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Manuscript Title: Blood flow restricted exercise for athletes: a review of available evidence

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Abstract

Objectives: This study aimed to collate current evidence regarding the efficacy of various blood flow restriction (BFR) strategies for well-trained athletes, and to provide insight regarding how such strategies can be used by these populations.

Design: Review article.

Methods: Studies that had investigated the acute or adaptive responses to BFR interventions in athletic participants were identified from searches in MEDLINE (PubMed), SPORTDiscus (EBSCO) and Google Scholar databases up to April 2015. The reference lists of identified papers were also examined for relevant studies.

Results: Twelve papers were identified from 11 separate investigations that had assessed acute and adaptive responses to BFR in athletic cohorts. Of these, 7 papers observed enhanced hypertrophic and/or strength responses and 2 reported alterations in the acute responses to low-load resistance exercise when combined with BFR. One paper had examined the adaptive responses to moderate-load resistance training with BFR, 1 noted improved training responses to low-work rate BFR cardiovascular exercise, and 1 reported on a case of injury following BFR exercise in an athlete.

Conclusions: Current evidence suggests that low-load resistance training with BFR can enhance muscle hypertrophy and strength in well-trained athletes, who would not normally benefit from using light loads. For healthy athletes, low-load BFR resistance training performed in conjunction with normal high-load training may provide an additional stimulus for muscular development. As low-load BFR resistance exercise does not appear to cause measureable muscle damage, supplementing normal high-load training using this novel strategy may elicit beneficial muscular responses in healthy athletes.

Key words: Hypertrophy; strength; vascular occlusion; ischemia; resistance training; kaatsu

Introduction

Athletes competing in a range of contact and non-contact sports employ resistance training to enhance sport-specific muscular development and subsequent performance.[1,2] Traditional guidelines state that for substantial increases in muscle size and strength, resistance training should be performed using at least 70% of the concentric 1-repetition maximum (1RM).[3] However, increasing evidence supports the use of low-load resistance exercise combined with moderate blood flow restriction (BFR) to facilitate hypertrophic and strength gains.[4,5] This novel strategy involves the use of cuffs placed proximally around a limb, with the aim of maintaining arterial inflow while occluding venous return during exercise.[6,7] While current research agrees that this strategy can promote improvements in muscular size and strength, the definitive mechanisms underpinning these responses have not been fully elucidated.[8-10] The primary mechanisms proposed include increased metabolic stress,[11] increased muscle fibre recruitment,[12,13] cellular swelling,[14] enhanced intramuscular signalling for protein synthesis[15-17] and proliferation of myogenic stem cells,[18] all of which are thought to promote muscular development.

An important benefit of BFR resistance exercise is that relatively light loads can be used to facilitate hypertrophic responses similar to traditional high-load unrestricted resistance training.[4,17,19] This has applications for individuals who may not be able to tolerate the mechanical stresses associated with higher-load resistance exercise.[20] As such, several investigations have focused on implementing BFR exercise within older and clinical populations.[21,22] While low-load BFR exercise has obvious implications for athletes during rehabilitation from an injury,[23] using this training strategy for healthy, well-trained athletes has not received as much research attention. With increasing interest in the applications of BFR exercise from strength and conditioning coaches, it is now important to collate current evidence and determine the efficacy of this training method for athletic cohorts. Therefore, the aim of this article was to review the research that has assessed the adaptive or acute responses to BFR exercise in well-trained athletes.

Methods (literature search)

During April 2015, an English language search of MEDLINE (PubMed), SPORTDiscus (EBSCO) and Google Scholar databases was performed to identify papers that had employed a BFR intervention for athletic participants. Combinations of the following keywords were used as search terms: ‘blood flow restriction’; ‘occlusion’; ‘athlete’; ‘well-trained’; ‘hypertrophy’; ‘strength’; ‘resistance exercise’; ‘kaatsu’; ‘vascular occlusion’; and ‘ischemia’. The reference lists of identified papers were also examined for relevant studies.

