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REVIEW ARTICLE

Exercise with Blood Flow Restriction: An Updated Evidence-Based Approach for Enhanced Muscular Development

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Abstract A growing body of evidence supports the use of moderate blood flow restriction (BFR) combined with low-load resistance exercise to enhance hypertrophic and strength responses in skeletal muscle. Research also suggests that BFR during low-workload aerobic exercise can result in small but significant morphological and strength gains, and BFR alone may attenuate atrophy during periods of unloading. While BFR appears to be beneficial for both clinical and athletic cohorts, there is currently no common consensus amongst scientists and practitioners regarding the best practice for implementing BFR methods. If BFR is not employed appropriately, there is a risk of injury to the participant. It is also important to understand how variations in the cuff application can affect the physiological responses and subsequent adaptation to BFR training. The optimal way to manipulate acute exercise variables, such as exercise type, load, volume, inter-set rest periods and training frequency, must also be considered prior to designing a BFR training programme. The purpose of this review is to provide an evidence-based approach to implementing BFR exercise. These guidelines could be useful for practitioners using BFR training in either clinical or athletic settings, or for researchers in the design of future studies investigating BFR exercise.

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Key Points

- The blood flow restriction (BFR) stimulus should be individualized for each participant. In particular, consideration should be given to the restrictive pressure applied and cuff width used.
- BFR elicits the largest increases in muscular development when combined with low-load resistance exercise, though some benefits may be seen using BFR alone during immobilization or combined with low-workload cardiovascular exercise.
- For healthy individuals, training adaptations are likely maximized by combining low-load BFR resistance exercise with traditional high-load resistance exercise.

1 Introduction

It is generally accepted that significant adaptation to resistance exercise requires moderate- or high-load training, using loads equivalent to at least 70 % of 1-repetition maximum (1RM) [1]. However, mounting evidence now supports the use of blood flow restriction (BFR) combined with low-load resistance exercise (∼20–40 % 1RM) to enhance morphological and strength responses. This novel strategy involves the application of an inflatable cuff or tourniquet around a limb (proximal to the muscles being trained), which limits blood delivery to and from contracting muscles. Training with BFR can facilitate muscular changes in clinical populations [2, 3] and athletes alike [4, 5]. While the physiological mechanisms that underpin adaptive responses to BFR training are not yet fully understood, this form of training is becoming popular as a way to enhance muscular responses without the need for high mechanical loads.

Currently, there are no standardized recommendations for the application of BFR during resistance exercise. Although injury resulting from this type of training is rare, the possibility exists that inappropriate implementation could result in detrimental side effects such as subcutaneous haemorrhage and numbness [6, 7]. Recently, it has been hypothesized that the optimal BFR pressure may follow a hormetic-like relationship [8]. It is likely that if the restrictive pressure is too low, muscular responses may not be significantly augmented. Furthermore, extremely high pressures (i.e. those that occlude arterial inflow during inter-set rest and/or exercise) may not enhance muscular development more than moderate pressures, and may in fact be a safety concern [8], particularly for individuals with compromised vascular function. Sub-optimal training responses are also likely if either the BFR stimulus or the training prescribed does not follow scientific rationale. It is therefore important to ensure that an evidence-based approach is employed when implementing BFR training. This paper aims to provide evidence-based recommendations for the safe implementation of BFR, particularly in combination with resistance training. The acute and adaptive responses to BFR resistance exercise are discussed, followed by explanation of the potential mechanisms that may facilitate these responses. Furthermore, other BFR strategies (application during rest or combined with low-workload cardiovascular exercise) are described. The current understanding of how best to apply BFR to a limb, effective manipulation of exercise variables for this training method, and the contexts in which BFR resistance exercise may provide benefit are then summarized.

2 Adaptive Responses and Potential Mechanisms Underpinning Blood Flow Restriction (BFR) Training

The muscular benefits arising from BFR training are often promoted for cohorts where high mechanical loads may be contraindicated or not possible, including post-operation rehabilitation patients [2, 3] and the elderly [9, 10]. While the vast majority of BFR research has been conducted using untrained participants, several investigations have also demonstrated muscular benefits from BFR in athletic populations [5, 11–17]. As these individuals have already achieved a high level of muscular development, low-load resistance training would not normally facilitate such benefits, suggesting that the addition of BFR stimulates these responses. Several investigations have also reported that even low-workload aerobic exercise performed with BFR can result in muscular hypertrophy and strength improvements, albeit small [18–22]. While these adaptive responses have been repeatedly demonstrated, the definitive mechanisms underpinning them are not well understood.

In a recent review, we highlighted the complex interplay of mechanisms that may drive the adaptive responses to resistance training with hypoxia [23]. We propose that a localized hypoxic stimulus may play an important mechanistic role with BFR in combination with low-load resistance exercise. Downstream of the hypoxic stimulus, it is likely that a greater accumulation of metabolites, due to both increased production in the more hypoxic state and limited removal due to the BFR itself, acts as a primary moderator of the anabolic response to this form of exercise [24]. Importantly, this accumulation of metabolites may increase muscle cell swelling [25], intramuscular anabolic/anti-catabolic signalling [9, 26, 27], and muscle fibre recruitment [4, 28], which are all thought to be beneficial for muscular adaptation [23]. Furthermore, evidence suggests that the hypoxic environment created during BFR may increase the activation and proliferation of myogenic stem cells, enhancing the hypertrophic response [29]. Significantly elevated endocrine responses have also been observed [4]. However, the role of acute endocrine responses in resistance training adaptation has been recently questioned, and may not have anabolic effects in healthy individuals as once thought [30].

