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Section III – Sports Training

Technical and Training Related Aspects of Resistance Training Using Blood Flow Restriction in Competitive Sport - A Review

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Blood flow restriction (BFR) combined with resistance training (RT-BFR) shows significant benefits in terms of muscle strength and hypertrophy. Such effects have been observed in clinical populations, in groups of physically active people, and among competitive athletes. These effects are comparable or, in some cases, even more efficient compared to conventional resistance training (CRT). RT-BFR stimulates muscle hypertrophy and improves muscle strength even at low external loads. Since no extensive scientific research has been done in relation to groups of athletes, the aim of the present study was to identify technical, physiological and methodological aspects related to the use of RT-BFR in competitive athletes from various sport disciplines. RT-BFR in groups of athletes has an effect not only on the improvement of muscle strength or muscle hypertrophy, but also on specific motor abilities related to a particular sport discipline. The literature review reveals that most experts do not recommend the use RT-BFR as the only training method, but rather as a complementary method to CRT. It is likely that optimal muscle adaptive changes can be induced by a combination of CRT and RT-BFR. Some research has confirmed benefits of using CRT followed by RT-BFR during a training session. The use of BFR in training also requires adequate progression or modifications in the duration of occlusion in a training session, the ratio of exercises performed with BFR to conventional exercises, the value of pressure or the cuff width.

Key words*: occlusion, resistance exercise, training variables, sports performance.*

Introduction

The American College of Sports Medicine recommends using external loads of at least 70% 1RM in resistance training in order to develop muscular strength. With regard to muscle hypertrophy, the literature shows a much wider range of training options. Some studies have demonstrated the effectiveness of both low (LL) and high (HL) values of the external load. Other studies have shown a substantial advantage of HL over LL exercise protocols in the effectiveness of muscle hypertrophy. It should be noted that in case of conventional resistance training (CRT), the key element of adaptation in terms of muscle hypertrophy is a sufficiently high exercise volume (Schoenfeld et al., 2016). However, for various reasons, not every person can use CRT, especially with high external loads and high exercise volume. Therefore, resistance training modifications to stimulate hypertrophy and increase muscle strength without the need to use HL are being extensively explored. One of the options is to combine physical exercise with blood flow restriction (BFR). BFR, also referred to as occlusion, can be used in any form of physical activity. However, much attention has been devoted to the use of BFR in RT. Resistance training with blood flow restriction (RT-BFR) can be successfully used at any external load.

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However the majority of studies have examined the effects of RT-BFR at low external loads. Occlusion significantly affects muscular adaptive processes in clinical populations, both in groups of physically active people and competitive athletes (Cook et al., 2014; Takarada et al., 2000a, 2000b). Scientific research shows comparable or, in some cases, even higher efficiency of RT-BFR compared to conventional resistance training (CRT) (Abe et al., 2006; Fujita et al., 2008; Madarame et al., 2008; Manimmanakorn et al., 2013b; Sumide et al., 2009). Interestingly, RT-BFR stimulates muscle hypertrophy and improves muscle strength especially in the group of non-athletes, even when using low external loads (LL) (Abe et al., 2005, 2006; Fujita et al., 2008; Madarame et al., 2008; Sumide et al., 2009; Takarada et al., 2000a).