Studies were selected based on the following inclusion criteria: (1) the study specifically states that the population investigated was comprised of athletes; (2) BFR was implemented during resistance or aerobic exercise to examine acute or adaptive responses; (3) the full text of the study was available in English; (4) the study was published in a peer-reviewed scientific journal. Thirteen separate papers from 12 investigations were identified. One study was excluded from further review, as the gender of participants and differences in the volume of exercise between groups was not reported.[24]

Due to the low number of investigations published, and the broad range of strategies and methodological approaches used in BFR research, this paper was constructed as a descriptive review article. These studies are summarised in Table 1, and the findings from these investigations are synthesised with the wider body of BFR research using non-athlete populations to provide further information regarding the efficacy of BFR exercise. Practical applications for the use of BFR exercise in athletic participants are also detailed, including recommendations for the implementation of BFR training.

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BFR training responses in athletes

Several investigations have demonstrated enhanced muscular development in athletes following low-load BFR resistance training. In early research, Takarada et al.[25] examined the effects of resistance exercise combined with BFR in elite rugby players. Participants performed 8 weeks of low-load resistance training (bilateral knee extension twice weekly), comprised of 4 sets to failure at 50% 1RM with 30 s inter-set recovery, either with or without BFR (196 ± 6 mmHg). Following the training period, the BFR group recorded greater increases in isokinetic knee extension torque and muscular endurance than the work-matched control group. Furthermore, cross-sectional area (CSA) of the knee extensors was significantly increased following the BFR training period, though this was not measured in the control training group. Similar findings have been reported for female netball athletes,[26,27] who trained 3 times per week for 5 weeks using bilateral knee extension and flexion (3 sets to fatigue with 30 s inter-set rest at 20% 1RM) with BFR (160-230 mmHg), or performed the equivalent training under systemic hypoxia (arterial oxygen saturation maintained at 80%) or with no additional stimulus (control). Increases in muscular strength, endurance and CSA were observed in the BFR and systemic hypoxia groups, compared to the control.

Collectively, these data demonstrate that significant improvements in muscular strength and size following low-load BFR training are possible in well-trained athletes. An interesting finding from Manimmanakorn et al.,[26] was that these enhanced muscular responses translated into improved performance in sport-specific fitness tests including 5 m sprint, 505 agility, and 20 m shuttle run tests. However, it is unclear whether similar improvements could have been observed if the athletes underwent a traditional resistance training program using heavier loads. Furthermore, it is likely that such changes in performance indicators following BFR training are dependent on the actual performance tests and the type of athlete.[28]

While the inflatable cuffs that are commonly used in research allow for strict control of the BFR stimulus, this equipment may not be practical for athletes training in large groups. Aside from the cost associated with purchasing many specialised BFR cuffs, it is important that the user is trained in how to apply and control the pressure of these cuffs. Therefore, to train large groups at one time using BFR, a more practical method may be necessary to make this training strategy viable. The use of elastic wraps for BFR, often referred to as practical BFR, was first proposed by Loenneke and Pujol[29] and has since been demonstrated to provide a safe, effective and ecologically valid occlusive stimulus for BFR training.[30] While this method of applying BFR does not allow for strict control of the pressure applied to the limb, which could have implications regarding subsequent training responses, its practicality makes this an attractive strategy for athletes. Recently, two separate investigations have demonstrated that low-load BFR training using elastic wraps can produce muscular changes in collegiate American football players.[31,32]

Yamanaka et al.[31] trained Division IA American football athletes with at least 5 years resistance training experience using a 30-20-20-20 repetition scheme for the bench press and squat (20% 1RM and 45 s inter-set rest). Participants performed this low-load training either with or without BFR 3 times per week in addition to their normal off-season strength training sessions for 4 weeks. Following the training period, 1RM for the bench press and squat increased significantly more in the BFR group (7.0% and 8.0%, respectively) than in the control group (3.2% and 4.9%, respectively). Furthermore, significantly greater increases in upper and lower chest girth were measured in the BFR group (3.7 and 2.6 cm, respectively) than the control (1.0 and 1.2 cm, respectively), though there were no differences in girth measurements for the thighs.

