Is there rationale for the cuff pressures prescribed for blood flow restriction exercise? A systematic review

Is there rationale for the cuff pressures prescribed for blood flow restriction exercise? A systematic review

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Abstract

Background: Blood flow restriction exercise has increasingly broad applications among healthy and clinical populations. Ensuring the technique is applied in a safe, controlled, and beneficial way for target populations is essential. Individualised cuff pressures are a favoured method for achieving this. However, there remains marked inconsistency in how individualised cuff pressures are applied.

Objectives: To quantify the cuff pressures used in the broader blood flow restriction exercise literature, and determine whether there is clear justification for the choice of pressure prescribed.

Methods: Studies were included in this review from database searches if they employed an experimental design using original data, involved either acute or chronic exercise using blood flow restriction, and they assessed limb or arterial occlusion pressure to determine an individualised cuff pressure. Methodologies of the studies was evaluated using a bespoke quality assessment tool.

Results: Fifty-one studies met the inclusion criteria. Individualised cuff pressures ranged from 30% to 100% arterial occlusion pressure. Only 7 out of 52 studies attempted to justify the individualised cuff pressure applied during exercise. The mean quality rating for all studies was 11.1 ± 1.2 out of 13.

Conclusions: The broader blood flow restriction exercise literature uses markedly heterogeneous prescription variables despite using individualised cuff pressures. This is problematic in the absence of any clear justification for the individualised cuff pressures selected. Systematically measuring and reporting all relevant acute responses and training adaptations to the full spectrum of BFR pressures, alongside increased clarity around the methodology used during blood flow restriction exercise is paramount.

1. Introduction

Blood flow restriction (BFR) exercise has become an increasingly popular research focus over the last 20 years. The technique involves exercising with partially inflated cuffs or tourniquets applied proximal to the muscle group being trained to moderate the blood flow to that muscle group [1]. Both low-load resistance exercise (20-40% one-repetition maximum [1RM]) and low-to-moderate intensity aerobic exercise (such as walking at 3.5-4.5 km.h^{-1}) when combined with BFR, predominately elicit beneficial adaptations in muscle size and strength [1]. Additional benefits may present regarding transient increases in muscle blood-flow due to reactive hyperaemia, possibly indicative of enhanced vascular capacity [2], physical function [3], and improved early-stage musculoskeletal rehabilitation [4,5]. There is also strong evidence supporting the use of BFR across multiple populations ranging from athletic, healthy adults [6,7] to older adults [8,9].

Despite the popularity of BFR as a technique, a common limitation in the field is the inconsistency in the methodology used when applying the technique [10]. Similarly, and despite the broad spectrum of exercise modalities to which BFR can be applied, there is a paucity of exercise prescription guidelines for tailoring BFR exercise programs to targeted populations. A recent position stand is perhaps the best source for such guidelines to-date, but still provides only generalised, rather broad prescription ranges for training variables applicable to generally healthy populations [1]. The suggestion is made that variables may need to be adjusted among individuals, for example if load is in the lower end of the suggested range, cuff pressure may need to be increased [1]. However, the specificity of such adjustments remains difficult to discern based on the existing evidence.

The growth in practitioner use of BFR exercise in general strength and conditioning as well as rehabilitation settings has also facilitated research in clinical populations such as chronic obstructive pulmonary disorder [11], end-stage kidney disease [12], ischemic heart disease [13], and sporadic inclusion body myositis [14]. These clinical populations require numerous considerations to account for altered haemodynamic responses, co-morbidities, and contraindications inherent to each individual condition when compared with healthy populations. As such, it is necessary to ensure that the methodologies used among these populations are precise and consistent in order to account for any condition-specific considerations that may be affected by the application of BFR. This is also relevant for the broader consistency of BFR application across all populations, particularly in research settings, to reduce the heterogeneity that makes comparisons between studies problematic [3]. For example, individualised applied pressures during BFR exercise can be derived from measures of limb occlusion pressure (LOP) or arterial occlusion pressure (AOP), usually as a percentage of this value [15]. These individualised pressures are favourable when applying cuff pressure during BFR exercise, as they help address some of the variability in restriction caused by differences in the equipment used, such as differing cuff widths, when set at the same absolute pressure [16]. Still, only recently has research begun to define minimal threshold pressure ranges suitable to attain the relevant acute affects needed for muscular adaptation to BFR exercise [17]. However, with significant heterogeneity of applied pressures across the broader BFR exercise literature, and even the recently published position stand on BFR exercise suggesting a large pressure range (between 40% - 80% of AOP or LOP), there is still no clear consensus on ideal individualised pressures during BFR [1]. There does not appear to be a dose-response relationship between applied pressure and exercise-related outcomes, acute or chronic, although, to the best of our knowledge, this has yet to be the focus of a review or independent study.

The prescribed pressure application is a primary variable in the application of BFR, making it of particular importance, and more so for clinical populations when vascular impairments must be considered. This is also relevant to ensure that discomfort caused by the compression of active musculature is minimised without compromising the efficacy of the technique [18-20]. However, the issue still remains that pressure is inconsistently applied. Some studies apply arbitrary pressures [21,22] compared with others using variable percentages of measured occlusion pressures [8,12,23,24]; some studies use static cuffs while others use dynamic cuffs [23,25]; and some studies apply pressures derived from estimation equations based on individual participant characteristics [26]. It is also unclear if there is substantiative reasoning for why studies choose to employ specific individualised pressures during BFR. Thus, the objective of the present review was to quantify the individualised cuff pressures being applied during BFR exercise in the broader literature and determine whether there is clear justification for why the prescribed individualised cuff pressures were used.

2. Methods

2.1 Study design

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.2 Search strategy

The electronic database search included Medline, Embase, CINAHL, Springer, and SPORTDiscus. Search strategy utilised the search strings identified in the supplementary material. Search terms were derived from 'limb occlusion pressure', 'blood flow restriction', and 'exercise' (Table 1). References were also identified in the reference lists of previous systematic reviews in addition to the results of our electronic database search. Search results were filtered within the database where possible for the filters 'Human', 'English', 'academic journals', 'research article' and/or 'full text'. Search results included dates from inception until the date of the search (15th October 2019).