Physiological responses following BFR

The BFR technique involves the use of a tourniquet, an inflatable cuff (Takano et al., 2005) or elastic wraps (Loenneke and Pujol, 2009). The compression is placed at the upper part of the limb to reduce the arterial blood flow and to shut the venous blood flow during physical exercise (Scott et al., 2015). Shutting the venous blood flow and limitation of the arterial blood flow are possible due to the differences between arteries and veins. Walls of the arteries are characterized by a more extended muscle layer, they are located deeper under the skin surface, and the blood flowing through these vessels has a higher pressure. The main mechanisms responsible for the adaptive responses associated with training under BFR conditions include increased mechanical tension and elevated metabolic stress. Mechanical muscle tension accompanying muscle contractions leads to the increased signalling of intracellular anabolic and catabolic pathways that intensifies muscle protein synthesis. Furthermore, the metabolic stress occurring during BFR results from the accumulation of by-products of physical exercise in the distal (with relation to the restriction used) part of the limb (Abe et al., 2006). Consequently, BFR causes more intense recruitment of fast twitch muscle fibres, cell swelling and elevated post-exercise GH levels (Suga et al., 2009). Importantly, the use of even low external loads (LL) in RT-BFR training leads to the immediate initiation of physiological responses such as metabolic stress (Takarada et al., 2000a, 2000b), responses of the endocrine system (Shimizu et al., 2016; Takano et al., 2005; Takarada et al., 2002), reinforcement of intramuscular signalling (Laurentino et al., 2012; Manini et al., 2011), increased cell swelling (Loenneke et al., 2012b), and increased recruitment of fast twitch muscle fibres (Manimmanakorn et al., 2013b; Takarada et al., 2000a). These responses are interdependent and may provide a theoretical explanation for the patterns of neuromuscular adaptations accompanying RT-BFR. Furthermore, the use of BFR during RT leads to decreased exercise volume determined according to the guidelines of Wilk et al. (2018) based on time under tension (Wernbom et al., 2009). It should also be mentioned that RT-BFR (LL) reduces the expression of the myostatin gene (45%) in a way comparable to what was observed during CRT (HL) (41%) (Laurentino et al., 2012), which is particularly important for muscle hypertrophy. The above mentioned factors reinforce intramuscular signalling stimulating the synthesis of muscle proteins (Fujita et al., 2007), such as mTOR, MAPK (Fujita et al., 2007), and proliferation of satellite cells (Nielsen et al., 2012). Combined with a limited increase in the levels of post-exercise muscle damage markers (CK, myoglobin, IL-6) following RT-BFT (LL) and a significant decrease in the level of proteolytic processes (Manini et al., 2011), these factors ensure suitable conditions for increased muscle hypertrophy. Gains in muscle strength following RT-BFR (LL) training are most likely strongly correlated with the increase in the cross-sectional area (CSA) of the muscle rather than with neural adaptations. However, it should be noted that although the physiological mechanisms underlying adaptive responses following BFR training have not been fully explored yet, this training method is becoming more and more popular, both among recreational and professional athletes.

Technical specifications of BFR cuffs

The basic methodological issue of resistance training with BFR is to determine the optimal compression values. The BFR pressure should be sufficiently high to restrict venous blood return from the area of the working muscles and sufficiently low to keep the arterial blood supply to the muscle. Insufficient pressure limits the effectiveness of adaptive processes following RT-BFR. On the other hand, excessive pressure can lead to discomfort felt by the athlete, without significant benefits compared to the exercise at an optimal BFR pressure (Loenneke et al., 2014a). Furthermore, safety issues should also be addressed, especially in case of complete occlusion of the arteries. Complete arterial occlusion can lead to formation of thrombus and may induce microvascular closure, even after reperfusion. The risk of thrombus formation following BFR may also be elevated if the exercise was performed until muscle failure, which is often the case in RT-BFR (Wernbom et al., 2009). Excessive occlusion may lead to slower nerve conduction velocity, which is particularly disadvantageous during prolonged training (Mittal et al., 2008). Different methods for determination of the optimal BFR pressure have been discussed in the scientific literature. However, no specific guidelines have been developed for both training and BFR pressure variables.