It should be noted, however, that the exact hypoxic response to BFR exercise is not well understood. While expression of hypoxia-inducible factor-1α is known to increase in response to hypoxia [31], some evidence suggests that it is expressed to a similar degree following low-load resistance exercise either with or without BFR [32]. However, conflicting results have been observed in another study, where hypoxia-inducible factor-1α was increased by a significantly larger amount at 4 hours following a bout of low-load BFR exercise than the equivalent unrestricted exercise [33]. While it is possible that a degree of hypoxia results from the addition of BFR during exercise, it is difficult at this point to reconcile whether tissue hypoxia does in fact drive downstream responses to a BFR stimulus.

Although there is growing interest in the mechanisms by which BFR can augment resistance training adaptation, we do not yet fully understand the myriad of physiological processes involved, and further research is required. That said, it is now well acknowledged that BFR can enhance the adaptive responses to low-load resistance exercise, and that these adaptations are dependent on both the BFR stimulus itself and the exercise protocol performed. The following sections of this review highlight the various factors that should be considered when implementing BFR training; they also provide practical recommendations for how best to manipulate these variables for optimal responses.

3 Cuff Application

3.1 Type of Cuff

The BFR technique generally involves application of a tourniquet [34], inflatable cuff [35] or elastic knee wraps [36] at the top of each arm or leg to restrict blood flow into the muscle, and occlude blood flow out of the muscle. While elastic automated cuff systems have been developed and popularized in Japan, it may be more practical to employ inflatable cuffs or simple elastic wraps, particularly when large groups are performing BFR. The use of elastic knee wraps in particular has been recently popularized in research and real-world contexts as a practical method for implementing BFR without the need for expensive specialized equipment [36]. Furthermore, it has been shown that the narrow nylon cuffs commonly used in BFR research provide a stimulus similar to 5 cm elastic cuffs when inflated to the same target pressure (with an initial pressure of 50 mmHg), both at rest [37] and during exercise [38]. This suggests that any differences between cuffs are predominantly due to cuff width and not to cuff material.

Therefore, one of the most important factors to consider when applying BFR is the width of the cuff. Researchers have used a range of cuff widths for both the legs (4.5–18.5 cm) and the arms (3–12 cm) [39]. Wider cuffs (13.5 cm) have been shown to cause greater ratings of pain and perceived exertion and to limit exercise volume during low-load BFR knee extension exercise when compared with narrow cuffs (5.0 cm) inflated to the same restrictive pressure [40]. Wider cuffs transmit pressure through soft tissue differently to narrow cuffs, which has obvious implications for subsequent training adaptations. To illustrate, Loenneke et al. [41] recently reported that wide cuffs (13.5 cm) restrict arterial blood flow at lower pressures than narrow cuffs (5.0 cm). Indeed, some individuals did not reach complete arterial occlusion using narrow cuffs on the legs, even at pressures of up to 300 mmHg [41]. These results suggest that it may be easier to reach the desired level of occlusive pressure using wider cuffs in the lower body. However, wider cuffs may inhibit the normal range of motion in some people, particularly when applied to the upper body. This may adversely affect exercise performance and negatively impact training adaptation. Furthermore, it is conceivable that the muscular hypertrophy stimulus may be attenuated directly below the cuff [42], though further research on this point is needed.

An interesting finding from Loenneke et al. [41] was that limbs with a larger circumference require higher occlusive pressures to reach the same level of arterial occlusion. Furthermore, limb circumference was as, if not more, effective than laboratory-based measures of limb composition in predicting the pressure required to restrict arterial blood flow [41]. It is therefore important when implementing BFR to consider the width of the cuff to be used, and to assess the circumference of the individual limbs to be trained. Wide cuffs may be necessary for training the lower limbs, due to the higher occlusive pressures required with increased limb circumference. However, wide cuffs may be cumbersome during training of the upper limbs, and narrow cuffs may therefore be more practical for the arms.

3.2 Restrictive Pressure

While early research utilized restrictive pressures in excess of 200 mmHg [4], it is now accepted that BFR pressure should be high enough to occlude venous return from the muscles, yet low enough to maintain arterial inflow into the muscle [8]. Logic therefore dictates that BFR should not be universally applied at an absolute pressure, but should vary relative to each individual [43]. The pressure applied should be dependent on both the cuff width and the size of the limb to which BFR is being applied [41]. This theory is also relevant when considering BFR of the lower and upper limbs; if equivalent restrictive pressures (and cuff widths) are used for both the arms and the legs, it is likely that either arterial inflow in the arms will be limited or that insufficient venous occlusion for venous pooling will occur in the legs. While some BFR investigations have attempted to standardize restrictive pressures relative to brachial systolic blood pressure (bSBP) [44, 45], there is no evidence to suggest that this provides a good estimate of BFR to the lower limbs. This is not surprising, given the large differences in upper and lower limb circumferences. Furthermore, Loenneke et al. [41] demonstrated that bSBP was not able to explain additional variance in estimation of lower body arterial occlusion pressures and questioned the continued use of this method to determine BFR pressures.

