changes utilized both single-joint [20, 41] and multi-joint movement [11, 50] for the upper and lower body. During multi-joint movement such as the bench press or back squat not all of the main muscles involved are directly affected by occlusion [32], in contrast to single-joint movement; however, currently there is no available research directly comparing single and multi-joint exercises during BFR external compression. Furthermore, it has been suggested that the acute performance enhancement under BFR during a particular resistance exercise may differ from that in other types of exercises [50].

BFR exercise protocols

There are different types of BFR application protocols applied during resistance exercise. Continuous BFR refers to occlusion used during exercise and rest intervals between sets [31, 44]. Intermittent BFR is used only during the exercise and released upon completion of the set [11]. Furthermore, ischemic preconditioning is also differentiated as a method utilizing occlusion only before the exercise [12, 29, 44]. Thus, the duration of occlusion may vary substantially between used protocols [44].

Continuous BFR is typically used in most studies [22, 31, 42]. However, as demonstrated by Yasuda et al. [53], when cuff pressure is high (160 mmHg), similar muscle activation occurs with both continuous and intermittent cuff pressure. Furthermore, intermittent BFR may reduce swelling as well as physiological and metabolic stress compared to continuous BFR [31, 44]. Intermittent BFR seems more attractive in order to achieve improved performance and to minimize the negative effects of BFR [44], especially during multi-joint resistance exercises with full rest intervals (3-5 minutes) and short duration of the effort [11, 48].

Acute effects of BFR on strength-endurance performance

Strength-endurance is usually determined by parameters such as the number of repetitions and time under tension, which amounts to the total sum of the concentric, eccentric and isometric components of repetition [15, 34, 43, 45, 52]. It has been shown in several studies that BFR impacts the level of strength-endurance performance during resistance exercise. Wernbom et al. [42] demonstrated that BFR decreases the maximal number of repetitions performed during single-leg knee extension exercise at 30% of the one repetition maximum (1RM). A similar result was obtained by Loenneke et al. [20], who also showed a significant decrease in the number of performed repetitions during the knee extension exercise under BFR at 30% 1RM compared to the control. Aforementioned studies are partially consistent with a study by Wernbom et al. [41], who examined the impact of the BFR on the number of repetitions performed at various external loads (20, 30, 40 and 50% 1RM). Although, in that the participants performed a significantly lower number of repetitions under BFR at 20, 30, and 40% 1RM compared to the control, there were no significant differences at load of 50% 1RM. Therefore, the result of the study by Wernbom et al. [41] suggested that the acute effect of BFR on the number of performed repetitions can be related to the value of external load used. However, a study by Dankel et al. [8] showed that exercise under BFR at a higher load (70% of 1RM) resulted in a significant decrease in the number of repetitions performed, which is contrary to the result of the above-mentioned study by Wernbom et al. [41].

On the other hand, resistance exercise under BFR has also been reported to improve strength-endurance performance during resistance exercise [32, 48]. However, these results were obtained based on multi-joint, upper-body movements and much higher loads (60, 80% 1RM) compared to studies by Wernbom et al. [41, 42] and Loenneke et al. [20]. In turn, Rawska et al. [32] recorded an increase in the number of performed repetitions during 5 sets of the bench press exercise at 80% 1RM for the variant under BFR compared to the control. An increase in the number of performed repetitions during resistance exercise under BFR was also observed in a study by Wilk et al. [48]. The results of that study [48] showed an increase in the number of performed repetitions and time under tension during the bench press exercise at 60% 1RM with an extremely high cuff pressure amounting to 150% AOP compared to the control. The lower cuff pressure amounting to 100% AOP also showed an increase in the number of performed repetitions, but only in the first set of the bench press exercise. Moreover, Wilk et al. [48] reported significant increases in the number of repetitions performed and time under tension during BFR with 150% AOP cuff pressure compared to BFR with 100% AOP cuff pressure. Therefore, the value of cuff pressure is an important factor affecting the acute effect of BFR during resistance exercise.

However, the characteristics of the exercise may be an important factor influencing the increase in strength and endurance performance under BFR conditions during the bench press exercises [32, 48]. In the bench press exercise the main muscles involved are the pectoralis major, triceps brachii and anterior deltoid [14, 16]. However, as was pointed out by Rawska et al. [32], occlusion during the bench press is applied only on the triceps brachii. The main muscles involved are not directly affected by the occlusion, thus whether or not BFR is applied during a single or multi-joint exercise should also be taken into account. Moreover, studies regarding single-joint, lower-body movement under BFR conditions [20, 41, 42] showed a lower number of repetitions performed when both narrow (7.6 cm) and wide (13.5 cm) cuffs were used. These findings suggest that cuff width does not influence acute strength-endurance performance in single-joint movements at low external loads (30% 1RM), which may occur due to the prevalence of the physiological mechanism (increased metabolic stress) rather than mechanical factors as regards the obtained results.