More recently, Luebbers et al.[32] employed a similar training protocol for collegiate American football players. Players trained 4 days each week for 7 weeks using an upper- and lower-body split program in one of four groups; 1) traditional high-load training, 2) traditional high-load training supplemented with low-load training, 3) traditional high-load training supplemented with low-load BFR training and 4) modified traditional training (excluding high-load bench press and squatting variations) with low-load BFR training. Supplemental bench press and squat exercises were performed following upper- and lower-body sessions, respectively. Results indicated that the group performing high-load training supplemented with low-load BFR training demonstrated the largest increases in squat 1RM (24.9 kg improvement, compared to 6.0-14.1 kg increase in other groups). This trend was also observed for the bench press, though the results did not reach significance (8.7 kg compared to 2.7-7.3 kg increase in other groups). However, there were no significant changes in post-training girth measurements recorded in any condition. Considering the extensive resistance training history of these participants (7.1 ± 2.2 years), it is possible that the duration of the training intervention was not long enough to significantly differentiate between the groups for the bench press strength. Furthermore, given the propensity of young males to include bench pressing into their own strength training programs, it is possible that these subjects were more experienced in the bench press than the squat exercise, which could partly explain the different strength responses to these exercises.

Interestingly, the group performing modified normal training with supplemental BFR exercise demonstrated the smallest increases in both bench press and squat 1RM. As all other groups in this study performed high-load exercise during their normal training, these data indicate that high-load strength training is paramount for maximal strength development in athletes. Similar results have been reported in recreationally active young men, with participants who underwent high-load unrestricted training or combined low-load BFR and unrestricted high-load training demonstrating increases in maximal isometric elbow extension.[33] However, a group who trained only with low-load BFR exercise did not demonstrate significant improvements in maximum isometric strength.[33] It should also be acknowledged that these results might reflect the specificity of training to the strength testing procedures; it is to be expected that participants who trained with heavy loads will perform better during maximal strength tests than those who trained exclusively with low- and moderate-loads. Therefore, the fact that the modified training group demonstrated the smallest increases in 1RM measurements could indicate that they had less experience with heavy loads for the specific exercises tested.[34]

A potential explanation for the findings of limited[31] or no[32] change in muscle size following traditional strength training combined with BFR training may be the method used to measure muscle size. While limb and torso girth measurement may be a practical field-based measure of circumference, it cannot specifically measure muscle hypertrophy. Girth measurements also reflect changes in subcutaneous adipose tissue and intracellular fluids,[31] which may affect inferences drawn from them regarding hypertrophy. Given that large hypertrophic responses are generally not observed in well-trained athletes following a brief training period, this girth measurement technique may not have been sensitive enough to reflect small hypertrophic changes. Nonetheless, previous research also noted that isokinetic BFR training increased muscular strength in the absence of CSA changes (measured via magnetic resonance imaging) in collegiate track and field athletes.[35]

These collective findings have important implications for the strength and conditioning coach. While some athletes can achieve significantly enhanced muscular size following brief periods of low-load BFR resistance training,[25-27] athletes with extensive strength training experience, may not be able to achieve the same level of hypertrophy, even with the addition of traditional high-load strength training.[31,32] Nonetheless, further research is required using more robust methods to quantify changes in muscular size before these conclusions can be confirmed. For highly-experienced athletes, using low-load BFR exercise as a supplemental stimulus following normal high-load training can enhance the adaptive strength responses. Improvements in strength are generally considered as a more functional adaptation than increases in muscle size, and will likely translate to improved sporting performance.[26,36] From the limited data available, it is evident that the training experience of the athlete must be considered when determining how best to incorporate BFR exercise into their training plan, as not all athletes will respond similarly.