To account for inter-individual differences, some investigators have implemented BFR as a percentage of estimated arterial occlusion pressure. Laurentino et al. [27] determined the pressure required for complete vascular restriction at the upper thigh during rest, and they subsequently employed a BFR pressure of 80 % arterial occlusive pressure during low-load resistance training. This training resulted in hypertrophic and strength responses similar to traditional high-load training. Recent results have demonstrated that an individualized BFR pressure of 50 % estimated arterial occlusion pressure appears to maximize electromyography amplitude and increase acute decrements in torque during and following low-load knee extension exercise [46]. Interestingly, increased restrictive pressures (60 % estimated arterial occlusion) did not result in further augmentation of these responses. Our laboratory has also noted that BFR pressures of 50 % arterial occlusion appear to maximize acute muscle swelling and blood lactate responses when combined with low-load resistance exercise (JP Loenneke, unpublished findings). However, while pre-determining arterial occlusion pressures may be effective with wide cuffs, it is likely that complete arterial occlusion may not be possible in some individuals using narrow cuffs.

Loenneke et al. [47] recently presented a method of applying BFR using a narrow cuff (5 cm) based on each individual's thigh circumference. This work was derived from their previous assessment of factors contributing to arterial occlusion pressures in a large cohort of men and women ($n = 116$) [41]. Thigh circumference was measured at 33 % of the distance from the inguinal crease to the superior border of the patella, as this was described as the position where cuffs would be applied during BFR [41]. This method used a BFR stimulus equivalent to 60 % of arterial occlusion, estimated from thigh circumference as follows: <45–50 cm = 120 mmHg; 51–55 cm = 150 mmHg; 56–59 cm = 180 mmHg; and ≥60 cm = 210 mmHg. However, published research has not yet examined the efficacy of these recommendations for enhancing adaptive responses to training. Additionally, these circumference-based pressure recommendations are specific to the lower limbs, and similar guidelines have not been presented for the upper limbs.

While using elastic knee wraps for BFR makes it difficult to apply the restrictive stimulus at an exact pressure, Wilson et al. [48] have shown that this method is effective when wraps are applied to be snug but not cause pain. These investigators standardized the restrictive stimulus using a perceived pressure scale from 0 to 10, with a score of 0 indicating no pressure and 10 indicating intense pressure with pain [48]. Wilson et al. [48] proposed that wraps should be applied so that a score of 7 (moderate pressure with no pain) is achieved, as this corresponded with occluded venous return without stopping arterial inflow. However, recent data from our laboratory (JP Loenneke, unpublished findings) do not find large differences in ratings of discomfort during exercise across a variety of pressures, indicating that perception may not provide the best estimate of actual restriction. With knee wraps, it may be better to gauge pressure on the total repetitions that can be completed. As higher pressures negatively impact total exercise volume (JP Loenneke, unpublished findings), the total repetitions completed per set may provide information regarding the overall tightness of the wraps. Thus, if wraps are applied and the participant cannot achieve close to the goal number of low-load repetitions each set, then they may be too tight and should be loosened.

Although it is difficult to make precise recommendations regarding the optimal pressure to use during BFR, the most important factors to consider are the width of the cuff, circumference of the limb being exercised, and the individual pressure for that limb where arterial blood flow is completely occluded. It is important to understand that both the pressure and the width of the cuff employed during BFR operate in concert to provide the restrictive stimulus, and therefore neither should be considered as an independent indicator of the restrictive effects. Further research is needed before a comprehensive understanding is reached, though it appears that a BFR pressure equivalent to 50–80 % of the pressure required to occlude arterial flow is appropriate during low-load resistance exercise [27, 46].

4 Exercise Stimulus

4.1 Type of Exercise

Interestingly, BFR alone during periods of muscular unloading has been found to attenuate disuse atrophy [2, 49, 50]. For example, Takarada et al. [2] reported that BFR alone (five sets of 5 min BFR with 3 min of free flow between sets at a pressure of 180–260 mmHg) can attenuate post-operative disuse atrophy in patients recovering from surgical reconstruction of the anterior cruciate ligament. Additionally, research using a cast immobilization model has demonstrated that BFR alone applied in an intermittent fashion (five sets of 5 min with 3 min of free flow between sets) may prevent disuse weakness induced by chronic unloading, even when using restrictive pressures as low as 50 mmHg [49, 50]. The application of BFR during periods of bed rest or immobilization is a novel strategy that may be used to aid in recovery from injury or surgery, even when unloaded movements cannot be tolerated. Nonetheless, BFR must be combined with an exercise stimulus for enhanced muscular development. Even simply walking with BFR has been shown to facilitate small improvements in muscle strength and size [19–22].

Ozaki et al. [21] have demonstrated that elderly adults who trained 4 days per week for 10 weeks using low-workload walk training (20 min at 45 % heart rate reserve) displayed increases in maximum knee joint strength

(~15 %) and thigh muscle cross-sectional area (CSA; ~3 %) when combined with BFR (140–200 mmHg). Similarly, Abe et al. [20] demonstrated that training 5 days per week for 6 weeks using low-workload walking (20 min at 67 m min^{-1}) with BFR (160–200 mmHg) increased knee extension and flexion torque and thigh CSA in elderly adults, though there were no changes in a non-restricted control group. Low-workload cycling exercise (15 min at 40 % of maximal aerobic capacity) has also been shown to elicit increases in thigh CSA and isometric strength when combined with BFR (160–210 mmHg) in young men. Taken together, these data demonstrate that low-workload walk and cycling training with BFR can produce small, albeit significant, improvements in muscle size and strength.