BFR pressure during resistance training

The absolute level of occlusion pressure should be adjusted with respect to the individual characteristics of the athlete. Many studies that have analysed the effects of RT-BFR on training adaptations have been conducted using a constant pressure, similar for the entire research group, regardless of individual morphological differences (Fahs et al., 2012), which seems methodologically incorrect. In other studies, BFR pressure has been determined based on brachial systolic blood pressure (bSBP) (Manini et al., 2011; Rossow et al., 2012). In such cases, the most frequently used value was 130% bSBP. However, Loenneke et al. (2013) found that determination of BFR based on bSBP was incorrect, especially in relation to the compression in the lower limbs, which is related to the difference in the circumference between the lower and upper limbs. Laurentino et al. (2012) evaluated pressure resulting in complete vascular restriction (F-BFR) of the lower limb at rest. It has also been shown that training at higher relative arterial restriction pressure causes a greater decrease in the rate of the blood flow (Mouser et al., 2017), and a greater increase in blood pressure compared to the exercises with lower relative restriction pressure (Jessee et al., 2016). Therefore, determination of BFR relative to the value of complete arterial restriction seems to be correct and objective. Studies have demonstrated that BFR pressure of 50% of the estimated F-BFR value is likely to be optimal for RT (Loenneke et al., 2014b). Laurentino et al. (2012) suggested a higher BFR pressure of 80% of the F-BFR. Other authors have also suggested that the value of pressure used should depend to a large extent on the circumference of the limb to which the compression is applied (Crenshaw et al., 1988; Loenneke et al., 2012b). Medical literature provides evidence that the most reliable predictor of optimal artery occlusion pressure is thigh circumference (Crenshaw et al., 1988). Studies also have found that higher BFR values are needed in people with larger limb circumferences compared to those with smaller circumferences (Jessee et al., 2016; Loenneke et al., 2015).

The width and type of material used in BFR

It was shown that BFR pressure depends not only on individual factors such as the circumference or cross-sectional area of the muscle, but also on the width and material of the tourniquet. There is no constant and standard cuff width for BFR training. The cuff width used in previous studies ranged from 5 to even 11-14 cm (Fujita et al., 2007; Gundermann et al., 2012). The study by Loenneke et al. (2012b) demonstrated that a constant pressure used with a wide cuff resulted in different physiological and adaptive responses compared to a narrow cuff (Loenneke et al., 2012b; Rossow et al., 2012). Loenneke et al. (2013) presented data in which the supine arterial compression was analysed using cuffs with widths of 5 and 13.5 cm. In case of the 5 cm cuff and a pressure of 200 mmHg, the compression led to closure of venous blood outflow in only 19 of 83 study participants. In the narrow cuff and the value of 130% bSBP, arterial occlusion was obtained only in one of the 83 study participants. However, the use of a 130% bSBP pressure in case of the 13.5 cm cuff resulted in arterial occlusion in 49 out of 116 study participants. These results confirm the significant effect of cuff width on BFR efficiency. This was also demonstrated in the study by Jessee et al. (2016), who found that less pressure was required to ensure complete blood restriction using the 12 cm cuff compared to 5 and 10 cm cuffs. Similar findings were presented in studies by Abe et al. (2006) and Gundermann et al. (2012). Abe et al. (2006) used a BFR pressure of 200 mmHg with a 5 cm cuff, whereas Gundermann et al. (2012) used the same BFR pressure with a 11 cm cuff. Although both cuffs were inflated to the same pressure, the cardiovascular response was different. The need for adjustment of BFR pressure in relation to the cuff width was also described by Rossow et al. (2012). In their study, two different cuffs were inflated to the same BFR (~ 150 mmHg). It was observed that a 13.5 cm cuff led to a greater change in the heart rate and blood pressure during exercise than it was the case with a 5 cm cuff. The authors found that the 5 cm cuff closed venous outflow at approximately 235 mmHg (for most people), whereas the 13.5 cm cuff required only 144 mmHg. Therefore, the efficiency of BFR is determined not only by the above mentioned limb circumference, but also by cuff width. Loenneke et al. (2013) used both, the influence of the limb circumference and the width of the cuff to describe the method of choosing BFR. Firstly, the thigh circumference was measured at a distance of 33% from the inguinal crease to the superior border of the patella (Loenneke et al., 2012b). Then a BFR stimulus equivalent to 60% F-BFR estimated relative to thigh circumference was evaluated. Based on the obtained results, the following guidelines concerning lower limbs and the 5 cm cuff were developed:

- 45-50 cm = 120 mmHg;
- 51-55 cm = 150 mmHg;
- 56-59 cm = 180 mmHg;
- over 60 cm = 210 mmHg.