2.3 Participants, interventions, comparators

Database search results were imported into Endnote X9 (Thompson Reuters, Philadelphia, Pennsylvania, USA). Duplicates were removed, and screening was completed by title, abstract, and full text. Excluded articles were sorted into individual folders indicating the reason for exclusion until only articles for inclusion remained. This process was completed by two researchers independently. The relevant inclusion criteria are identified below and reasons for exclusions noted in the PRISMA flow chart (Figure 1):

1. Language: only studies published in English were included in this review.
2. Study Design: only studies that employed an experimental design were included. Systematic reviews, narrative reviews, conference abstracts, editorials, letters or publications not inclusive of original data were excluded.
3. Exercise component: studies must have included either an acute exercise bout during which BFR was employed or an exercise training intervention. Exercise training interventions must have included chronic aerobic, resistance, combined, or alternative types of progressive exercise training over multiple weeks in conjunction with BFR.
4. Measurement of occlusion pressure: studies included in this review must have conducted assessments of total LOP or total AOP (this does not include systolic blood pressure). A pressure derived from this assessment must have been prescribed during the exercise component of the study.

2.4 Assessment of included study quality

The quality and risk of bias of included studies was independently evaluated by two reviewers (MJC, AKM). As no suitable published assessment criteria were available to directly assess the variable study designs and outcomes of the studies in this review, specific criteria were developed. These criteria were broadly adapted from tools utilised by the Cochrane Group for quality assessments in both screening and diagnostic tests and risk of bias in interventions [27,28]. These included assessment of the level of evidence as defined by the Oxford Centre for Evidence-Based Medicine [29], and reporting of the design, selection criteria, setting, participant description, and transparency of methodological reporting. Scores were allocated based on how well each criterion was covered in the included studies, up to a maximum possible score of 13 (low risk of bias/high quality). Contention between quality assessments was resolved through follow up consultation between reviewers. Studies with an assessed rating below 7 (<50% of maximum) were considered poor quality, or high risk of bias. This did not prohibit or invalidate the discussion points in the present review, it merely highlights the methodological quality in individual blood flow restriction exercise studies, and the potential reporting short-falls including the consistency and clarity surrounding the assessment, equipment used, and reporting of applied BFR pressures.

2.5 Data extraction

Following the initial screening, information from the included studies was extracted, including basic study characteristics, mean participant age, sample size, acute exercise or exercise training intervention prescription, justification for prescribed restriction pressure or lack thereof, and details of the blood flow restriction equipment and assessment used.

3. Results

3.1 Literature search

A total of 3139 articles were retrieved from searches including those from inception to 11th March 2020 from Medline (446), Embase (2287), CINAHL (93), Springer (181), and SPORTDiscus (132). Duplicates were removed, refining the total number of articles for screening down to 2696. Of these results, 2495 were excluded based on title or abstract, and the full texts of the remaining 188 articles were evaluated using the inclusion criteria for this review. Articles removed in this manner are outlined in the PRISMA flow chart (Figure 1). Two studies were removed for utilising the same data set as another included study. An additional 5 studies that fulfilled the inclusion criteria were identified from the reference lists of prior reviews related to the topic of blood flow restriction exercise and were approved for inclusion among the original search results. Subsequently, the total number of studies included for review was 52. The assessment of the methodological quality of the included studies is shown in Table 2, with the mean quality rating of included studies being 11.1 ± 1.2 out of 13.

3.2 Study characteristics

Information extracted from studies included in this review are summarised in Table 3. This included population evaluated, sample sizes, whether the study was acute or chronic (training), exercise modality employed, the degree of restriction used, justification for the pressure applied during the study, and details of the BFR equipment used. The 52 studies included a total of 1133 participants. Sample sizes, excluding the one individual case study, ranged from n = 8 [25,30] to n = 137 [31].

The populations examined were relatively heterogeneous between studies, with the most common population being healthy non-resistance trained but recreationally active adults, examined in 23 of the 52 included studies [17,24,31-51]. Other populations included resistance-trained adults, adults with musculoskeletal or soft tissue injuries, older adults, or adults with hypertension. There were far more studies (26 of 52) examining only male participants [17,24,25,30,32-38,41-43,46,48,50-59], compared with just 8 of 52 examining only female participants [40,49,60-65], leaving 18 studies examining both of these genders [8,19,20,39,44,45,47,66-75].

The majority of the included studies were acute studies, with only 16 of the 52 included studies assessing adaptations to BFR exercise training [8,35,38,39,41,44,48,50,51,56,59,62,64-66,74]. Most studies employed traditional upper or lower body resistance exercise protocols, commonly utilising elbow flexion, leg press, or knee extension exercises. Only six studies employed aerobic or alternative exercise protocols, namely cycling [37], walking [8,46], repeated sprint training [30], and water aerobics [64,65].

Sixteen of the 52 included studies applied multiple different cuff pressures as a means of comparing acute responses or chronic adaptations to different applied pressures [17,20,31,32,36,39,43,44,48,54,67,68,70,72,73,75]. Among the remaining 36 studies using a single individualised pressure for their application of BFR, 13 studies used 80% AOP/LOP [24,37,40,49,50,57,61,62,64-66,71,74], 7 studies used 60% AOP/LOP [8,33,34,38,46,52,56], 5 studies used 50% AOP/LOP [25,41,42,59,60], 4 studies used 100% AOP [47,51,58,63], 4 studies used 40% AOP/LOP [19,30,45,69], and 3 studies used 30% AOP [35,53,55]. The technique and postures used to determine each of these individualised restriction pressures was similarly variable. Upper limb restriction was generally measured using either the radial or brachial arteries, and lower body restriction measured in one of the tibial arteries, or the popliteal artery. The posture in which assessment of occlusion pressure was conducted was not reported in 15 of the 52 included studies [24,30,32,34,35,43,47,49,51,53,58,61-63,74]. Among those reporting participant posture during assessment, supine [17,36,37,40,42,48,50,54,56,57,59,64,65] or standing [8,19,20,31,41,44,46,52,69,70,72,73,75] were each chosen in 13 studies, and sitting was used in 11 studies [25,33,38,39,45,55,60,66-68,71].

Of the 16 studies examining multiple cuff pressures none provided clear justification for the selection of pressures they included. Among the 36 included studies that utilised a single individualised pressure when applying BFR, only 7 provided justifications of pressure used [19,41,46,53,55,66,71]. The remaining 29 either provided no reasoning for the pressure selection, or only cited the pressure having been used in a previous study. The reasons provided for pressure selection included: to occlude venous flow during expected increased blood pressure [53]; lower pressures reduce the risk of autonomic dysreflexia and deep vein thrombosis [53]; pressures greater than 30% AOP not being required to produce training adaptations or targeted increases in total muscle work [55]; higher pressures maximise fast twitch fibre recruitment and strength adaptations to BFR training [66,71]; the lowest pressure possible to minimise client discomfort but also provide a similar level of restriction to higher pressures [19,41,46].