However, it appears that BFR provides the most substantial muscular gains when combined with low-load resistance exercise. As BFR limits blood flow to and from the limb, muscles of the trunk are unable to be trained under the same conditions, and research has predominantly focused on changes in the size of the limb muscles. Several investigations have reported significant muscular adaptations in both the arms [51, 52] and the legs [27, 53] following single-joint training with BFR. However, evidence suggests that BFR resistance training with multi-joint exercise can also facilitate significant hypertrophy in muscles of the trunk [54–56].

Yasuda et al. [56] demonstrated that 6 weeks of low-load BFR bench press training (3 days each week using 30 % 1RM) increased the CSA of the triceps brachii (4.9 %) as well as the pectoralis major (8.3 %). However, it must be acknowledged that a high-load training group (three sets of ten at 75 % 1RM) resulted in greater increases in CSA than low-load BFR training for both the triceps brachii (8.6 %) and pectoralis major (17.6 %) [56]. Furthermore, while increases in the CSA of limb and trunk muscles were significantly related in the high-load training group ($r = 0.70$, $p = 0.02$), they were not related in the BFR group ($r = 0.54$, $p = 0.13$) [56]. Nevertheless, this study was not of a crossover design, and each training group contained only ten participants. It is possible that individual differences in training responses may have influenced the correlational analyses, and further research is therefore required to comprehensively understand the relationships between trunk and limb hypertrophy following BFR training.

An interesting factor to consider is whether the relative contribution of trunk and limb muscles to multi-joint actions is altered following BFR training. While it does appear the BFR can benefit muscles of the trunk, these effects may be somewhat smaller than changes in the limb musculature. Currently, there is not sufficient evidence to state whether muscles of the trunk can benefit as much from BFR training as muscles of the limbs, and caution should be taken to ensure that muscular imbalances are not induced by disproportionate adaptations to BFR training. While multi-joint actions may be more related to everyday and athletic movement patterns, it is possible that long-term use of BFR training only could result in muscular imbalances between limb and trunk muscles. Future research should investigate this further. Taken together, current data suggest that for individuals who are immobile or cannot tolerate even low-load resistance exercise, using BFR at rest or during walking can attenuate muscular atrophy and stimulate hypertrophy, respectively. For untrained populations, it appears that intermittent BFR (5 × 5 min BFR with 3 min of free flow between) applied twice daily may reduce functional strength declines, even when using pressures as low as 50 mmHg. Furthermore, 15–20 min of low-workload cardiovascular exercise (e.g. 40 % of maximal aerobic capacity) combined with BFR can produce muscular development. However, the largest muscular benefits will result from BFR in combination with single- and multi-joint low-load resistance training.

4.2 Exercise Loads

Proponents of BFR training highlight that one of its primary benefits is that muscular adaptations are possible without using heavy loads. Therefore, low-load BFR training may be beneficial for both clinical populations for whom high-load training is contraindicated and athletic cohorts looking to manage their total training stress [23]. Low mechanical loads combined with BFR do not result in skeletal muscle damage, prolonged decrements in muscle function, or exaggerated muscle soreness ratings [57].

The minimum resistance exercise intensities to elicit muscular hypertrophy in the restricted limb and non-restricted trunk and hip muscles are approximately 10 and 20 % of maximum voluntary contraction (MVC), respectively [58]. In a recent meta-analysis, low-load BFR resistance exercise was observed to have the largest effect on muscle hypertrophy and strength when intensities of 15–30 % 1RM or MVC were used [59]. To illustrate, Laurentino et al. [27] demonstrated that 8 weeks of low-load knee extension training (twice per week using three sets of 15 repetitions) at 20 % 1RM resulted in a large increase in knee extension 1RM (40.1 %) in concert with a substantial increase in quadriceps CSA (6.3 %). Similarly, Abe et al. [54] reported that 2 weeks of BFR training (twice daily 6 days per week with three sets of 15 repetitions of squats and leg curls) using 20 % 1RM resulted in large increases in squat and leg curl 1RM (17 and 23 %, respectively) as well as considerable increases in quadriceps, biceps femoris and gluteus maximus muscle volume (7.7, 10.1 and 9.1 %, respectively).

Evidence suggests that when training with multiple sets, as is typical in real-world training protocols, a load of 20 % 1RM combined with continuous BFR (i.e. maintained during inter-set rest periods) results in a metabolic stimulus similar to multiple sets of high-load resistance exercise [60]. Interestingly, while metabolic stress during intermittent BFR (i.e. BFR released between sets) was greater than the equivalent exercise without BFR, it did not reach the same levels as following the continuous BFR or high-load protocols. The degree of metabolic stress is proposed to be a powerful moderator of hypertrophic responses to resistance training [24]. Therefore, these data also suggest that BFR should be applied continuously across an exercise protocol to optimize the metabolic stress and subsequent adaptive responses.

Interestingly, Cook et al. [5] recently reported that BFR applied to the lower limbs during higher-load strength training (five sets of five repetitions with 70 % 1RM) resulted in significantly greater improvements in bench press and squat strength than non-restricted training. These findings contradict those of Laurentino et al. [61], who have previously demonstrated no additional benefit for BFR during moderate-load (12RM) and high-load (6RM) resistance exercise on measures of muscular strength and size. However, considering the small strength improvements reported by Cook et al. [5] (1.4 ± 0.8 and 2.0 ± 0.6 % for the bench press and squat, respectively), it is possible that these changes were within the range of error associated with maximal strength testing. Indeed, the test–retest reliability of 1RM assessment in well-trained males using a back squat variation has a typical error (expressed as a coefficient of variation) of 2.6 % [62]. Further research is therefore required before the effects of high-load BFR training in well-trained participants can be understood. Considering the prevailing body of research, training intensities of 20–40 % 1RM or MVC for BFR resistance exercise appear beneficial for enhanced hypertrophy and strength.

