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Blood flow restriction during training for improving the aerobic capacity and sport performance of trained athletes: A systematic review and meta-analysis

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A B S T R A C T

Background: /Objective: Combining blood flow restriction (BFR) with endurance training is exponentially increasing although the benefits are unclear in trained athletes. We aimed to describe the effects of aerobic and/or anaerobic training programmes combined with BFR on the aerobic capacity and related sport performance of trained athletes.
Methods: Databases used were MEDLINE, SPORTDiscus, LILACS, IBECS, CINHAL, COCHRANE, SCIELO and PEDro, through October 2021. For study selection, criteria included (a) clinical trials that recruited trained healthy athletes, that (b) proposed BFR in combination with aerobic/anaerobic training programmes (≥8 sessions) and that (c) evaluated either aerobic capacity or related sport performance. For data extraction, a reviewer extracted the data, and another reviewer independently verified it. The tool RoB 2 (Risk of bias 2) was used to assess risk of bias.
Results: Ten studies met the eligibility criteria, capturing a total of 207 participants. Although it did not reveal any significant effects from training with BFR on aerobic capacity compared to the same training without BFR, effect sizes were extremely high. Subgroup analyses according to the intensity of the training programmes found similar results for low-to-moderate or high-intensity training compared to the same sessions without BFR.
Conclusion: Although adding BFR to training sessions always produce benefits from baseline in aerobic capacity and sport performance of trained athletes, these results are not better than those observed after the same training sessions without BFR. The reduced number of studies, small sample sizes and some concerns regarding risk of bias should be highlighted as limitations.
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1. Introduction

Enhancing the sport performance of experienced and trained athletes is a permanent challenge of sport professionals. For planning training programmes, coaches often consider more and/or different physical stimulus to achieve physiological adaptations and thus the best sport performance.[1]

Blood flow restriction (BFR) is one of these new stimuli that coaches are including during training sessions more and more frequently in order to improve sport performance.[2] Although BFR has traditionally been included in sport rehabilitation contexts,[3] beneficial results obtained in muscle characteristics and strength when it is combined with resistance training have increased the interest of coaches.[4] Therefore, BFR is also being combined with running or sport-specific sessions to achieve additional effects on aerobic capacity and sport performance.[5]

Reviews to date have shown that aerobic exercise with BFR could improve aerobic capacity and performance, but most of the selected studies considered untrained or physically active healthy

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adults, without considering the influence of the training experience.[6] For the trained population, there are specific physiological characteristics to take into account. Although VO_{2max} (maximal oxygen consumption) is also important, it is not determinant for the endurance performance of trained athletes. For this reason, other key parameters like running economy, vVO_{2max} (velocity at maximal oxygen uptake) or direct sport performance tests are frequently evaluated.[7] To date, studies that investigated effects from BFR training on aerobic performance have shown scarce and controversial results that make it impossible to draw firm conclusions.[8]

If adding BFR to training allows additional benefits with respect to the aforementioned variables, it could be a great strategy to increase endurance performance without increasing training volume or intensity. Therefore, the objective of this systematic review with meta-analysis was to describe the effects of aerobic and/or anaerobic training programmes combined with BFR on the aerobic capacity and related sport performance of trained athletes. We took into account possible benefits according to the intensity of the training programme that athletes performed. Also, we explored possible effects on perceived exhaustion as an important parameter that may affect endurance performance since a lower point would mean lower fatigue at the same situation.[9]