The equipment used to apply BFR was described in all but 5 of the included studies. Cuff dimensions were described in 47 studies, with mean cuff width being 11 ± 5 cm and ranging from 3 cm [19] to 18 cm [58]. However, this was affected by whether the cuffs were designed for upper limb (mean width 7 ± 4 cm) or lower limb (mean width 14 ± 4 cm) application. Cuff material was described in 19 of the 52 studies, with most being nylon, and others being elastic. Seventeen of the included studies reported using a 'standard sphygmomanometer' to apply BFR, rather than a dynamic pneumatically regulated system. The pattern of inflation was described in 43 out of the 52 included studies, with 38 studies using continuous inflation across the full duration of exercise (multiple sets and repetitions) [8,17,25,31-36,38,39,42,43,46-50,52-54,56-65,67-71,74], only 3 studies using an intermittent inflation pattern whereby cuffs were deflated between sets of each exercise [37,51,55], and 2 studies including both continuous and intermittent inflation patterns in separate experimental groups [24,40].

4. Discussion

The present review highlights a clear lack of consistency among the individualised cuff pressures used in the BFR exercise literature, and even more concerning is the absence of a clear justification for the pressure selection by the vast majority of studies. The purpose of utilising individualised cuff pressures is to overcome the variability in magnitude of limb blood flow that is restricted when using arbitrary pressures or a percentage of measured systolic blood pressure due to individual participant differences in body composition and haemodynamics [1,15,76]. These individualised cuff pressures are attained through direct measurement of the pressure required to completely occlude limb blood flow (i.e. AOP/LOP), and then using a percentage of AOP/LOP that is expected to allow arterial inflow, but restrict venous outflow at rest [1]. This reduction in resting venous outflow is largely overcome during exercise by the mechanics of skeletal muscle contraction (the skeletal muscle pump) [1]. Even though there is a plethora of studies employing this method, the percentage of AOP or LOP utilised is markedly variable, ranging from 30% to 100% of AOP/LOP across studies with no clear justification for the pressures selected. Moreover, although a recent BFR exercise position stand recommends a very broad range of individualised restriction pressures to employ (40-80% AOP/LOP), 12% of included studies in the present review applied pressures outside of this range mostly without clear reasoning to support this [1,35,47,51,55,58,63]. This is an area of concern that needs to be further explored in order to provide clear reasoning for how the technique should be applied by practitioners.

Out of 52 studies included in this review, only 7 studies provided a justification for their selection of restriction pressures [19,41,46,53,55,66,71]. Even then, among the 7 studies providing a justification, reasons were sometimes vague, such as "*to selectively occlude venous flow during periods of expected increases in blood pressure*" [53], or simply based on other studies having shown a certain pressure to be effective in producing a particular outcome [46] even though the underlying mechanism was not well understood [41,46,53]. More valuable reasoning may be derived from those studies that alluded to mitigation of adverse events (autonomic dysreflexia and deep vein thrombosis, albeit specific to participants who had incomplete spinal cord injuries and a greater established risk of these adverse events), or to a balance of participant comfort with lowest established pressure for producing favourable adaptations to BFR training [19,53,55]. This emphasis on lower pressures to balance comfort and efficacy is a direct contrast to included studies that justified their use of a high pressure as having been shown to maximise fast twitch fibre recruitment and strength adaptations to BFR training [66,71].

This highlights the lack of a clear rationale underpinning the selection of restriction pressures based on physiological measurements alone. Instead, it is likely that decisions around prescribed restriction pressures are multifaceted. It is a logical approach to minimise participant discomfort while still obtaining a large degree of the physiological benefit that can be achieved through BFR exercise training. However, it is also valid to try to maximise the physical benefit that can be gained from using BFR exercise. Perhaps it is not so much a question as to which of these options is better, but more so a matter of when one of these options is more applicable than the other. If the target population is likely to report an elevated degree of discomfort, display significant fear avoidance with exercise or is intrinsically lacking in motivation to exercise in the first place, reducing pressure to minimise discomfort is likely to be more valuable. This would be particularly relevant for clinical populations, such as those with end-stage kidney disease known to be markedly physically inactive and report elevated difficulty and discomfort with exercise [8,77,78]. This would also apply to generally sedentary populations, who may not have been exposed to the level of exertion intrinsically required during exercise, and thus may be deterred with unnecessarily elevated discomfort. Conversely, in healthy, physically active populations, particularly those that are resistance trained, the most commonly examined population among the included studies in this review [17,19,20,24,25,31-52,55,57,58,67-70,72,73,75], maximising the physiological benefits of BFR may be preferable, despite potentially elevated discomfort. Regular exercise has also been shown to have a chronic-acute analgesic effect and reduce nociceptor excitability, suggesting that physically active populations may be less prone to exercise-induced discomfort [79,80]. This approach implies that the justification for an 'ideal' individualised pressure may be dependent on the population being examined, and there may be validity in both high and low-to-moderate pressures being employed in different situations.

One factor that prevents the identification of any one specific ideal pressure is the absence of a comprehensive understanding of all the physiological responses to specific individualised restriction pressures. Among the included studies in this review, sixteen studies examined how several different individualised pressures affected various outcome measures, although there was still no reasoning provided for why each of the pressures examined were selected [17,20,31,32,36,39,43,44,48,54,67,68,70,72,73,75]. In general, it could be assumed that assessing the effect of a low, a moderate and a high pressure provides some indication as to how increasing the applied pressure affects physiological responses. While this may narrow down the range of pressures that are deemed to be more appropriate than others, it still does not pinpoint any single individualised pressure as being the 'ideal' balance of comfort, safety, physiology, or ability to induce training adaptations. Nevertheless, this is the type of research that is needed most in order to help refine our understanding of how differences in pressure can enhance or detract from the efficacy of BFR as a technique.