4.3 Training Volume

The volume of training (i.e. amount of work performed in a single session) has a profound effect on resistance training adaptations [63, 64]. Low-load BFR training typically entails substantially more repetitions per session than traditional high-load resistance training, owing to the inverse relationship between exercise intensity and the number of repetitions that can be performed in a set. BFR training research typically employs training volumes ranging from 45 [13] to 75 [55] repetitions of each exercise per session. Several investigations have utilized BFR combined with low-load resistance exercise to volitional fatigue [4, 65, 66]. However, exercise to failure is not submaximal by definition, and therefore may not be appropriate for many clinical populations who would otherwise benefit from BFR training [67]. In addition, evidence suggests that low-load BFR exercise can significantly increase muscle size and strength without the need to train to failure [59]. Extended periods of training to failure can increase physiological markers of over-training [68]. Therefore, while some sets may be taken to failure across a resistance training programme to apply a planned overload stimulus, not all training sessions should follow this approach.

A BFR resistance exercise protocol that has become popular in recent research is four sets of an exercise, with goal repetitions of 30 in the first set, and 15 in sets 2–4, for a total of 75 repetitions [47, 48, 55, 69]. While the optimal resistance training protocol for BFR exercise has not been firmly established, this repetition scheme has been demonstrated to aid in rehabilitation from knee injury [70], enhance acute muscle activation [48] and increase muscle strength and size [53], without increasing indices of muscle damage [47, 48, 69]. As the cuff is applied immediately before the first set, there is no substantial accumulation of metabolites, and participants can perform a high number of repetitions in the first set. In each subsequent set, the number of possible repetitions is reduced, owing to the accumulation of fatiguing metabolites and the impact of metabolic acidosis on contractile function [65].

Interestingly, a recent investigation has demonstrated that, while this standard repetition scheme (30, 15, 15 and 15 repetitions at 20 % 1RM with 60 s inter-set rest) can facilitate hypertrophic and strength responses, doubling the volume of training per session (i.e. performing the protocol twice) had no additive effect on these adaptive responses [71]. This indicates that there may be a volume threshold over which further increases are not advantageous for muscular development. This relationship has been previously observed following traditional resistance training [72, 73]. However, it is also possible that muscular adaptations to BFR training could be maximised at a volume threshold lower than those tested in this study, and further research is warranted.

However, Wernbom et al. [65] reported that active participants performing knee extension to fatigue at 30 % 1RM with 45 s inter-set rest and sustained BFR (90–100 mmHg) could only complete 28 ± 5, 10 ± 2 and 6 ± 1 repetitions in the first, second and fifth sets, respectively. Similarly, Loenneke et al. [74] noted that participants could only perform 26 ± 1 repetitions in a single set at 30 % 1RM with moderate practical BFR. Therefore, it is likely that in the initial phases of training with this repetition scheme, participants may not be able to achieve the desired number of repetitions. In this case, exercise intensity may need to be decreased (i.e. from 30 to 20 % 1RM) and/or inter-set rest periods slightly increased (i.e. from 30 to 45 s) in an attempt to complete the desired number of repetitions. Training intensity and inter-set rest periods should be manipulated in preference to decreasing the volume of each set, as beneficial muscular responses have been demonstrated numerous times at ~20 % 1RM and with greater than 30 s rest between sets [15, 16, 75]. Furthermore, the increased metabolic stress associated with high-repetition sets is likely a key moderator of BFR training adaptation [23, 24]. These collective data highlight the importance of implementing BFR training on an individualized basis, as some participants may require alterations in the exercise loads prescribed, particularly those who are previously untrained or in a detrained state.

Luebbers et al. [15] recently highlighted that the work volume for a session of low-load BFR training may be similar to a traditional high-load session. For example, if an individual with a bench press 1RM of 100 kg were to undertake a common BFR training protocol comprising 75 repetitions using 30 % 1RM, the volume load for that session (repetitions × load) would be 2,250 kg. Similarly, using a typical high-load protocol comprising five sets of six repetitions at 80 % 1RM, a volume load of 2,400 kg would be experienced. Indeed, growing evidence suggests that skeletal muscle hypertrophy may not be mediated by exercise intensity as once believed, and that the volume of training may be a more important variable [76]. When considering the totality of evidence, it appears that individuals new to BFR training should take care to avoid regularly training to muscular failure. As the individual becomes more accustomed to the training stimulus, progressive overload should be applied, with the goal to train using the standard protocol of 30, 15, 15 and 15 repetitions at 30 % 1RM with 30 s inter-set rest.

4.4 Inter-Set Rest Periods

The vast majority of research examining low-load resistance exercise with BFR has used relatively brief inter-set rest periods of 30–60 s. Brief rest periods between sets are associated with an increase in metabolic stress [77], which is thought to be a primary moderator of physiological and subsequent adaptive responses to BFR resistance exercise [23, 24]. Importantly, recovery time between sets of BFR exercise should not be structured to ensure force and power output is maintained in subsequent sets, as is common during maximal strength training [63, 64, 78], but to potentiate targeted physiological responses [23, 79, 80]. Similarly, the general consensus is that the restrictive stimulus should be maintained during the inter-set rest periods, to further amplify the degree of metabolic stress. If BFR is applied appropriately, venous outflow will be occluded, and the clearance of metabolites between sets will be drastically diminished. Although this accumulation of metabolites will no doubt affect performance in subsequent sets, it is likely to be a predominant mechanism underpinning adaptation to BFR exercise [81]. Furthermore, venous pooling between sets will increase cellular swelling, which is also considered to have an important role in the hypertrophic response [25, 82].