Abe et al.[37] demonstrated that collegiate track and field athletes can benefit from brief periods of high-frequency training using low-load BFR exercise. Subjects trained twice daily for 8 consecutive days using squat and leg flexion exercises with BFR (3 x 15 repetitions at 20% 1RM with 30 s inter-set rest). While a training period this short would not normally facilitate significant muscular gains in athletes, increases were observed in thigh muscle thickness (measured via ultrasound) and leg press 1RM following the training program. Furthermore, 10 m acceleration and 30 m sprint times were significantly improved following BFR training, suggesting that adaptations to low-load BFR training translate to enhanced sport-specific performance in athletes. Low-load BFR resistance exercise does not appear to cause muscle damage,[38] and due to the low mechanical loads used, is not likely to excessively stress connective tissues. Brief periods of high-frequency BFR resistance training like the one used by Abe et al.[37] may therefore be beneficial for athletes during a phase of planned overload. However, it is important to consider that while the low mechanical forces used with BFR exercise may improve muscle strength, disproportionate adaptations could occur in the tendons if progressions in exercise load are not implemented, increasing the risk for subsequent tendon injuries.[19]

While the majority of BFR research has utilised light loads (20-50% 1RM),[25,26,37] a recent investigation has employed higher-load BFR training for athletes. Cook et al.[36] examined rugby union players performing squat, pull-up and bench press training (5 sets of 5 repetitions with 70% 1RM) either with or without BFR applied to the lower limbs (180 mmHg). The BFR training condition resulted in significantly greater improvements in 1RM for the bench press (5.4 ± 2.6 kg) and squat (7.8 ± 2.1 kg), compared to the control condition (3.3 ± 1.4 and 4.3 ± 1.4 kg, respectively). The results of Cook et al.[36] contradict those of Laurentino et al.[39] 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. These contrasting findings may be related to methodological differences. For example, subjects in the study of Cook et al.[36] trained 3 times per week using 5 sets of three different exercises for 3 weeks, whereas those in the study of Laurentino et al.[39] trained twice weekly using 3-5 sets of a single exercise for 8 weeks. In addition, Laurentino et al.[39] used subjects with limited resistance training experience and extended inter-set rest periods (120 s), whereas those in the study by Cook et al.[36] were well-trained and used shorter inter-set rest periods (90 s). This may have allowed for greater clearance of metabolic by-products between sets, especially considering that both investigations used intermittent BFR (pressure released between sets), which could have caused different degrees of metabolic stress between the studies. Increased metabolic stress is thought to be a primary moderator of adaptation to BFR exercise.[8,40]

It is also possible that the small changes in strength reported by Cook et al.[36] were within the range of error associated with maximal strength testing. We have previously determined that 1RM assessment of a back squat variation in well-trained males has a typical error (expressed as a coefficient of variation) of 2.6%,[41] which is greater than the relative changes observed by Cook et al.[36] (1.4 ± 0.8 and 2.0 ± 0.6 % for the bench press and squat, respectively). Further research is therefore required before sound recommendations can be made regarding the efficacy of moderate- or high-load resistance training with BFR for athletes.

Several investigations have shown low-work rate walking or cycling combined with BFR to produce small but significant increases in the strength and size of leg muscles for untrained or recreationally active individuals.[42-45] One investigation has examined the responses of healthy athletes to BFR walk training.[46] Male collegiate basketball players trained twice daily, 6 days each week for 2 weeks following a treadmill walking protocol (5 sets of 3 minutes at 4-6 $km \cdot h^{-1}$ and 5% grade with 60 s inter-set rest) either with or without BFR (160-220 mmHg). Prior to and following the training period, maximal aerobic capacity (maximal graded exercise test) and anaerobic power and capacity

(Wingate test) were assessed on a cycle ergometer. Significant improvements were observed in maximum aerobic capacity (11.6%), maximal ventilation (10.6%), and anaerobic capacity (2.5%) in the BFR group, but not in the non-restricted control. These increases in maximum aerobic capacity and ventilation are similar to those previously reported following traditional high-intensity interval training without BFR in athletes.[47] This suggests that low-work rate cardiovascular exercise with BFR provide a stimulus for improved aerobic and anaerobic capacity in already well-trained athletes. However, it should be noted that while walking speed increased throughout the training period in the BFR group (up to 6 km·h^{-1}), it remained constant for the non-BFR control group (4 km·h^{-1}).[46] It is therefore possible that the observed differences in training adaptations between the groups may have been affected, at least in part, by the lack of progressive overload in the control condition.