The optimal BFR values indicated by Loenneke et al. (2012b) have a physiological background, take individual characteristics into account and, among the many criteria presented earlier, they seem to be very precise. However, it should be noted that not every athlete that follows RT-BFR training has an access to precise occlusion devices that monitor the restriction pressure. In order to promote a wider application of RT-BFR, the authors decided to evaluate the effectiveness of BFR using elastic wraps, without precise determination of the compression pressure. Elastic knee wraps (~ 76 mm wide), which represent an inexpensive and easily available tool, were first used for BFR in 2009 (Loenneke and Pujol, 2009). In the following years, a series of tests were conducted and it was found that the use of elastic wraps led to similar adaptive modifications to those observed using cuffs with precise evaluation of the pressure (Loenneke et al., 2012a, 2012b). However, the use of elastic wraps led to the problem with not only using comparable compression in subsequent training sessions, but also with obtaining a similar BFR value between the left and right limbs. Consequently, people who train using the RT-BFR method stimulated one limb more or even excessively while the other was stimulated to an insufficient degree. In subsequent years, Wilson et al. (2013) introduced a simple yet effective tool for BFR. Researchers proposed using a subjective scale of pain sensation. They found that the BFR value for using elastic knee wraps was effective when the wraps were fitted sufficiently tight while not causing pain. The value of compression was assessed with a subjective scale of pain perception from 0 to 10, where 0 means no compression and 10 means high compression causing a high pain perception. Wilson et al. (2013) found that the optimal BFR value using wraps should be evaluated on a scale of 7. However, the assessment of the subjective pain perception does not seem to be an optimal solution - all the more so because this method does not refer to the limb circumference or the cuff width. Furthermore, wider cuffs (13.5 cm) lead to higher pain scores and assessment of perceived physical effort compared to narrow cuffs (5.0 cm) (Rossow et al., 2012). An interesting, practical and effective solution for optimal BFR determination is also offered by the method developed by Yamanaka et al. (2012) and Luebbers et al. (2014). Instead of pain assessment, these studies chose optimal BFR based on actual value of the tourniquet circumference. The more compression applied by the tourniquet, the higher the BFR. The value was determined based on the width of the tourniquet. Research results indicated that BFR using elastic tourniquets could be an effective substitute for pneumatic cuffs. Confirmation of this was obtained in a study that examined the use of bands in a group of athletes (Luebbers et al., 2014; Yamanaka et al., 2012).

In addition to the cuff width and the size of the muscular circumference, the BFR effect also depends on the type of material from which tourniquets are made. Many narrow cuffs are made of elastic material, while the wider cuffs are made of nylon. The differences in the material structure alone may lead to differences in the efficiency of blood flow restriction, despite the use of similar pressures. Elastic (Abe et al., 2006) and nylon (Jessee et al., 2016) are the most common materials used in BFR training. Loenneke et al. (2013) did not show any significant differences in resting blood pressure and the maximum number of repetitions between nylon and elastic cuffs. Buckner et al. (2017) performed similar examinations for the upper body. In their study, the authors found that resting pressure of arterial occlusion was significantly greater when a 3 cm elastic cuff was used compared to a 5 cm nylon cuff. However, this difference may have resulted from the fact that the cuffs had different widths (the 3 cm elastic compared to the 5 cm nylon cuff).

Although it is difficult to precisely evaluate the optimal pressure used during RT-BFR, the most important factors to be considered include the limb circumference, resting pressure for this limb, and cuff width. However, it can be assumed that the BFR value of 50-80% of F-BFR is optimal (Laurentino et al., 2012; Loenneke et al., 2014a).