An ongoing limitation with blood flow restriction exercise research is the inconsistency in the equipment that is used to induce BFR, while the absence of this information being reported is common. Narrower cuff widths require higher pressures to fully occlude limb blood flow, as do elastic cuffs compared with nylon cuffs [19,76,81], so reporting only the pressure used without indication of percentage AOP/LOP or the equipment employed makes reproducibility impossible. However, this problem is mitigated with the use of individualised pressures, provided that the measure of LOP or AOP uses the same cuff as that employed during the exercise itself [19,76]. Similarly, continuous compared with intermittent inflation patterns have been shown to impose greater discomfort, higher double product and elevate lactate accumulation [82,83], although continuous inflation has also been shown to produce similar oxidative stress [84], and even a reduction in haemodynamic stress [85] despite this seeming to oppose those studies indicating an increase in double product. This discrepancy is the result of different pressure applications for studies producing these conflicting results. While one study reported a greater double product with continuous inflation using the same pressure for both intermittent and continuous protocols [83], another study observed lower haemodynamic stress with continuous inflation when using a lower pressure for the continuous protocol [85]. This further emphasises the need for transparency in reporting applied pressures and justifying those choices for individualised pressure.

In the present review, cuff-width was reported in 90% of the included studies, and while positive, this is largely overcome with individualised pressures and so may be less important than cuff material (reported in only 36% of studies), and inflation pattern (reported in 83% of studies). The inflation pattern most commonly employed was continuous inflation, with only 5 studies using intermittent inflation [24,37,40,51,55]. Among these 5 studies using intermittent inflation, 4 employed higher restriction pressures (80-100% AOP) [24,37,40,51], which may suggest that intermittent inflation patterns require increased pressures. This would align with the previous study suggesting that continuous inflation patterns, and thus a lower but persistent cuff pressure evoked reduced haemodynamic stress [85]. This may also support why 88% of the studies in this review reporting inflation pattern employed continuous inflation instead of intermittent inflation.

A final consideration identified as a part of this review is the type of device used to apply BFR, where seventeen of the included studies report using a 'standard sphygmomanometer' to apply BFR, rather than a dynamic pneumatically regulated system. Static cuffs do not adjust the pressure of the cuff in response to muscular contractions occurring under the cuff, and thus are likely to induce elevations in pressure, and subsequently increase haemodynamic stress, as well as increase levels of discomfort and RPE [71]. Not having a regulated pressure may create increased unpredictability and reduced control of the acute responses to BFR exercise, and while these differences warrant greater exploration, the recommendation should likely remain that dynamic pneumatically regulated systems be used in future BFR exercise studies.

4.1 Limitations of the review

Due to the differences in study design, populations examined, exercise modality and prescription variables, the outcomes of each of the included studies were not reported in this review. While this was outside the scope of the present review, which was concerned with the rationale for prescribed cuff pressure, it may have provided insight as to whether certain pressures were more consistent in achieving positive outcomes. However, given the variable number of studies examining each of the individualised cuff pressures identified in this review, it would also have made any direct comparisons difficult.

4.2 Conclusion and Perspective

The current preference in BFR exercise research is for the use of individualised cuff pressures that account for differences in equipment such as cuff width and material, and reduce the inter-participant variability in acute responses to BFR exercise that occur when using a set arbitrary pressure value. Despite this preference when prescribing BFR exercise, there remains a lack of consistency among restriction pressures applied within the literature. Even more problematic is the absence of any clear justification for the selected BFR pressures in the vast majority of BFR exercise studies. Given the inconsistencies in methodology, populations examined and reporting of BFR equipment, it is apparent from this review that significant emphasis needs to be placed on systematically measuring and reporting all relevant acute responses and training adaptations to the full spectrum of BFR pressures, and preferably using the same equipment. Only with this degree and depth of data can "ideal" restriction pressures be ultimately justified for any specific populations.