It is also important to note that in opposition to studies conducted with untrained individuals,[42-45] low-work rate cardiovascular BFR training did not enhance muscular strength. It is likely that specific resistance exercise is necessary for muscular development in athletes. Furthermore, some research has not found low-work rate cardiovascular training with BFR to facilitate increased aerobic adaptations, even for older adults.[44] Further evidence is therefore needed before sound recommendations can be made as to the use of low-work rate cardiovascular BFR exercise for enhanced aerobic adaptations in athletes.

Acute responses to BFR exercise in athletes

To elucidate the mechanisms underpinning enhanced muscular responses to low-load BFR resistance exercise, some investigations have examined the acute responses following exercise bouts in athletes. Takarada et al.[12] demonstrated that bilateral knee extension exercise (5 sets to failure at 20% 1RM with 30 s inter-set rest) performed with BFR (214 ± 8 mmHg) resulted in significantly greater blood lactate and growth hormone concentrations than a work-matched unrestricted control condition. Notably, growth hormone concentrations following the BFR exercise were ~290 times greater than baseline. Furthermore, markers of muscle damage (creatine kinase) and oxidative damage (lipid peroxide) were not different between conditions. These results were among the first to provide evidence of the anabolic potential of the BFR stimulus, although the role of acute elevations in growth hormone in skeletal muscle protein synthesis has recently been questioned.[48,49]

While metabolic stress is proposed as a key moderator of adaptation to BFR exercise, a wide range of inter-individual metabolic responses to BFR training have been noted.[50,51] To assess whether this variation may be related to the training status of an athlete, Takada et al.[28] examined the acute metabolic responses to low-load BFR exercise in endurance and sprint athletes. Results indicated that metabolic stress, estimated via decreases in phosphocreatine and intramuscular pH levels, was significantly greater in endurance runners compared with sprinters. It is possible that the endurance runners are more dependent on oxygen delivery during exercise, and therefore suffered a greater disturbance in energetic metabolism during BFR exercise.[28] Similarly, as sprint athletes are generally more accustomed to performing under conditions where oxygen availability does not match demand, they may not be as metabolically challenged by the addition of BFR to low-load resistance exercise as endurance athletes.[28] These data indicate that the training background of an athlete is related to the acute physiological response to BFR exercise, which may also translate into different adaptive responses between athlete groups.

Practical applications of BFR training for athletes

Many athletes are required to concurrently develop several physiological qualities in conjunction with skills specific to their sport. It is important to consider not only the time required to train for numerous physical adaptations, but also the stress that high-load training can have on an athlete's body. To this end, implementing BFR during various phases of an athlete's periodised training plan could help counter the potential negative effects of high mechanical training loads. Indeed, while BFR training seems to provide a physiological stimulus for muscular adaptations, the low-loads used do not cause measureable muscle damage.[38] This strategy may therefore be useful for athletes with a decreased capacity for recovery from high-load exercise (e.g. masters athletes). Furthermore, athletes who may not tolerate training with high-loads for either physiological or psychological reasons may benefit from BFR training with low-loads. While evidence suggests that unrestricted low-load resistance exercise performed to failure can also promote muscular development,[52] this strategy is not submaximal by definition, and it is possible that some participants may not tolerate it well.