Physical exercise using RT-BFR

The effectiveness of using the RT-BFR method applies to various forms of physical activity, whereas its greatest advantage is that high exercise intensity is not needed to induce adaptive changes. Low exercise intensity is particularly useful in clinical cases where high-intensity training cannot be applied. Furthermore, physical exercise with BFR does not lead to extensive muscle damage, DOMS or exaggerated muscle soreness ratings (Loenneke et al., 2014a). Takarada et al. (2000a) demonstrated that the use of BFR alone, without any additional physical activity (5 sets of 5 min BFR with 3 min of free flow between sets at a pressure of 180–260 mmHg), supresses the postoperative process of muscular atrophy. Even an ordinary walk with simultaneous BFR leads to increased muscle strength and CSA in subjects without any experience in various forms of physical activity (Abe et al., 2006). In case of RT-BFR, hypertrophic effects and increased muscle strength were already present at low external loads (20% 1RM) (Loenneke et al., 2012a). Moderate BFR values (e.g. 40% F-BFR) in RT-BFR (LL) are sufficient to increase muscle strength and hypertrophy (Counts et al., 2016; Lixandrao et al., 2015). Studies have shown that muscle hypertrophy following RT-BFR (LL) or RT-BFR (ML) is similar to that observed in CRT (HL) (Loenneke et al., 2014a). The efficiency of particular strength training protocols is affected not only by the external load, but also by the number of sets, repetitions or movement tempo (Wilk et al., 2018). When using RT with BFR, training variables have to be adjusted for particular subjects, with an additional determination of the BFR pressure and the actual arterial restriction. Research indicates that if the external load in RT-BFR is lower than 30% RM, higher restriction pressures (80% F-BFR) should be applied to induce muscle hypertrophy (Lixandrao et al., 2015). Laurentino et al. (2012) showed that 8-week RT-BFR at (20%1RM) resulted in a nearly 40% increase in muscle strength, and a 6% increase in CSA. However, these results were obtained in a group of people without previous experience in resistance training or other forms of regular physical activity.

Effects of RT-BFR on muscle hypertrophy

Training adaptations in the form of muscle hypertrophy can be initiated using CRT even at low external loads (20%1RM). However, in case of CRT (LL), muscle hypertrophy effects can be achieved if muscle failure is ensured during particular sets, which is associated with a significant increase in exercise volume compared to CRT (HL) (Schoenfeld et al., 2016). Even if the condition related to complete muscle fatigue is met, the increase in muscle mass following CRT (20% 1RM) will be significantly lower than that obtained as a result of CRT (80% 1RM). However, in case of RT-BFR (LL), a significant increase in CSA was observed even without reaching muscle failure in particular sets, as is the case in CRT (LL) (Abe et al., 2005; Kubo et al., 2006). However, studies have suggested that the increase in muscle mass following RT-BFR training (20-30%1RM) does not exceed that observed after the use of CRT (80%1RM) (Ellefsen et al., 2015; Farup et al., 2015; Lowery et al., 2014). The effectiveness of using BFR concerns various research groups, both non-athletes (Lixandrao et al., 2015; Laurentino et al., 2012), people with moderate experience in RT (> 1 year) (Lowery et al., 2014) and advanced RT athletes (Cook et al., 2018; Yamanaka et al., 2012). Morphological adaptations induced by resistance training are observed much earlier in case of RT-