Acute effects of BFR on power output and velocity of the movement

Power output is considered a crucial factor impacting performance in many athletic and sporting activities [18, 38]. The optimal level of the force generated by the muscles and velocity of the movement allows for maximal power output to be achieved [2, 47]. Resistance training is a fundamental tool used in improving power output and its variables have been extensively explored [2, 47]. Recently attention has also been focused on the acute impact of BFR on power output and velocity of the movement during multi-joint resistance exercises.

BFR applied during resistance exercise has been shown to increase power output and bar velocity [11, 44, 49, 50]. Such increases were observed during the back squat [11] and bench press exercise [44, 49, 50]. Wilk et al. [50] assessed the impact of intermittent BFR on power output and bar velocity changes during the bench press at 70% 1RM. For BFR both narrow (4 cm) and wide (10 cm) cuffs with pressure at 90% AOP were used. Significant increases in bar velocity and power output were recorded, but only when the wide cuff was used. However, such an improvement was not observed during resistance exercise under the narrow cuff, suggesting that cuff width significantly affects acute exercise responses during BFR resistance training [50], which is also compatible with the previous studies [13, 21, 33]. Results of the study by Wilk et al. [50] were confirmed by Wilk et al. [49], who also reported significant increases in power output and bar velocity during the bench press exercise at 70% 1RM for the BFR condition compared to the control. Moreover, the study by Wilk et al. [49] demonstrated that acute increases in power output and bar velocity under BFR occur during several sets of bench press exercise.

Although the above-mentioned studies by Wilk et al. [49, 50] showed an acute increase in power performance for BFR conditions, it applies only to the constant value of the external load. The acute impact of BFR on movement velocity during the bench press using variable loads was assessed in another study by Wilk et al. [44]. Wilk et al. [44] showed that peak bar velocity significantly increased during the intermittent and continuous BFR bench press exercise, but only at lower external loads (20-50% 1RM). No such improvement was observed at higher external loads (above 60% 1RM). Furthermore, intermittent or continuous BFR did not change the mean bar velocity at all used loads. It might be concluded that power performance enhancement under BFR is associated with the external load used. Furthermore, it has been suggested that in order to achieve an increase in bar velocity during exercise under BFR at higher external loads, a higher occlusion pressure and wider cuffs are necessary [44].

The acute impact of BFR on power output and bar velocity has been examined not only when applying various external loads, but also different types of movement (upper body/lower body). A study by Gepfert et al. [11] focused on the acute BFR impact on power output and bar velocity in lower-body, multi-joint movement. Similarly to the study by Wilk et al. [48], during the experimental protocol intermittent BFR with an extremely high cuff pressure (100 and 150% AOP) was used. Gepfert et al. [11] showed that only extremely high-pressure external compression (150% AOP) significantly increased the peak and mean values of power output and bar velocity during the back squat exercise at 70% 1RM. However, no such improvement of performance was observed at lower cuff pressure (100% AOP), which is contradictory to the findings reported by Wilk et al. [50]. In that study Wilk et al. [50] showed a significant increase in power output and bar velocity during the bench press exercise with cuff pressure amounting to 90% AOP. It seems that compression pressure during the back squat needs to be higher than the compression pressure during the bench press in order to provide a similar enhancement in power output and bar velocity, which is possibly due to the larger circumference and length of the lower limb in comparison to the upper limb [11]. Therefore, the level of cuff pressure may be a critical factor in BFR multi-joint resistance exercises in terms of power output and bar velocity enhancement. A higher cuff pressure may allow to store and recoil larger amounts of elastic energy [48], which may be the main factor affecting the increase in performance [11].

Furthermore, as previously suggested by Rawska et al. [32], the performance increase under the BFR condition occurred regardless of the fact that the main muscles involved in the movement are not directly affected by occlusion. While Rawska et al. [32] refered to the bench press exercise, a similar phenomenon occurs during the back squat exercise investigated in a study by Gepfert et al. [11]. During the back squat cuffs are located at the most proximal region of each leg [11]; however, a major contributor, particularly during the concentric part of the squat, is the gluteus maximus, which exhibits greater EMG activity compared to the vastus lateralis, vastus medialis and biceps femoris [4]. Thus, exercise characteristics may also partially contribute to the improved power output performance during the back squat exercise under BFR.