4.5 Training Frequency

Low-load resistance exercise with BFR can be completed more frequently than more traditional resistance training programmes. High-frequency low-load resistance training (twice daily for 2 weeks with 20 % 1RM) has resulted in greater increases in squat and leg curl 1RM, and CSA of the thigh and hip muscles, when combined with BFR [54]. Similarly, just 6 days of twice-daily low-load BFR resistance training has produced substantial hypertrophic and strength responses, comparable to studies employing longer training durations and a higher load or volume of exercise [53]. Importantly, even with high training frequencies, markers of muscle damage (creatine phosphokinase and myoglobin) and oxidative stress (lipid peroxide) were not elevated during or after BFR training [54]. Collectively, research has observed BFR resistance exercise to cause no prolonged decrements in muscle function, no prolonged muscle swelling, muscle soreness ratings similar to those with submaximal low-load controls, and no elevation in blood biomarkers of muscle damage [57].

Brief periods of high-frequency BFR resistance training may therefore be beneficial during a period of planned overload. However, extended periods of high-frequency training using only BFR resistance exercise may result in increased levels of training monotony in participants, particularly in athletic populations. As with any resistance training programme, BFR training should be periodized appropriately to ensure both optimal adaptive responses and to limit boredom in participants. Table 1 presents a summary of the recommendations presented in this review regarding the implementation of BFR exercise for both clinical and athletic cohorts.

5 Practical Applications of BFR

5.1 Elderly and Rehabilitation Participants

The muscular adaptations to BFR training may benefit populations such as the elderly or post-surgery rehabilitation patients who exhibit compromised strength and/or joint stability [83]. Periods of bed rest or immobilisation following an illness, surgery or injury have been found to have a deleterious effect on overall muscle mass [67] in both young [84] and elderly [85] populations. As

Table 1 Summary of recommendations for the application of blood flow restriction during resistance training for enhanced hypertrophic and strength adaptations

	Recommendation	Factors to consider
Cuff application	Proximally around the limb to be trained	Trunk muscles can also benefit from BFR during multi-joint exercises
Cuff type	Wide cuffs (~6–13.5 cm) for the legs, and narrow cuffs (3–6 cm) for the arms	Inflatable cuffs and elastic knee wraps may be most practical
Occlusive pressure	Inflatable cuffs: 50–80 % of pressure to occlude arterial flow at rest Elastic wraps: should feel snug but not substantially restrict completion of desired repetition scheme	Limb circumference: Larger limbs require higher pressure Cuff width: Wider cuffs achieve occlusion at lower pressures
Exercise stimulus	BFR alone: Attenuated ↓ in muscle mass and strength BFR + walking/cycling: Moderate ↑ or maintenance of muscle mass and strength Low-load resistance exercise + BFR: substantial ↑ in muscle mass and strength	The type of exercise that can be tolerated should be considered before deciding on an appropriate BFR strategy (Fig. 1). The progressive model proposed by Loenneke et al. [67] should be followed for clinical populations
Type of exercise	Both single- and multi-joint exercises can provide benefit	Hypertrophy between limb and trunk muscles following multi-joint BFR training may be disproportionate
Exercise loads	Low-load exercise (~20–40 % 1RM or MVC)	Multiple sets of low-load BFR exercise provides similar metabolic stimulus to high-load training, but may not replicate neural demands
Training volume	50–80 repetitions per exercise (sets do not need to be performed to muscular failure)	Standard scheme of 30–15–15–15 repetitions equates to 75 total repetitions
Inter-set rest	30–45 s	To ensure sufficient venous pooling, occlusion should be maintained during inter-set rest periods
Training frequency	Clinical populations: 2–3 training sessions per week is sufficient Athletic populations: 2–4 sessions per week, in addition to normal high-load resistance training	May be possible to train twice per day with BFR

BFR blood flow restriction, *MVC* maximum voluntary contraction, *1RM* 1-repetition maximum, ↓ indicates decrease, ↑ indicates increase

mentioned previously, research has demonstrated that BFR alone during periods of cast-immobilisation is able to attenuate these normal atrophic effects, and limit functional declines in muscular strength [2, 49, 50]. A potential application of BFR in this setting is speeding up a patient's post-surgery recovery. By limiting functional declines in muscle size and strength, patients will likely achieve sufficient mobility to engage in rehabilitation exercise sooner, optimizing their recovery process.

Another intriguing application for BFR in these cohorts is during low-workload aerobic exercise. Even walking or cycling, when combined with BFR, can lead to small yet significant improvements in the strength and size of the leg muscles [18–22]. This is important, particularly during the early stages of rehabilitation when only low external loads can be tolerated and even walking unassisted may be challenging. While hypertrophic and strength gains have been reported following aerobic exercise in the elderly, the intensity used was relatively high for this cohort (60–80 % of heart rate reserve) [86]. The benefit of aerobic exercise with BFR, is that both young [18, 19] and elderly [20–22] populations can experience increases in muscle CSA and strength following walk or cycle training at much lower intensities, which is of particular benefit during the early progressions from surgery or illness [67].