An important application of BFR for athletes is during the recovery phase following an injury or periods of detraining. BFR alone can attenuate post-operative disuse atrophy in patients recovering from surgical reconstruction of the anterior cruciate ligament.[53] Additionally, BFR during low-load rehabilitation exercises has been shown to enhance muscular development in patients also recovering from reconstruction of the anterior cruciate ligament.[21] When considering the beneficial effects of BFR on muscle during periods of immobilisation or rest, and when combined with low-work rate walking and resistance exercise, an application of BFR for athletes may be decreasing the time required to recover from an injury. A progressive model for the use of BFR from the early phases of rehabilitation through to the resumption of high-load training has been recently proposed by Loenneke et al.[23] This model is comprised of four sequential phases; 1) BFR alone during periods of bed rest or immobilisation, 2) BFR during low-work rate walking, 3) BFR during low-load resistance exercise and 4) low-load BFR training combined with normal high-load training. Progression through these different phases should follow a continuum, with gradually increasing exercise intensities even within each stage, to limit any chance of further injury resulting from a return to training too early.

Although injury from BFR training is rare,[54] a case report has detailed an example of this in a male ice hockey player.[55] This athlete was recovering from a previous injury, and performed a single bout of unilateral knee extension exercise (30-15-15-15 repetition scheme with 45 s inter-set rest and 12 kg load) with BFR (100 mmHg). At 48 h post-exercise the athlete exhibited serum creatine kinase levels of 12, 400 U/L, and was diagnosed with rhabdomyolysis. However, from this report it is not clear whether the detrimental effects were triggered by the BFR stimulus, the exercise regime, or the combination of these factors. A survey of 105 training facilities in Japan has previously reported that rhabdomyolysis occurred following BFR training in only 0.008% of participants.[56] Furthermore, after the detrimental effects of the initial bout of BFR exercise, the aforementioned athlete returned to low-load BFR training after 18 days without further incident, and to competition after 7 weeks.

It should also be acknowledged that low-load BFR resistance exercise produces lower levels of muscle recruitment than high-load exercise without BFR.[57,58] Therefore, the neurological stimulus resulting from BFR training would not likely benefit athletes in sports where rapid force production is required. Furthermore, investigations have demonstrated that for untrained or recreationally active populations, relative strength (maximal strength per unit of muscle size) in muscles trained using low-load BFR exercise is not changed significantly from pre-training levels,[4,19,25,59] suggesting that the majority of the strength gain is due to increases in muscle mass. However, some BFR research using athletes has demonstrated increases in maximum strength despite no or limited change in limb and torso circumference measurements,[31,32] which suggests a possible role of neuromuscular adaptations for these cohorts (though this may also be influenced by high-load training also performed in these studies). Considering these results, BFR training should not be used as a sole means of muscular development in athletes. It is likely that optimal muscular adaptation will result from a combination of traditional resistance training and BFR methods.[33]

It has also been hypothesised that while low-load resistance exercise with BFR can increase the strength and CSA of skeletal muscle, concomitant increases in the strength of connective tissues may not occur due to decreased mechanical loading.[8] A disproportionate increase in muscle and connective tissues strength may result in musculotendinous injury, particularly if heavy loads are subsequently used which can be lifted by the muscles but not tolerated by connective tissues.[19] Further research is required to investigate the adaptations of the entire musculotendinous unit to low-load BFR training. One study has also suggested that the tissue directly underlying the site of cuff application may not benefit from the BFR stimulus.[60] It is not presently known whether that finding is due to the BFR *per se*, the size of the cuff applied, the high arbitrary pressure used for all subjects, or if this finding is repeatable. Regardless, given that the effects of BFR on the tissue at these sites are not well understood, any potential side effects should be assessed. For the strength and conditioning coach looking to incorporate BFR exercise into the training program of healthy athletes, it is important to ensure that athletes are periodically exposed to heavier loads, according with the periodised training plan.

Summary

Evidence suggests that significant muscular development is possible in well-trained athletes following low-load resistance training with BFR. However, low-load BFR exercise provides a dissimilar neural stimulus compared to high-load resistance exercise. For athletes with extensive strength training experiance, optimal muscular adaptations may require traditional high-load resistance training in combination with low-load BFR training. A useful strategy to combine these two training methods is using low-load BFR exercise as supplemental exercise following a high-load strength training session.[31,32] Studies have also noted that the adaptive responses to BFR training translate to improved performance in sport-specific fitness tests, though physiological responses may differ between different types of athletes. Together, these findings indicate that beneficial training responses can occur with appropriate implementation of BFR strategies, even in well-trained athletes.