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Figure Legends

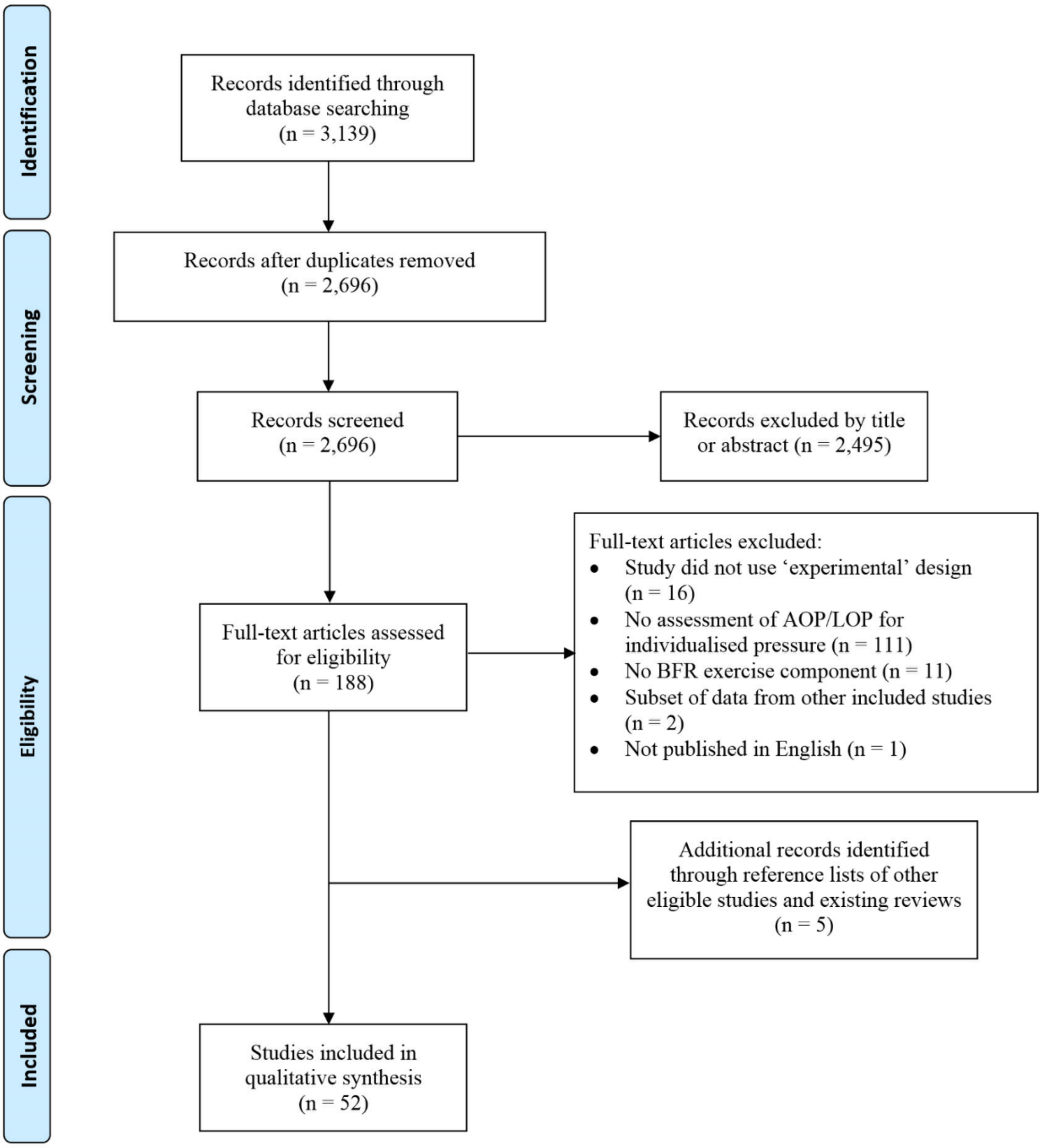

Fig. 1 PRISMA flow chart of study selection process.

Table 1: Search strategy by database.

Search strings used for CINAHL, Medline, SPORTDiscus, and SpringerLink		
1.	**Limb occlusion pressure**	"limb occlusion" OR "arterial occlusion" OR "venous occlusion" OR "pressur*" OR "arterial restrict*" OR "venous restrict*"
2.	**Blood flow restriction**	"blood flow restrict*" OR "restrict blood" OR "vascular occlusi*" or "vascular restrict*" OR "occlud*" OR "kaatsu" OR "cuff*"
3.	**Exercise**	"acute" OR "chronic" OR "train*" OR "exercis*" OR "resistance" OR "resistive" OR "resistance train*" OR "weight train*" OR "strength train*" OR "weight lift*" OR "circuit train*" OR "aerobic" OR "endurance" OR "walk*" OR "run*" OR "cycling"
4.	**Terms excluded in search**	NOT "mouse" NOT "mice" NOT "rat" NOT "rodent" NOT "animal*" NOT "precondition*" NOT "fetal" NOT "foetal" NOT "altitude"
5.	**Filters manually applied**	*English, Academic Journals, Full text, Journal article, Human*
Search strings used for EMBASE		
1.	**Limb occlusion pressure**	'limb occlusion' OR 'arterial occlusion' OR 'venous occlusion' OR 'pressur*' OR 'arterial restrict*' OR 'venous restrict*'
2.	**Blood flow restriction**	'blood flow restrict*' OR 'restrict blood' OR 'vascular occlusi*' OR 'vascular restrict*' OR 'occlud*' OR 'kaatsu' OR 'cuff*'
3.	**Exercise**	'acute' OR 'chronic' OR 'train*' OR 'exercis*' OR 'resistance' OR 'resistive' OR 'resistance train*' OR 'weight train*' OR 'strength train*' OR 'weight lift*' OR 'circuit train*' OR 'aerobic' OR 'endurance' OR 'walk*' OR 'run*' OR 'cycling'
4.	**Terms excluded in search**	NOT 'mouse' NOT 'mice' NOT 'rat' NOT 'rodent' NOT 'animal*' NOT 'precondition*' NOT 'fetal' NOT 'foetal' NOT 'altitude'
5.	**Filters**	([article]/lim OR [article in press]/lim) AND [humans]/lim AND [english]/lim AND [embase]/lim

Table 2: Quality assessment of included studies.

Study	Level of evidence [a]	Selection criteria [b]	Setting [c]	Demographic information [d]	Regional Anthropometric data [e]	BFR method [f]	Pressure quantified [g]	Pressure rationale [h]	Missing data reporting [i]	Total Score (max = 13)
Valenzuela et al. [30]	5	0	1	1	0	1	1	0	1	10
Reis et al. [32]	5	1	1	1	0	1	1	0	1	11
Petrick et al. [33]	5	1	1	1	0	1	1	0	1	11
Montgomery et al. [34]	5	1	1	1	0	1	0	0	1	10
Ilett et al. [17]	5	1	1	1	1	1	1	0	1	12
Hughes et al. [66]	5	1	1	1	0	1	1	1	1	12
Chulvi-Medrano et al. [35]	5	1	1	1	1	1	0	0	1	11
Centner et al. [52]	5	1	1	1	0	1	1	0	1	11
Jessee et al. [67]	5	1	1	1	1	1	1	0	1	12
Kilgas et al. [36]	5	1	1	1	1	1	1	0	1	12
Dankel et al. [68]	5	1	1	1	0	1	1	0	1	11
Thomas et al. [37]	5	1	1	1	0	1	1	0	1	11
Stavres et al. [53]	5	1	1	1	0	1	1	1	1	12
Soligon et al. [54]	5	1	1	1	0	1	1	0	1	11
Scott et al. [60]	5	1	1	1	0	1	0	0	1	10
Pinto et al. [61]	5	1	1	1	0	1	1	0	1	11
Picón et al. [55]	5	1	1	1	0	1	1	1	1	12

May et al. [38]	5	1	1	1	1	1	1	0	1	12
Letieri et al. [62]	5	1	1	1	0	1	1	0	1	10
Ladlow et al. [56]	5	1	1	1	1	1	1	0	1	12
Jessee et al. [69]	5	1	1	1	0	1	1	0	1	12
Jessee et al. [39]	5	1	1	1	1	1	0	0	1	11
Jessee et al. [70]	5	1	1	1	1	1	0	0	1	11
Hughes et al. [71]	5	1	1	1	0	1	1	1	1	12
Curty et al. [57]	5	1	1	1	1	1	1	0	1	12
Buckner et al. [72]	5	1	1	1	1	1	0	0	1	11
Bell et al. [73]	5	1	1	1	0	1	0	0	1	10
Tennent et al. [74]	5	1	1	1	1	1	0	0	0	10
Neto et al. [40]	5	1	1	1	0	1	1	0	1	11
Mouser et al. [31]	5	1	1	1	1	1	1	0	1	12
Mattocks et al. [20]	5	1	1	1	0	1	0	0	1	10
Kim et al. [41]	5	1	1	1	1	0	1	1	1	12
Ferreira et al. [42]	5	1	1	1	0	1	0	0	1	10
Dankel et al. [75]	5	0	1	1	1	1	0	0	1	10
Clarkson et al. [8]	5	1	1	1	0	1	1	0	1	11
Buckner et al. [19]	5	1	1	1	1	1	1	1	1	13