As presented in the aforementioned studies regarding the acute effects of BFR on power output and velocity of the movement, BFR resistance training focused on power development should consider the use of a wide cuff and high or extremely high cuff pressure. Resistance training under BFR may serve as a novel tool in power development, particularly for high-level athletes [11, 44, 49, 50].

Acute effects of BFR on maximal strength

Maximal strength has been acknowledged as a major factor influencing sports performance [38] and is usually measured by the maximal load lifted for 1RM [7]. BFR impact on maximal strength currently remains insufficiently examined. Although some research indicated that BFR may improve 1RM performance, the authors examined chronic adaptations following 6- and 7-week resistance training programs [25, 26]. Only one study by Wilk et al. [48] examined the acute impact of BFR on the result of the 1RM test. In that study Wilk et al. [48] showed significant increases in the result of the 1RM test during the bench press exercise under BFR at the pressure of 150% AOP; however, such increases were not observed at 100% AOP. It should be noted that both conditions (100 and 150% AOP) caused full arterial occlusion and a similar level of metabolic stress and fatigue, which was relatively low given the short duration of the effort [48]. Thus, the effectiveness of BFR was possibly less related to the metabolic factors and more to the mechanical factors, such as the mechanical energy accumulated in the cuff proportional to its width [48]. Therefore, similarly to the result related to power performance it seems that in order to increase the maximal load lifted under BFR extremely high pressure values need to be applied. However, to the best of the authors' knowledge there is no other study analyzing the acute impact of BFR on 1RM performance, which limits the possibility for comparison to other results.

Furthermore, a similar increase in the maximal load lifted is also observed during the bench press exercise when the bench press shirt is used [46]. Similarly to the cuff, the bench press shirt is a passive element, but during movement (especially in the eccentric contraction) the strain of the material, of which the shirt is made, may provide additional elastic energy [46]. Moreover, the effectiveness of the bench press shirt is related to the level of compression [46], which may confirm that the effectiveness of BFR in increasing 1RM performance during the bench press exercise is related to mechanical factors [48].

Conclusions

The results of the studies focused on the acute effect of BFR during isotonic resistance exercise are indicative of its utility as a tool to increase athletic performance; however, long term adaptations are rather unclear [11]. It should be taken into account that BFR resistance exercise is not devoid of drawbacks and potential side effects. It should be introduced gradually, carefully and with proper periodization as a supplemental training method [44]. Furthermore, it should be mentioned that certain individuals do not benefit from exercise under BFR (non-responders) and individual characteristics of an athlete may also influence resistance training under BFR [51], establishing a need for personalized training programs [50]. BFR resistance exercise effectiveness seems to be dependent on mechanical factors such as mechanical energy accumulated and generated by the cuff, which may explain increased acute exercise responses under BFR, particularly when multi-joint exercises and high or extremely high cuff pressures are used. It is also important to note that the magnitude of impact of respective factors on performance enhancement during resistance exercise under BFR still requires further research.

Conflict of interests

The authors declare no conflict of interest.

References

1. Andreas M, Schmid AI, Keilani M, Doberer D, Bartko J, Crevenna R, et al. Effect of ischemic preconditioning in skeletal muscle measured by functional magnetic resonance imaging and spectroscopy: a randomized crossover trial. J Cardiovasc Magn Reson. 2011;13(1):32. https://doi.org/10.1186/1532-429X-13-32.
2. Argus CK, Gill ND, Keogh JW, Hopkins WG. Assessing the variation in the load that produces maximal upper-body power. J Strength Cond Res. 2014;28(1):240-244. https://doi.org/10.1519/JSC.0b013e318295d1c9.
3. Bailey TG, Birk GK, Cable NT, Atkinson G, Green DJ, Jones H. Remote ischemic preconditioning prevents reduction in brachial artery flow-mediated dilation after strenuous exercise. Am J Physiol Heart Circ

Physiol. 2012;303(5):H533-8. https://doi.org/10.1152/ajpheart.00272.2012.