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Table captions

Table 1. Summary of the research examining BFR exercise for athletes that is discussed in this review

Table 1. Summary of the research examining BFR exercise for athletes that is discussed in this review.

Reference	Athletes	BFR training or testing protocol	Training frequency and duration	Cuff pressure (width)	Main findings	Comments
Training responses to low-load resistance exercise with BFR						
Abe et al.[37]	Male collegiate track and field (n=15)	Squat and leg curl: 3 x 15 (30 s inter-set rest, 20% 1RM)	Twice daily for 8 consecutive days	160-240 mmHg (5 cm)	• ↑ thigh muscle thickness and leg press 1RM in BFR group but not control group (no resistance training). • ↓ 30 m sprint and 10 m acceleration time in BFR but not control.	• Jump performance (standing jump, standing triple jump and standing 5 jump) did not improve in either the BFR or the control group.
Luebbers et al.[32]	Male collegiate American football (n=62)	Bench press and squat: 30-20-20-20 repetition scheme (45 s inter-set rest, 20% 1RM)	4 times per week for 7 weeks following normal high-load training, or modified moderate-load training (upper- and lower-body split program)	Practical BFR (elastic wraps; 7.6 cm)	• Low-load BFR training following unrestricted high-load training caused greatest ↑ in squat 1RM. • Similar findings observed for bench press, though not significant. • No significant differences for post-training girth measurements.	• High-load training combined with low-load BFR training provides the most potent stimulus for strength.
Manimmanakorn et al.[26,27]	Female netball (n=30)	Bilateral knee extension and flexion: 3 x failure (30 s inter-set rest, 20% 1RM)	3 times per week for 5 weeks	160-230 mmHg (5 cm)	• ↑ muscular strength, endurance and CSA in BFR training group compared to work-matched unrestricted control. • BFR training enhanced performance in sport-specific tasks compared with control. • Pain scores were not different between BFR and control groups. • BFR enhanced neuromuscular adaptation (↑ EMG during maximal voluntary contractions).	• IHRT was also found to enhance muscular strength, endurance and CSA, though was not as effective in improving sport-specific performance. • Greater neuromuscular adaptations following BFR compared to IHRT and control training are difficult to explain, given that muscular oxygen status was not measured.
Sakuraba and Ishikawa[35]	Male collegiate track and field (n=21)	Isokinetic knee extension and flexion: 3 x 10 (60 s inter-set rest, 60 or 300°s^{-1})	2 times per week for 4 weeks	200 mmHg (width not reported)	• Greatest ↑ muscular strength at various velocities following high-speed isokinetic BFR training • ↔ muscle CSA in any group.	• Training dose may not have been sufficient to elicit hypertrophy.
Takarada et al.[25]	Male elite rugby union (n=17)	Bilateral knee extension: 4 x failure (30 s inter-set rest, 50% 1RM)	2 times per week for 8 weeks	196 ± 6 mmHg (3.3 cm)	• BFR training resulted in greater ↑ isokinetic knee extension torque and muscular endurance than work-matched unrestricted and non-training control. • Knee extensor CSA ↑ in BFR group.	• Muscle CSA was only measured in the BFR group.

Table 1. Continued.