Poton and Polito [58]	5	1	1	1	0	1	1	0	1	11
Pinto and Polito [63]	5	1	1	1	0	1	1	0	1	11
Neto et al. [24]	5	1	1	1	0	1	1	0	1	11
Fatela et al. [43]	5	1	1	1	0	1	1	0	1	11
Counts et al. [44]	5	1	1	1	1	1	1	0	1	12
Barnett et al. [45]	5	1	1	1	1	1	0	0	1	11
Staunton et al. [46]	5	1	1	1	0	1	0	1	1	11
Poton and Polito [47]	5	1	1	1	0	1	0	0	1	10
Moriggi Jr et al. [25]	5	1	1	1	0	1	1	0	1	11
Lixandrão et al. [48]	5	1	1	1	1	1	1	0	1	12
Araújo et al. [64]	5	1	1	1	0	1	1	0	1	11
Araújo et al. [65]	5	1	1	1	0	1	1	0	1	11
Santos et al. [59]	2	0	1	1	0	0	0	0	1	5
Araújo et al. [49]	5	1	1	1	0	1	0	0	1	10
Laurentino et al. [50]	5	1	1	1	1	1	1	0	1	12
Laurentino et al. [51]	5	1	1	1	1	1	1	0	1	12

Abbreviations: BFR – Blood flow restriction.

a. Oxford Centre for Evidence Based Medicine level of evidence (Level 1 = 5 points; level 2 = 4 points; level 3 = 3 points; level 4 = 2 points; level 5 = 1 point).

b. Inclusion and exclusion criteria clearly described (1 point)

c. Enough information provided to identify the general setting, or reproducible conditions (1 point)

d. Age and gender reported (1 point)

e. Relevant region-specific participant anthropometric data (regional or limb-specific body composition or size, not general body mass or body mass index alone) provided (1 point)
f. Description of pressure assessment, method of application (continuous or intermittent) and equipment sufficient to allow replication (1 point)
g. For applied pressure, mean or median and variance provided in absolute pressure (mmHg) (1 point).
h. Attempted to rationalise or describe choice of applied pressure (1 point)
i. All included participants measured and, if appropriate, missing data or withdrawals from study reported or explained (1 point)

Table 3: Summary of included study characteristics.

Author	Year	Sample (Population, age, gender)	Study *N*	Acute or training study	Modality	Details of AOP/LOP assessment (artery/limb + posture)	% AOP/LOP in BFR trial/s	Justification of pressure (Y/N) + detail	BFR details (cuff width, material, inflation pattern)
Valenzuela et al. [30]	2019	Elite male badminton players, 20 ± 2 years	8	Acute	Repeated Sprint Training	Posterior tibial artery; Posture not reported	40% AOP	N	13 cm width, material not reported, continuous inflation
Reis et al. [32]	2019	Physically active young males, 24 ± 5 years	13	Acute	Resistance – Unilateral knee extension	Posterior tibial artery; Posture not reported	0%, 40%, 60%, 80% AOP	N	13 cm width, material not reported (inflation system model reported), continuous inflation
Petrick et al. [33]	2019	*In vivo* study: Healthy males, 24 ± 1 years *In vitro* study: Healthy males, 25 ± 2 years	*In vivo* study: 10 *In vitro* study: 6	Acute	Resistance – Single-leg squats to volitional fatigue	BFR machine function; Seated	60-70% LOP	N	11 cm cuff, material not reported (inflation system model reported), continuous inflation
Montgomery et al. [34]	2019	Healthy males 21 ± 1 years	9	Acute	Resistance – Unilateral knee extension	Posterior tibial artery; Posture not reported	60% LOP	N	Width and material not reported, continuous inflation
Ilett et al. [17]	2019	Physically inactive males, 25 ± 6 years	10	Acute	Resistance – Isometric unilateral knee extensions	BFR machine function; Supine	40%, 60%, 80% LOP	N	10.5 cm width, material not reported (inflation system model reported), continuous inflation

Hughes et al. [66]	2019	Anterior cruciate ligament repair patients, 29 ± 6 years (23 male, 7 female)	28	Training	Resistance – Unilateral leg press	BFR machine function; Seated	80% LOP	Y – To maximise fast twitch fibre recruitment	11.5 cm width, nylon, inflation pattern not reported
Chulvi-Medrano et al. [35]	2019	Healthy male college students, 23 ± 3 years	15	Training	Resistance – Elbow flexion	Brachial artery; Posture not reported	30% LOP	N	9 cm width, material not reported, continuous inflation
Centner et al. [52]	2019	Healthy resistance trained males, 25 ± 4 years	15	Acute	Resistance – Isometric squat with whole body vibration	Posterior tibial artery; Standing	60% AOP	N	12 cm width, nylon, continuous inflation
Jessee et al. [67]	2019	Healthy resistance trained young adults 22 ± 3 years	12	Acute	Resistance – Unilateral knee extensions to volitional failure	Posterior tibial artery; Seated	40%, 80% AOP	N	10 cm width, nylon, continuous inflation
Kilgas et al. [36]	2019	Physically active males, 27 ± 4 years	10	Acute	Resistance – Unilateral handgrip exercises	Brachial artery; Supine	0%, 60%, 80%, 100%, 120% AOP (reported as LOP)	N	10 cm width, nylon, continuous inflation
Dankel et al. [68]	2019	Resistance trained adults, 22 ± 2 years (12 male, 11 female)	23	Acute	Resistance – Unilateral knee extension	Posterior tibial artery; Seated	40%, 80% AOP	N	10 cm width, nylon, continuous inflation