BFR compared to CRT. With CRT (HL), adaptations in the first stage occur in the nervous system, manifesting themselves in improved muscle strength. A significant increase in cross-sectional areas of the exercised muscles occurred after 6 weeks of CRT in a study conducted by Wilson et al. (2013). On the other hand, Abe et al. (2005) applied an exercise protocol of RT-BFR (LL-20% 1RM) twice a day in youth athletes, which resulted in a significant increase in the thickness of the quadriceps and biceps muscles (mid-thigh muscle thickness) after 8 days compared to the non-BFR group. An interesting solution in striving for muscle hypertrophy may be offered by a combination of CRT (HL) and RT-BFR (LL). Yasuda et al. (2011b) published a study where athletes performed the bench press exercise 3 times a week for 6 weeks. One group followed a CRT program (75%1RM, 3 sets, 10 repetitions, 2-3 min rest interval), while the second group performed RT-BFR (30%1RM, 30 repetitions, 3 sets, 15 repetitions, 30 s rest intervals between sets), while the third group used a combination of these two training methods, with two RT-BFR (LL) sessions and one CRT (HL) session a week. A comparable increase in the cross-sectional area (CSA) of the triceps muscle was found in the CRT (HL) group and the group using the combined training protocols. The lowest increase in CSA was observed in the group using only RT-BFR (LL), which indicates that a high external load is needed to ensure optimal muscle hypertrophy. What is particularly important in RT-BFR (LL) is that the effect of increased hypertrophy is not limited to places affected by blood flow restriction. Yasuda et al. (2011b) showed that after 6 weeks of bench press training using the RT-BFR method (30%1RM, 3 times a week), the cross-sectional area of the pectoralis major muscle increased by 8.3%. However, it should be acknowledged that the group using CRT (75%1RM) achieved significantly higher increases in CSA (17.6%). CRT (HL) causes significant catabolic responses, including muscle protein degradation. In contrast to CRT (HL), the use of RT-BFR (LL) does not induce severe muscle damage (Loenneke et al., 2014a) leading to limitation of contractile protein degradation. It allows for acceleration of muscle recovery and adaptive processes. Neto et al. (2018) reported a significantly higher creatine kinase and lactate dehydrogenase activity following CRT (80%1RM) compared to RT-BFR (20% 1RM), both after 24h and 48h. The reduced catabolic response following RT-BFR may partly explain the faster hypertrophic effects induced by occlusion training.

Muscle strength training under BFR conditions

The use of high external loads is a prerequisite for the development and maintenance of muscle strength. However, this form of training cannot be used as a reliable solution for people with injuries, older adults or athletes during or after the competitive period. The substitute for CRT (HL) in terms of the development of maximum strength may be offered by RT-BFR (LL). The results of scientific studies have demonstrated significantly higher effectiveness in the development of muscle strength following RT-BFR (LL) compared to CRT (LL) (Segal et al., 2014; Wilson et al., 2013) and comparable to CRT (HL) (Laurentino et al., 2012; Takarada et al., 2000b). However, in terms of comparison of the effectiveness of CRT (HL) and RT-BFR (LL), the results have been inconclusive and some of them indicated higher efficacy of CRT (HL) (Cook et al., 2018; Yasuda et al., 2011a). The beneficial effects of using BFR in the development of muscle strength are not limited to clinical populations or people without experience in resistance training (Segal et al., 2014), but this also applies to healthy and physically active people (Laurentino et al., 2012), as well as athletes (Cook et al., 2014; Manimmanakorn et al., 2013a; Yamanaka et al., 2012). The experiment conducted by Laurentino et al. (2012) showed that healthy individuals who were beginners in CRT could achieve strength increments following RT-BFR (LL) similar to those observed after CRT (HL), at the level of 36.2 and 40.1%, respectively, after 8 weeks of training. Similarly, a study by Yasuda et al. (2011b) showed an increase in muscle strength by 8.7% in the RT-BFR (LL) group, 15.3% in the CRT (75%1RM) group, and the highest (19.9%) increase in the group following RT-BFR (LL) combined with CRT (HL). The results documented by these authors indicate that the most effective mode of resistance training for experienced athletes includes the combination of CRT (HL) with RT-BFR (LL). This solution was used by Yamanaka et al. (2012) in a group of American football players. After completing CRT

(HL), the participants additionally performed the bench press and barbell squats using the BFR method (20%1RM, 3 sets, 20 repetitions, 45 s rest). The group using the additional effort with BFR obtained a significantly higher increase in muscle strength, in both exercises (bench press + 9.3 kg) and (barbell squat + 14 kg).