4. Caterisano A, Moss RE, Pellinger TK, Woodruff K, Lewis VC, Booth W, et al. The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. J Strength Cond Res. 2002;16(3):428-432.
5. Cook SB, Scott BR, Hayes KL, Murphy BG. Neuromuscular adaptations to low-load blood flow restricted resistance training. J Sports Sci Med. 2018;17(1):66-73.
6. Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B. Wide tourniquet cuffs more effective at lower inflation pressures. Acta Orthop Scand. 1988;59:447-451. https://doi.org/10.3109/17453678809149401.
7. Cronin JB, McNair PJ, Marshall RN. The role of maximal strength and load on initial power production. Med Sci Sports Exerc. 2000;32(10):1763-1769. https://doi.org/10.1097/00005768-200010000-00016.
8. Dankel SJ, Buckner SL, Jessee MB, Mattocks KT, Mouser JG, Counts BR, et al. Can blood flow restriction augment muscle activation during high-load training? Clin Physiol Funct Imaging. 2018;38(2):291-295. https://doi.org/10.1111/cpf.12414.
9. Farup J, Paoli F, Bjerg K, Riis S, Ringgard S, Vissing K. Blood flow restricted and traditional resistance training performed to fatigue produce equal muscle hypertrophy. Scand J Med Sci Sports. 2015;25:754-763. https://doi.org/10.1111/sms.12396.
10. Fujita T, Brechue W, Kurita K, Sato Y, Abe T. Increased muscle volume and strength following six days of low-intensity resistance training with restricted muscle blood flow. Int J KAATSU Train Res. 2008;4:1-8. https://doi.org/10.3806/ijktr.4.1.
11. Gepfert M, Krzysztofik M, Kostrzewa M, Jarosz J, Trybulski R, Zajac A, et al. The acute impact of external compression on back squat performance in competitive athletes. Int J Environ Res Public Health. 2020;17(13):4674. https://doi.org/10.3390/ijerph17134674.
12. Incognito AV, Burr JF, Millar PJ. The effects of ischemic preconditioning on human exercise performance. Sports Med. 2015;46(10):1575-1576. https://doi.org/10.1007/s40279-015-0433-5.
13. Jessee MB, Buckner SL, Dankel SJ, Counts BR, Abe T, Loenneke JP. The influence of cuff width, sex, and race on arterial occlusion: implications for blood flow restriction research. Sports Med. 2016;46:913-921. https://doi.org/10.1007/s40279-016-0473-5.
14. Krzysztofik M, Golas A, Wilk M, Stastny P, Lockie RG, Zajac A. A comparison of muscle activity between the cambered and standard bar during the bench press exercise. Front Physiol. 2020;11:875. https://doi.org/10.3389/fphys.2020.00875.
15. Krzysztofik M, Wilk M, Filip A, Zmijewski P, Zajac A, Tufano JJ. Can post-activation performance enhancement (PAPE) improve resistance training volume during the bench press exercise? Int J Environ Res Public Health. 2020;17(7):2554. https://doi.org/10.3390/ijerph17072554.
16. Krzysztofik M, Wilk M, Golas A, Lockie RG, Maszczyk A, Zajac A. Does eccentric-only and concentric-only activation increase power output? Med Sci Sports Exerc. 2020;52(2):484-489. https://doi.org/10.1249/MSS.0000000000002131.
17. Krzysztofik M, Wilk M, Wojdala G, Golas A. Maximizing muscle hypertrophy: a systematic review of advanced resistance training techniques and methods. Int J Environ Res Public Health. 2019;16(24):4897. https://doi.org/10.3390/ijerph16244897.
18. Krzysztofik M, Zajac A, Zmijewski P, Wilk M. Can the cambered bar enhance acute performance in the bench press exercise? Front Physiol. 2020;11:577400. https://doi.org/10.3389/fphys.2020.577400.
19. Laurentino GC, Ugrinowitsch C, Roschel H, Aoki MS, Soares AG, Neves MJ, et al. Strength training with blood flow restriction diminishes myostatin gene expression. Med Sci Sports Exerc. 2012;44:406-412. https://doi.org/10.1249/MSS.0b013e318233b4bc.
20. Loenneke JP, Balapur A, Thrower AD, Barnes J, Pujol TJ. Blood flow restriction reduces time to muscular failure. Eur J Sport Sci. 2012;12(3):238-243. https://doi.org/10.1080/17461391.2010.551420.
21. Loenneke JP, Fahs CA, Rossow LM, Sherk VD, Thiebaud RS, Abe T. Effects of cuff width on arterial occlusion: implications for blood flow restricted exercise. J Appl Physiol. 2012;112(8):2903-2912. https://doi.org/10.1007/s00421-011-2266-8.
22. Loenneke JP, Pujol TJ. The use of occlusion training to produce muscle hypertrophy. Strength Cond J. 2009;31:77--84. https://doi.org/10.1519/SSC.0b013e3181a5a352.
23. Loenneke JP, Thiebaud RS, Abe T, Bemben MG. Blood flow restriction pressure recommendations: the hormesis hypothesis. Med Hypotheses. 2014;82(5):623-626. https://doi.org/10.1016/j.mehy.2014.02.023.
24. Loenneke PJ, Wilson JM, Marin PJ, Zourdos MC, Bemben MG. Low intensity blood flow restriction training: a meta-analysis. Eur J Appl Physiol. 2012;112(5):1849--1859. https://doi.org/10.1007/s00421-011-2167-x.
25. Luebbers PE, Fry AC, Kriley LM, Butler MS. The effects of a 7-week practical blood flow restriction program on well-trained collegiate athletes. J Strength Cond Res. 2014;28(8):2270-2280. https://doi.org/10.1519/JSC.0000000000000385.
26. Luebbers PE, Witte EV, Oshel JQ, Butler MS. The effects of practical blood flow restriction training on