Thomas et al. [37]	2018	Males, 23 ± 3 years	18	Acute	Cycling	Tibial artery; Supine	80% AOP	N – Only referenced Loenneke et al. [76]	10 cm width, material not reported (inflation system model reported), intermittent inflation (pressure released in rest intervals)
Stavres et al. [53]	2018	Males with chronic incomplete spinal cord injury, 63 ± 12 years	9	Acute	Resistance – Unilateral knee extension	Popliteal vein and artery; Posture not reported	30% AOP	Y – To occlude venous flow during expected increased blood pressure. Lower pressures also selected to reduce risk of autonomic dysreflexia and deep vein thrombosis	Width and material not reported, continuous inflation
Soligon et al. [54]	2018	Untrained males, 24.5 ± 1.5 years	12	Acute	Resistance – Bilateral knee extension	Tibial artery; Supine	40%, 50%, 60%, 70%, 80%	N	17.5 cm width (94 cm length), standard sphygmomanometers, continuous inflation
Scott et al. [60]	2018	Non-resistance trained older females, 67 ± 4 years	15	Acute	Resistance – Bilateral leg press and knee extension	Posterior tibial artery; Recumbent	50% AOP	N	10 cm width, material not reported (inflation system model reported), continuous inflation (pressure released between exercises)
Pinto et al. [61]	2018	Sedentary older females, 67 ± 2 years	18	Acute	Resistance – Bilateral knee extension	Tibial artery; Posture not reported	80% AOP	N	18 cm width (90 cm length), material not reported, continuous inflation

Picón et al. [55]	2018	Resistance trained males, 24 ± 4 years	24	Acute	Resistance – Unilateral plantar flexion (on leg press)	Popliteal artery; Seated on leg press machine	30% AOP	Y – Pressures greater than 30% AOP are not necessary to achieve strength + hypertrophy [44], increases total muscle work [86]	9 cm width (57 cm length), standard sphygmomanometer, intermittent inflation (pressure released between sets)
May et al. [38]	2018	Recreationally active, non-resistance trained young adult males, 22 ± 3 years	24 (12 in BFR group)	Training	Resistance – Bilateral knee flexion and extension	BFR machine function; Seated	60% LOP	N – The pressure was used previously [46]	10.5 cm width (8 cm bladder width), material not reported (inflation system model reported), continuous inflation
Letieri et al. [62]	2018	Non-resistance trained older females, 69 ± 5 years;	56 (11 in BFR group)	Training	Resistance – Squat, bilateral leg press, knee extension and knee flexion	Tibial artery; Posture not reported	80% AOP	N – Referenced Loenneke et al. [26] (determined via either direct measurement or predictive equation)	Width not reported, pneumatic sleeves, continuous inflation (pressure released between exercises)
Ladlow et al. [56]	2018	Males with lower limb musculoskeletal injuries, 31 ± 7 years	28 (14 in BFR group)	Training	Resistance – Bilateral leg press and knee extension	Posterior tibial or dorsalis pedis artery; Supine	60% AOP	N – Referenced Scott et al. [87]	10 cm width, material not reported (cuff model reported), continuous inflation (pressure released between exercises)
Jessee et al. [69]	2018a	Resistance trained adults, 22 ± 3 years (11 male, 13 female)	24	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	40% AOP	N	5 cm width, nylon, continuous inflation

Jessee et al. [39]	2018b	Untrained adults, 21 ± 2 years (20 male, 20 female) (sex of participants in specific groups not reported)	40	Training	Resistance – Unilateral knee extension	Posterior tibialis artery; Seated	0%, 40%, 80% AOP	N	10 cm width, nylon, continuous inflation
Jessee et al. [70]	2018c	Resistance trained adults, 22 ± 1 years (22 male, 7 female)	29	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	0%, 10%, 20% 30%, 50%, 90% AOP	N – Lower pressures not previously examined	5 cm width, nylon, continuous inflation
Hughes et al. [71]	2018	Anterior cruciate ligament repair patients, 29 ± 6 years (23 male, 7 female)	30 (6 male, 4 female patients in ACL BFR group; 10 males in healthy BFR group)	Acute	Resistance – Unilateral leg press	Trained leg; Seated on leg press machine	80% LOP	Y – Based on previous evidence suggesting high pressures maximise fast twitch fibre recruitment and strength adaptations to BFR training [48,88,89]	11.5 cm width (86 cm length, 5.5 cm thickness), nylon (contoured), continuous inflation
Curty et al. [57]	2018	Resistance trained males, 26 ± 3 years	9	Acute	Resistance – Eccentric unilateral elbow flexion	Radial artery; Supine	80% AOP	N	14 cm width (52 cm length), standard sphygmomanometer, continuous inflation
Buckner et al. [72]	2018	Resistance trained adults, 22 ± 2 years (12 male, 10 female)	22	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	0%, 40%, 80% AOP	N	5 cm width, nylon, inflation pattern not reported

Bell et al. [73]	2018	Resistance trained adults, 22 ± 3 years (12 male, 10 female)	22	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	0%, 40%, 80% AOP	N	5 cm width, nylon, inflation pattern not reported
Tennent et al. [74]	2017	Post-non-reconstructive knee arthroscopy patients, 38 ± 4 years (12 male, 5 female)	17 (7 male, 3 female in BFR group)	Training	Resistance – Unilateral leg press, knee extension, reverse press (also other non-BFR treatments)	Artery not reported; Posture not reported	80% AOP	N – To achieve venous but not arterial occlusion	Width and material not reported (inflation system model reported) (varying cuff length based on participant thigh size, contoured), continuous inflation
Neto et al. [40]	2017	Untrained females with regular menstrual cycles, 22 ± 3 years	30 (10 in BFR group)	Acute	Resistance - Bilateral elbow flexion and knee extension	Radial and tibial artery; Supine	80% AOP	N	6 cm (arm) and 10 cm (leg) width (47 cm and 54 cm length, respectively), standard sphygmomanometers, both continuous and intermittent inflation (pressure released between sets)
Mouser et al. [31]	2017	Recreationally active adults, 22 ± 2 years (64 male, 73 female)	137 (42 males and 48 females in BFR groups)	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	0%, 40%, 80% AOP	N	5 cm width, nylon, continuous inflation
Mattocks et al. [20]	2017	Resistance trained adults, 22 ± 1 years (20 male, 6 female)	26	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	0%, 10%, 20%, 30%, 50%, 90% AOP	N – Lower pressures not previously examined	5 cm width, nylon, inflation pattern not reported