BFR in training of athletes

The use of RT-BFR offers benefits not only to beginners but also to competitive athletes (Abe et al., 2005; Cook et al., 2014; Manimmanakorn et al., 2013a; Yamanaka et al., 2012). RT-BFR has been shown to significantly improve muscle strength, power, maximum and repetitive sprinting performance, general fitness, agility and results of the aerobic shuttle test (Abe et al., 2005; Cook et al., 2014; Manimmanakorn et al., 2013a). Takarada et al. (2002) evaluated the effectiveness of an 8-week RT-BFR (LL) program of bilateral knee extension training in a group of athletes. Higher improvements in muscle strength and increased CSA of the knee extensor muscles were observed in the group using RT-BFR (LL) compared to the control group. American football players using an RT-BFR (20%1RM) program for 4 weeks achieved significant improvements in muscle strength in the bench press and squat (by 8 and 7%, respectively) compared to the control group (Yamanaka et al., 2012). Some studies in elite athletes have shown that RT-BFR (70%1RM, 5 sets, 5 repetitions) does not only improve muscle strength in areas of restriction, but also applies to global exercises such as the squat (2.0 ± 0.6%) and the bench press (1.4 ± 0.8%) (Cook et al., 2014). These findings expand the scope of opportunities for application of BFR in areas which, due to technical reasons, cannot be directly exposed to occlusion (torso, chest, shoulder girdle).

In most sports, athletes use CRT as a training means aimed to improve not only muscle strength, but to indirectly enhance various sport-specific skills needed to meet the demands of a given sport or event. In this case, several studies have also demonstrated the benefits of using BFR. Abe et al. (2005) examined a group of track and field athletes (jumpers and sprinters) and found not only a significant increase in muscle mass (mid - thigh CSA) or muscle strength (leg press), but also an improvement in sprinting performance following an 8-day training cycle based on RT-BFR. A significant improvement is particularly impressive while taking into account the duration of the training cycle of 8 days and the high sports level of the study participants. It should be noted, however, that the participants performed as many as 23 training sessions during the 8 days, consisting of 3 sets of 15 repetitions of squats and leg curls (20%1RM), which alone is a factor strongly stimulating adaptive changes. Manimmanakorn et al. (2013a) also showed the effects of RT-BFR (5 weeks) on motor abilities of netball players. In this study, the researchers compared the effects of BFR training to exercise under hypoxia. Maximum oxygen uptake ($\dot{V}O_{2max}$), 5 m sprint, agility, muscle strength and endurance were significantly improved in the BFR group and in the group of subjects who trained in hypoxia compared to the control group (Manimmanakorn et al., 2013a). A significant increase in power and improved sprinting performance (40 m) following BFR were also demonstrated by Cook et al. (2014). These authors confirmed the legitimacy of using BFR in resistance training of athletes. However, it seems questionable whether RT-BFR is always a better form of training compared to CRT? Similar to CRT, the selection of training variables plays a major role. A study by Luebbers et al. (2014) conducted in a group of American football players confirmed that regardless of whether BFR was applied or not, the external load (RM) had a significant effect on the effectiveness of training. RT-BFR (7 weeks) was used as a training protocol, using elastic knee wraps. It was found that RT-BFR (HL) caused the greatest increase in muscle strength in the squat, while the RT-BFR (LL) group reached the level of adaptive changes similar to the group using CRT (HL) without BFR. Consequently, it can be stated that the external load determines the scope of adaptive changes.

Frequency of BFR training sessions

BFR training does not necessarily mean the use of occlusion in each training session and in each exercise. Correct training periodization should optimize the use of all training means to induce desired muscle adaptations. Both CRT and RT-BFR can be used in combination or alternatively within training sessions and training cycles. Yasuda et al. (2011b) examined the effectiveness of 3 training sessions in a microcycle for a period of 6 weeks. Participants performed the bench press divided into several groups. One group performed RT-BFR (30%1RM), the second group - CRT (75%1RM), and the third group used a combination of these two methods. The improvements in strength were similar in the CRT (HL) groups and in the combined training group, with 19.9 and 15.3% improvement, respectively. However, a lower increase (7%) in muscle strength was observed in the group using RT-BFR (LL). Relative strength (1RM divided by CSA of the triceps brachii) increased in the CRT (HL) group and in the combined training group (10.5 and 6.7%, respectively), but such changes were not demonstrated in the RT-BFR group (LL). In addition to the combined effect of CRT and RT-BFR used in these training cycles, Yamanaka et al. (2012) proposed combining these two forms of effort within one training session. These authors demonstrated that RT-BFR (LL) performed as an additional stimulus after sets of CRT (HL) significantly improved performance in the bench press and in squats in American football players. Although this study found no neural adaptations, it is likely that using CRT (HL) followed by BFR (LL) exercises provides a strong stimulus for neural adaptations induced by CRT (HL), combined with enhanced morphological responses after RT-BFR (LL).