Reference	Athletes	BFR training or testing protocol	Training frequency and duration	Cuff pressure (width)	Main findings	Comments
Yamanaka et al.[31]	Male collegiate American football (n=32)	Bench press and squat with or without BFR: 30-20-20-20 repetition scheme (45 s inter-set rest, 20% 1RM)	3 times per week for 4 weeks following normal training	Practical BFR (elastic wraps; 5 cm)	• Bench press and squat 1RM ↑ significantly more for BFR group than non-restricted control. • Upper and lower chest and left upper arm girths ↑ significantly more for BFR group than non-restricted control.	• The change in girth for the thighs and the right upper arm were not significantly different between training groups.
Acute responses to low-load resistance exercise with BFR						
Takada et al.[28]	Male sprinters (n=6) and endurance runners (n=6)	Unilateral plantar flexion without BFR: 30 repetitions per minute at 20% 1RM and 65% 1RM (120 s) Unilateral plantar flexion with BFR: 30 repetitions per minute at 20% 1RM (120 and 180 s)	Acute study (cross-over design)	130% resting systolic blood pressure (18.5 cm)	• Muscular metabolic stress (↓ PCr and intramuscular pH) during BFR exercise is significantly elevated in endurance compared to sprint athletes. • Metabolic stress is similar between low-load BFR exercise and unrestricted moderate-load exercise in endurance but not sprint athletes.	• The effects of low-load resistance exercise with BFR may be greater in endurance than in sprint athletes, owing to their higher aerobic capacity and therefore larger disturbances in energetic metabolism during BFR.
Takarada et al.[12]	Male athletes; sport not specified (n=6)	Bilateral knee extension: 5 x failure (30 s inter-set rest, 20% 1RM)	Acute study (cross-over design)	214 ± 8 mmHg (3.3 cm)	• BFR resistance exercise caused ↑ in GH, NE and BLa$^-$, whereas non-restricted exercise did not. • Markers of muscle damage (CK) and oxidative damage (LP) were not different between conditions, though inflammatory responses (IL-6) were ↑ following BFR exercise.	• GH concentration reached ~290 times baseline levels following BFR exercise.
Training responses to moderate-load resistance exercise with BFR						
Cook et al.[36]	Male semi-professional rugby union (n=20)	Squat, bench press and weighted pull-up: 5 x 5 (90 s inter-set rest, 70% 1RM)	3 times per week for 3 weeks	180 mmHg (10.5 cm)	• BFR condition caused greater ↑ in squat and bench press 1RM, and larger improvements in CMJ and sprint performance. • Salivary testosterone and cortisol following exercise was higher in the BFR condition (cortisol response was attenuated over 3 week training block).	• Cuff was applied to the legs during all exercises, and was deflated between sets (intermittent occlusion). • Improvements in strength may be within the error associated with maximum strength tests.

Table 1. Continued.

Reference	Athletes	BFR training or testing protocol	Training frequency and duration	Cuff pressure (width)	Main findings	Comments
Training responses to low-work rate cardiovascular exercise with BFR						
Park et al.[46]	Male collegiate basketball (n=12)	Treadmill walking: 5 sets of 3 minutes (4-6 km·h^{-1} at 5% grade, 60 s inter-set rest)	Twice daily, 6 days per week for 2 weeks	160-220 mmHg (11 cm)	• ↑ $\dot{V}O_{2max}$, $\dot{V}E_{max}$ and anaerobic power (Wingate test) following low-work rate walk training when combined with BFR. • ↔ muscle strength after walk training with and without BFR.	• Increases in $\dot{V}O_{2max}$, $\dot{V}E_{max}$ are similar to those reported following high-intensity training without BFR in athletes.
BFR exercise for special cases						
Iversen and Røstad[55]	Male ice hockey (n=1; case report)	Unilateral knee extension: 30-15-15-15 repetition scheme (45 s inter-set rest, 12 kg load)	Single session	100 mmHg (14 cm)	• Serum CK values elevated to 12 400 U/L at 48 h following session; diagnosed with rhabdomyolysis. • Returned to low-load BFR training 18 days after incident, and to competition after 7 weeks.	• This type of injury following BFR training is rare; CK does not typically ↑ following BFR exercise.

BFR blood flow restriction, *BLa^-* blood lactate, *CK* creatine kinase, *CMJ* countermovement jump, *CSA* cross-sectional area, *EMG* electromyography, *GH* growth hormone, *IHRT* intermittent hypoxic resistance training, *IL-6* interleukin-6, *LP* lipid peroxide, *NE* norepin