Kim et al. [41]	2017	Untrained males, 23 ± 5 years	14 (9 in BFR group)	Acute and training	Resistance – Unilateral elbow flexion	Radial artery; Standing	50% AOP	Y – 50% assessed to determine if sufficient restriction to augment muscle adaptations	5 cm width, nylon, inflation pattern not reported
Ferreira et al. [42]	2017	Untrained males, 48 ± 1 years	15	Acute	Resistance – Leg press and knee extension (uni- or bilateral not reported)	Tibial artery; Supine	50% AOP	N	17.5 cm width (92 cm length), standard sphygmomanometer/s, continuous inflation
Dankel et al. [75]	2017	Resistance trained adults, 25 ± 4 years (11 male, 3 female)	14	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	40%, 80% AOP	N – Selected based on a previous study [48]	5 cm width, nylon, inflation pattern not reported
Clarkson et al. [8]	2017	Sedentary older adults, 69 ± 6 years (11 male, 8 female)	19 (6 male, 4 female in BFR group)	Training	Walking	BFR machine function; Standing	60% LOP	N	10.5 cm width, material not reported (inflation system model reported), continuous inflation
Buckner et al. [19]	2017	Resistance trained adults, 25 ± 2 years (12 male, 3 female)	15	Acute	Resistance – Unilateral elbow flexion	Radial artery; Standing	40% AOP	Y – The lowest pressure examined that appears to elicit similar muscle activation and growth in the upper body as higher pressures [44]	Cuff 1: 5 cm width, nylon; Cuff 2: 3 cm width, elastic; Inflation pattern not reported
Poton and Polito [58]	2016	Resistance trained males, 23 ± 4 years	12	Acute	Resistance – Unilateral knee extension	Tibial artery; Posture not reported	100% AOP	N – Aim appeared to be inducing total blood flow occlusion	18 cm width (90 cm length), standard sphygmomanometer, continuous inflation,

Pinto and Polito [63]	2016	Hypertensive women, 57 ± 7 years	12	Acute	Resistance – Bilateral leg press	Tibial artery; Posture not reported	100% AOP	N	18 cm width (70 cm length), standard sphygmomanometers, continuous inflation
Neto et al. [24]	2016	Recreationally active males, 22 ± 3 years	24	Acute	Resistance – Bilateral elbow flexion & extension, knee flexion & extension	Radial and tibial artery; Posture not reported	80% AOP	N	AOP measured with standard sphygmomanometers, BFR applied with 'specially designed elastic cuffs', both intermittent and continuous inflation
Fatela et al. [43]	2016	Untrained males, 25 ± 5 years	14	Acute	Resistance – Unilateral knee extension	Tibial artery; Posture not reported	40%, 60%, 80% AOP	N	13 cm width (124 cm length, material not reported (cuff model stated), continuous inflation
Counts et al. [44]	2016	Acute study – Resistance trained adults, 24 ± 3 years (10 male, 4 female) Training study – Untrained adults, 23 ± 3 years (5 male, 3 female)	Acute study – 14 Training study – 8	Acute and training	Resistance – Unilateral elbow flexion	Radial artery; Standing	40%, 50%, 60%, 70%, 80%, 90% AOP	N	5 cm width, nylon, inflation pattern not reported
Barnett et al. [45]	2016	Adults, 23 ± 3 years (19 male, 12 female)	31	Acute	Resistance – Unilateral elbow flexion	Radial artery; Seated	40% AOP	N	5 cm width, nylon, inflation pattern not reported

Staunton et al. [46]	2015	Non-resistance trained young male adults, 23 ± 2 years; Older males, 70 ± 5 years	24 (11 young males, 13 older males)	Acute	Walking (treadmill) and resistance – Bilateral leg press	BFR machine function; Standing for walking trial, Supine for leg press trial	60% LOP	Y – Within a range of absolute pressures used known to induce muscle adaptations [86,90,91]	10.5 cm width (86 cm length), material not reported (inflation system model stated), continuous inflation
Poton and Polito [47]	2015	Physically active adults, 23 ± 6 years (11 male, 6 female)	17	Acute	Resistance – Bilateral leg press	Tibial artery; Posture not reported	100% AOP	N	18 cm width (90 cm length), standard sphygmomanometers, continuous inflation
Moriggi Jr et al. [25]	2015	Resistance trained males, 24 ± 4 years	8	Acute	Resistance – Bilateral elbow flexion, elbow extension, bench press	Brachial artery; Seated	50% AOP	N	15 cm width (51 cm length), standard sphygmomanometers, continuous inflation (pressure released between exercises)
Lixandrão et al. [48]	2015	Untrained males, 28 ± 9 years	26	Training	Resistance – Unilateral knee extension	Tibial artery; Supine	40%, 80% AOP	N	17.5 cm width (9.2 cm length; likely reported incorrectly), standard sphygmomanometer, continuous inflation
Araújo et al. [64]	2015a	Middle-aged females, 54 ± 4 years	29 (10 in BFR group)	Training	Water aerobics	Tibial artery; Supine	80% AOP	N	18 cm width (80 cm length), adapted sphygmomanometers, continuous inflation
Araújo et al. [65]	2015b	Post-menopausal females, 54 ± 4 years;	28 (10 in BFR group)	Training	Water aerobics	Tibial artery; Supine	80% AOP	N	18 cm width (80 cm length), adapted sphygmomanometers, continuous inflation

Santos et al. [59]	2014	Male with inclusion body myositis 65 years	1	Training	Resistance – Bilateral knee extension, leg press, half-squat	Tibial artery; Supine	50% AOP	N	8 cm width (18 cm length; likely reported incorrectly), adapted sphygmomanometers, continuous inflation
Araújo et al. [49]	2014	Non-resistance trained females, 46 ± 10 years	14 (7 in BFR group)	Acute	Resistance – Bilateral knee extension	Determination site and posture not reported	80% AOP	N	18 cm width (80 cm length), adapted sphygmomanometers, continuous inflation
Laurentino et al. [50]	2012	Physically active, non-resistance trained males, 21 ± 5 years	29 (10 in BFR group)	Training	Resistance – Bilateral knee extension	Tibial artery; Supine	80% AOP	N	17.5 cm width (92 cm length), standard sphygmomanometers, continuous inflation
Laurentino et al. [51]	2008	Recreationally active, non-resistance trained males, 23 ± 3 year	16	Training	Resistance – Unilateral knee extension	Tibial artery; Posture not reported	100% AOP	N – Likely intended to achieve full vascular occlusion during exercise	14 cm width (90 cm length), standard sphygmomanometer, intermittent inflation (pressure released between sets)

Abbreviations: BFR – blood flow restriction; AOP – arterial occlusion pressure; LOP – limb occlusion pressure; ACL – anterior cruciate ligament.