The low-load resistance exercise that is typically performed with BFR can reduce the joint articular and ligament stress forces when compared with training with higher loads [23]. As discussed extensively in this paper, low-load resistance exercise combined with BFR can promote the physiological responses necessary for increased muscle mass and strength in individuals who would be unable to facilitate these responses by more traditional training. However, an important consideration for these populations is the prescription of training loads; participants who can only manage relatively low loads obviously cannot safely undertake 1RM tests to determine maximum strength and aid in load prescriptions, as is typically done in research. Future research should aim to establish whether other methods to prescribe exercise loads (for example, a rating of perceived exertion) could be used by these individuals.

Loenneke et al. [67] recently proposed a progressive model for the implementation of BFR from the early phases of rehabilitation through to a resumption of high-load resistance training. This model follows a four-phase approach: (1) BFR alone during periods of bed rest; (2) BFR combined with low-workload walking exercise; (3) BFR combined with low-load resistance exercise; and (4) low-load BFR training combined with traditional high-load resistance exercise. This progressive model is based upon sound scientific rationale for increasing the training stress as the participant progresses, and should be used as a framework for implementing BFR in elderly and post-surgery populations. Figure 1 illustrates how the practitioner should assess the functional capabilities of an individual to determine the most appropriate BFR strategies.

5.2 Healthy and Athletic Participants

Many athletes are required to concurrently develop muscular size and strength in conjunction with other physiological qualities specific to their sport. Training for numerous adaptations is obviously time consuming and demanding on an athlete's body. Due to the low loads used and the limited muscle damage that results from BFR training, this novel training strategy may be useful for athletes as a method to decrease their training loads, whilst still providing a physiological stimulus for muscular adaptation. Similarly, athletes looking to increase their longevity in sport may benefit from decreases in mechanical stress when substituting some high-load resistance exercise for low-load training with BFR.

Numerous investigations have reported beneficial muscular adaptations to BFR training in athletes [5, 11, 13, 14, 16]. Furthermore, these adaptive responses have translated into enhanced performance across a range of athletic tasks, including maximum strength [5, 14, 16], countermovement jump power [5], maximal and repeated sprint performance [5, 13, 14], agility performance [14] and an aerobic shuttle run test [14]. These data demonstrate that not only does low-load BFR training benefit untrained individuals, but it can also enhance markers of physical performance in already well-trained athletes.

While improvements in maximum strength have been frequently reported following low-load resistance training with BFR, the percentage increase in 1RM strength is not larger than the increase in muscle size [55]. Several investigations have demonstrated that the relative strength (i.e. the maximal strength per unit of muscle size) of muscles trained using low-load resistance exercise with BFR is not changed significantly from pre-training levels [12, 51, 53, 87]. In addition, low-load BFR resistance exercise does not appear to increase muscle activation (as estimated by surface electromyography) to the same degree as traditional high-load resistance exercise without BFR [79, 88], and therefore cannot stimulate the complete pool of high-threshold motor units. Taken together, these data indicate that changes in muscle strength following BFR training are more closely related to rapid increases in muscle hypertrophy as opposed to neural adaptations. This is different to traditional high-load resistance training, where increases in muscle strength arise from neural changes as well as increases in muscles size [89]. Therefore, for comprehensive athletic development, it is important not to use BFR training as a sole means of muscular