Effectiveness of BFR training and athlete's individual characteristics

Another equally important factor (in addition to training variables and the value of pressure used) that impacts responses induced by RT-BFR may be the type of sport, the nature of exercise metabolism, and the FT/ST muscle fiber ratio of the athlete. Takada et al. (2012) demonstrated that metabolic stress during BFR exercises was much greater in the group of endurance runners compared to sprinters. This is likely due to the fact that long-distance runners have a higher aerobic capacity compared to sprinters and are in fact more dependent on the aerobic metabolism during exercise, and therefore experience greater metabolic disturbances during BFR. Furthermore, sprinters may be physiologically more accustomed to the anaerobic environment induced by BFR, and, consequently, BFR does not provide the same metabolic load to them compared to endurance runners (Takada et al., 2012).

Disadvantages of using BFR

Although RT-BFR has been shown in many cases to lead to outstanding effects in terms of muscle strength and hypertrophy, the findings of various studies are inconsistent. Laurentino et al. (2012) failed to demonstrate the benefits of RT-BFR (ML) and RT-BFR (HL) with regard to muscle strength and muscle hypertrophy. Relative muscle strength following RT-BFR (LL) did not change significantly compared to the pre-training levels (Fujita et al., 2008; Kubo et al., 2006; Takarada et al., 2000b, 2002). Furthermore, it seems that RT-BFR (LL) does not improve muscle activity to the same level as CRT (HL) (Cook et al., 2013), which also seems to be a disadvantage. It is particularly important with regard to professional athletes that studies have emphasized a significant drawback resulting from the use of BFR. The muscle hypertrophy induced by RT-BFR can be significantly impaired directly in the region under the cuff (Ellefsen et al., 2015; Kacin and Strazar, 2011). Kacin and Strazar (2011) examined the effects of RT-BFR following 4 weeks of training with a 13 cm (230 mmHg) cuff. These studies indicated an increase in CSA of the quadriceps muscle, but muscle growth was found to be inhibited in the location under the cuff, which poses a huge risk not only to sports performance, but also to the health and safety of the athlete. Another study by Ellefsen et al. (2015) also found a decrease in CSA near the BFR location following 12-week RT-BFR (LL) compared to the CRT (HL) group. These findings suggest that narrower cuffs are more effective compared to wider ones, but BFR training cannot be used as a single resistance training stimulus. A combination of CRT and RB-BFR seems to provide the most beneficial solution.

Conclusions

Scientific data related to physical exercise with BFR indicate that in contrast to neural adaptations, changes in strength induced by RT-BFR are more closely related to muscle hypertrophy. This is a particularly important difference compared to CRT (HL), where an increase in muscle strength results from neural changes and increased muscle mass. Therefore, it is important for a comprehensive development of the athlete not to use RT-BFR as the only training means. It is likely that optimal muscle adaptations can be induced by a combination of CRT and RT-BFR due to low mechanical loads and limited post-exercise muscle damage generated by RT-BFR. It seems reasonable to use CRT followed by RT-BFR, especially if the training objective is to develop muscle strength. The optimal use of BFR should fit the training periodization design, both in the macro and microcycle arrangement. The use of BFR in training also requires adequate progression or modifications in terms of duration of occlusion, the ratio of exercises with BFR to conventional exercise, and most of all the value of pressure or cuff width.

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