adolescent lower body strength. J Strength Cond Res. 2019;33(10): 2674-2683. https://doi.org/10.1519/JSC.0000000000002302.

27. Manimmanakorn A, Manimmanakorn N, Taylor R, Draper N, Billaut F, Shearman JP, et al. Effects of resistance training combined with vascular occlusion or hypoxia on neuromuscular function in athletes. Eur J Appl Physiol. 2013;113:1767-1774. https://doi.org/10.1007/s00421-013-2605-z.
28. Manini TM, Vincent KR, Leeuwenburgh CL, Lees HA, Kavazis AN, Borst SE, et al. Myogenic and proteolytic mRNA expression following blood flow restricted exercise. Acta Physiol (Oxf). 2011;201:255-263. https://doi.org/10.1111/j.1748-1716.2010.02172.x.
29. Marocolo IC, Da Mota GR, Londe AM, Patterson SD, Neto OB, Marocolo M. Acute ischemic preconditioning does not influence high-intensity intermittent exercise performance. PeerJ. 2017;30(5):e4118. https://doi.org/10.7717/peerj.4118.
30. McEwen JA, Owens JG, Jeyasurya J. Why is it crucial to use personalized occlusion pressures in blood flow restriction (BFR) rehabilitation? J Med Biol Eng. 2019;39(3):173-177. https://doi.org/10.1007/s40846-018-0397-7.
31. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, et al. Blood flow restriction exercise: considerations of methodology, application, and safety. Front Physiol. 2019;15:10:533. https://doi.org/10.3389/fphys.2019.00533.
32. Rawska M, Gepfert M, Mostowik A, Krzysztofik M, Wojdala G, Lulinska A, et al. Does blood flow restriction influence the maximal number of repetitions performed during the bench press? A pilot study. Balt J Health Phys Act. 2019;11:9-17. https://doi.org/10.29359/BJHPA.11.4.02.
33. Rossow LM, Fahs CA, Loenneke JP, Thiebaud RS, Sherk VD, Abe T, et al. Cardiovascular and perceptual responses to blood-flow-restricted resistance exercise with differing restrictive cuffs. Clin Physiol Funct Imaging. 2012;32(5):331-337. https://doi.org/10.1111/j.1475-097X.2012.01131.x.
34. Schoenfeld BJ, Ogborn DI, Krieger JW. Effect of repetition duration during resistance training on muscle hypertrophy: a systematic review and meta-analysis. Sports Med. 2015;45:577-585. https://doi.org/10.1007/s40279-015-0304-0.
35. Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Exercise with blood flow restriction: an updated evidence-based approach for enhanced muscular development. Sports Med. 2015;45:313-325. https://doi.org/10.1007/s40279-014-0288-1.
36. Shimizu R, Hotta K, Yamamoto S, Matsumoto T, Kamiya K, Kato M, et al. Low-intensity resistance training with blood flow restriction improves vascular endothelial function and peripheral blood circulation in healthy elderly people. Eur J Appl Physiol. 2016;116:749-757. https://doi.org/10.1007/s00421-016-3328-8.
37. Singh L, Randhawa PK, Singh N, Jaggi AS. Redox signaling in remote ischemic preconditioning-induced cardioprotection: evidences and mechanisms. Eur J Pharmacol. 2017;809:151-155. https://doi.org/10.1016/j.ejphar.2017.05.033.
38. Taber C, Bellon C, Abbott H, Bingham GE. Roles of maximal strength and rate of force development in maximizing muscular power. Strength Cond J. 2016;38(1):71-78. https://doi.org/10.1519/SSC.0000000000000193.
39. Takano H, Morita T, Iida H, Asada K, Kato M, Uno K, et al. Hemodynamic and hormonal responses to a short-term low-intensity resistance exercise with the reduction of muscle blood flow. Eur J Appl Physiol. 2005;95:65--73. https://doi.org/10.1007/s00421-005-1389-1.
40. Takarada Y, Takazawa H, Sato Y, Takebayashi S, Tanaka Y, Ishii N. Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. J Appl Physiol. 2000;88:2097-2106. https://doi.org/10.1152/jappl.2000.88.6.2097.
41. Wernbom M, Augustsson J, Thomee R. Effects of vascular occlusion on muscular endurance in dynamic knee extension exercise at different submaximal loads. J Strength Cond Res. 2006;20(2):372-377. https://doi.org/10.1519/R-16884.1.
42. Wernbom M, Järrebring R, Andreasson M, Augustsson J. Acute effects of blood flow restriction on muscle activity and endurance during fatiguing dynamic knee extensions at low load. J Strength Cond Res. 2009;23(8):2389-2395. https://doi.org/10.1519/JSC.0b013e3181bc1c2a.
43. Wilk M, Gepfert M, Krzysztofik M, Mostowik A, Filip A, Hajduk G, et al. Impact of duration of eccentric movement in the one-repetition maximum test result in the bench press among women. J Sports Sci Med. 2020;19(2):317--322.
44. Wilk M, Gepfert M, Krzysztofik M, Stastny P, Zajac A, Bogdanis GC. Acute effects of continuous and intermittent blood flow restriction on movement velocity during bench press exercise against different loads. Front Physiol. 2020;27:11:569915. https://doi.org/10.3389/fphys.2020.569915.
45. Wilk M, Golas A, Zmijewski P, Krzysztofik M, Filip A, Del Coso J, et al. The effects of the movement tempo on the one-repetition maximum bench press results. J Hum Kinet. 2020;72:151-159. https://doi.org/10.2478/hukin-2020-0001.