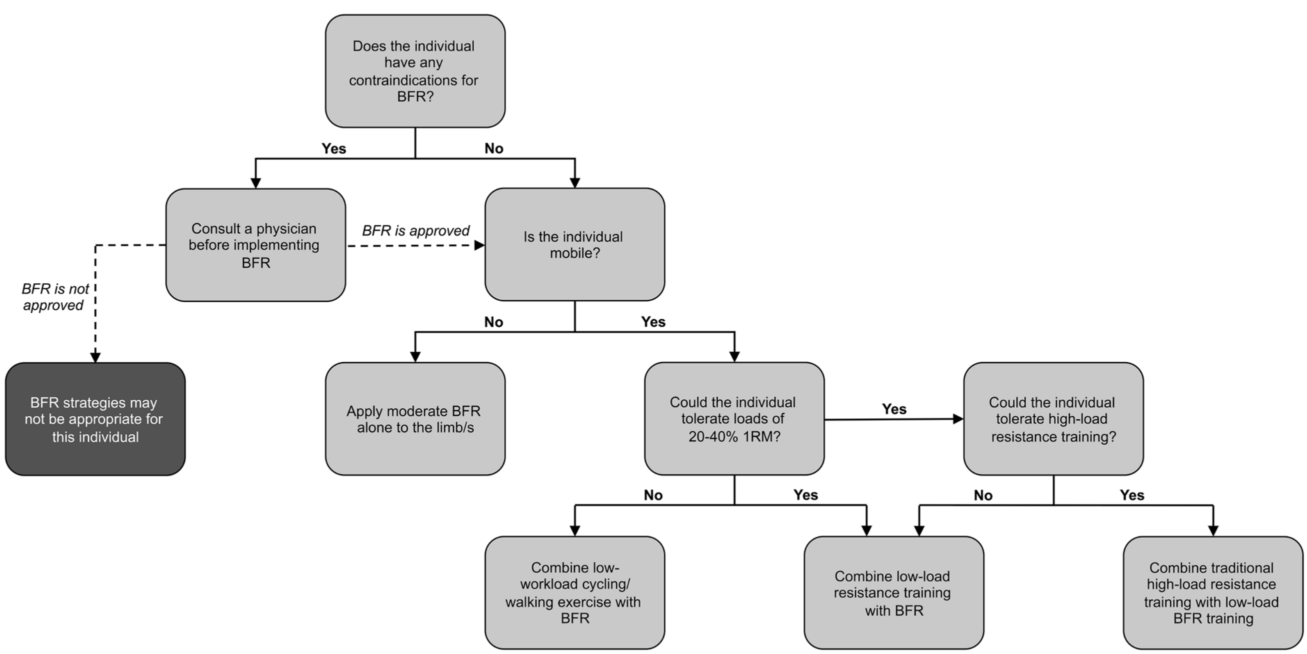

Fig. 1 Simplified flowchart for the practical implementation of blood flow restriction strategies for clinical, healthy and athletic populations. Contraindications for blood flow restriction have been described by Nakajima et al. [6]. *BFR* blood flow restriction, *1RM* 1-repetition maximum

development. It is likely that optimal muscular adaptation will result from a combination of traditional resistance training and BFR methods.

Yasuda et al. [90] demonstrated the benefits of combining low-load BFR exercise with traditional high-load exercise. Participants trained the bench press exercise 3 days per week for 6 weeks using either low-load BFR exercise (30 % 1RM), traditional high-load exercise (75 % 1RM), or a combination of these methods (2 days low-load BFR and 1 day traditional high-load training). Following the training period, increases in 1RM were similar between the high-load and combined training groups (19.9 and 15.3 %, respectively), which were higher than in the BFR group (8.7 %). Relative dynamic strength (1RM divided by CSA of the triceps brachii) was increased in the high-load and combined groups (10.5 and 6.7 %, respectively), but not in the BFR group. These data confirm that, while neural adaptations (as assessed via changes in strength relative to muscle size) do not generally occur following a period of low-load BFR training, functional muscle adaptations can be enhanced by combining this training with traditional high-load resistance exercise.

Similarly, Yamanaka et al. [16] demonstrated that low-load BFR training performed as a supplemental stimulus following traditional strength training can significantly enhance bench press and squat 1RM in American Football players. Although neurological changes were not reported in this study, it is likely that performing high-load resistance training followed by low-load BFR exercise in the same session will provide a potent stimulus for neural adaptation (traditional high-load training) in conjunction with an enhanced morphological (low-load BFR training) response. Due to the low mechanical loads and limited muscle damage associated with BFR exercise, it is unlikely that this practice would negatively affect performance in subsequent exercise bouts.

Interestingly, evidence suggests that the responses to BFR resistance exercise in athletes may be dependent on the type of athlete. Takada et al. [17] recently observed that metabolic stress during BFR exercise was significantly greater in endurance runners than in sprinters. It is possible that the endurance runners, who had a higher aerobic capacity than the sprinters, are essentially more dependent on oxygen delivery during exercise, and therefore suffered a greater disturbance in energetic metabolism during BFR exercise. Furthermore, it is likely that the sprinters were physiologically more accustomed to the anaerobic environment induced by BFR, and thus were not metabolically stressed to the same degree as endurance runners [17]. These findings should be investigated further to assess whether these acute differences in metabolic stress between different types of athletes do in fact result in dissimilar muscular adaptations.

6 Potential Limitations and Contraindications for BFR

While BFR appears to benefit skeletal muscle adaptation, it is important to recognize the potential limitations and contraindications associated with this method. A 2006 survey of Japanese facilities that were employing BFR exercise reported the most common side effects to be subcutaneous haemorrhage and numbness, which were experienced by 13.1 and 1.3 % of participants, respectively [7]. However, these symptoms are often discovered at the beginning of a BFR training programme, and dissipate as the individual becomes more accustomed to this training modality [6].

To determine a participant's level of risk during BFR exercise, Nakajima et al. [6] have proposed a points system whereby the practitioner assigns each patient a numerical score based on the number and severity of BFR contraindications they exhibit. Contraindications include a history of deep-vein thrombosis, pregnancy, varicose veins, and several other factors relating to the patient's history of disease and inactivity. This approach may be beneficial for identifying those at risk of detrimental complications during BFR. Nonetheless, when used in a controlled environment by trained and experienced personnel, BFR training appears to provide a safe training alternative for most individuals regardless of age and training status [91].

7 Conclusions

The addition of BFR to low-load resistance exercise enhances hypertrophic and strength responses. Although the mechanisms that drive these adaptations are not yet clear, this novel training strategy has important implications for individuals who cannot train using heavy loads. BFR alone can attenuate muscle atrophy during periods of disuse, and BFR combined with low-workload aerobic exercise can result in hypertrophy and strength increases (albeit small). Recent research has also demonstrated that well-trained athletes can benefit from low-load BFR training, either as an independent training method, or more substantially in combination with traditional high-load resistance training. When training with BFR, it is important to ensure that the cuff width used is appropriate and the restrictive pressure is specific to each individual limb. It appears that muscles of the limbs and trunk can benefit from BFR training, meaning that both single- and multi-joint exercises can be prescribed for training programmes. Low exercise loads should be employed (20–40 % 1RM) in conjunction with short inter-set rest periods (30–60 s) and relatively high training volumes (50–80 repetitions per exercise) to ensure a sufficient physiological stimulus is achieved. Furthermore, as BFR training does not markedly increase muscle damage, brief periods of high training frequencies may be possible.

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