46. Wilk M, Krzysztofik M, Bialas M. The influence of compressive gear on maximal load lifted in competitive powerlifting. Biol Sport. 2020;37(4):437-441. https://doi.org/10.5114/biolsport.2021.100145.
47. Wilk M, Krzysztofik M, Drozd M, Zajac A. Changes of power output and velocity during successive sets of the bench press with different duration of eccentric movement. Int J Sports Physiol Perform. 2020;15:162--167. https://doi.org/10.1123/ijspp.2019-0164.
48. Wilk M, Krzysztofik M, Filip A, Lockie RG, Zajac A. The acute effects of external compression with blood flow restriction on maximal strength and strength-endurance performance of the upper limbs. Front Physiol. 2020;11:567. https://doi.org/10.3389/fphys.2020.00567.
49. Wilk M, Krzysztofik M, Filip A, Szkudlarek A, Lockie RG, Zajac A. Does post-activation performance enhancement occur during the bench press exercise under blood flow restriction? Int J Environ Res Public Health. 2020;17(11):3752. https://doi.org/10.3390/ijerph17113752.
50. Wilk M, Krzysztofik M, Filip A, Zajac A., Bogdanis GC, Lockie RG. Short-term blood flow restriction increases power output and bar velocity during the bench press. J Strength Cond Res. Epub 2020 May 5. https://doi.org/10.1519/JSC.0000000000003649.
51. Wilk M, Krzysztofik M, Gepfert M, Poprzecki S, Gołaś A, Maszczyk A. Technical and training related aspects of resistance training using blood flow restriction in competitive sport – a review. J Hum Kinet. 2018;65:249--260. https://doi.org/10.2478/hukin-2018-0101.
52. Wilk M, Tufano JJ, Zajac A. The influence of movement tempo on acute neuromuscular, hormonal, and mechanical responses to resistance exercise – a mini review. J Strength Cond Res. 2020;34(8):2369-2383. https://doi.org/10.1519/JSC.0000000000003636.
53. Yasuda T, Loenneke JP, Ogasawara R, Abe T. Influence of continuous or intermittent blood flow restriction on muscle activation during low-intensity multiple sets of resistance exercise. Acta Physiol Hung. 2013;100(4):419--426. https://doi.org/10.1556/aphysiol.100.2013.4.6.
54. Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. Eur J Appl Physiol. 2011;111:2525-2533. https://doi.org/10.1007/s00421-011-1873-8.