2. Material and methods

2.1. Search strategy

The present systematic review was conducted according to PRISMA guidelines (Supplemental Table S1: https://figshare.com/s/410090056cb609c1bc29 or https://doi.org/10.6084/m9.figshare.16553964) and was registered in the PROSPERO database. To search the existing literature, the following databases were used by selecting eligible studies published from January 2010 to October 2021: MEDLINE (throughout PubMed), SPORTDiscus, LILACS (Literatura Latinoamericana de Información en Ciencias de la Salud), IBECS database (Índice Bibliográfico Español en Ciencias de la Salud), CINAHL, COCHRANE, PEDro (Physiotherapy Evidence), SCIELO and ScienceDirect. The “similar articles” tool from PubMed was used, and the reference lists of all selected studies were checked in order to collect all studies that met eligibility criteria. Boolean operators “AND” and “OR” were used to conduct database searches and included the following key English terms: ("Kaatsu" OR "blood flow restriction" OR "tourniquets" OR "ischemia" OR "vascular occlusion" OR "occlusion training") AND ("endurance" OR “VO_{2max}” OR "aerobic") AND (“sport” OR "athlete"). Details of the search strategies for all databases are shown in Supplemental Table S2 (https://figshare.com/s/d5093fc30348fde8d117 or https://doi.org/10.6084/m9.figshare.16553961). Mendeley (Elsevier, London, England) was used to import references and delete duplicated copies. Searches were rerun prior to the final analysis (October 2021).

2.2. Selection of studies

Two independent reviewers completed the online search and applied predetermined eligibility criteria to screen titles and abstracts of the records in a blind manner. Once potentially eligible studies were selected, the same two reviewers screened full texts through re-applying the eligibility criteria. Disagreement regarding the definitive inclusion of studies was resolved by a third reviewer. To be included in the systematic review and meta-analysis, studies were eligible if they met the following criteria (a) the study was conducted in healthy (i.e. free from injuries at the moment of intervention): trained athletes (maximum oxygen uptake at least 38.0 and 45.0 ml/kg/min for women and men, respectively,[10] active at least three times per week, sports experience $\geq$3 years or competitive at least at regional level),[11] (b) the study examined either aerobic capacity (i.e. VO_{2max}), or direct endurance performance parameters (i.e. time to exhaustion or time trial), (c) the study was either a randomised or non-randomised clinical trial, (d) the study included an aerobic or anaerobic training programme at the same time that blood flow restriction (BFR) was applied during at least 8 sessions (as the minimum recommended to produce effects from BFR training),[12] and (e) the study was written in English, Portuguese or Spanish.

2.3. Data collection

2.3.1. Risk-of-bias assessment

The valid tool designed by Cochrane named RoB 2 (Risk of bias 2) was used to assess risk of bias for randomised studies.[13] The RoB 2 tool is an update of the original tool to assess risk of bias designed by Cochrane in 2008. The current version from 2019 is compounded of five domains as possible sources of bias: (1) randomisation process, (2) deviation from intended intervention (effects of assignment and adhering to intervention), (3) missing outcome data, (4) measurement in the outcome and (5) selection of the reported result. Every domain was appraised according to specific criteria that helped to determine the degree of risk, and they were scored as “yes,” “probably yes,” “probably no” or “no”. To interpret risk of bias, each domain level was considered “high”, “some concerns” or “low”, according to the algorithms and recommendations regarding a proposed risk-of-bias judgment from Cochrane.[14] The overall qualification of risk for each study was calculated depending on the number of domains falling within the “high” (the study was judged to be at high risk of bias in at least one domain), “some concerns” (the study was judged to be of some concern in at least one domain but not to be at high risk of bias for any domain) and “low” (the study was judged to be at low risk of bias for all domains) classification.[14] Two reviewers (#1 and #2) independently verified the qualification of the domains and the overall qualification for every single study. A third reviewer (#3) resolved possible discrepancies. Reviewers #1 and #2 were the same ones for the reviewing criteria for each article. All reviewer had always the same function and were not interchangeable. The RoB 2 Excel tool was used to implement RoB 2 (available on the riskofbiasinfo.org website).

2.3.2. Data extraction

While a reviewer extracted the data, another reviewer independently verified it. The data focused on the study design (type and duration), participants (age, sport type, level of competition), exercise programme (type, duration, frequency and intensity) and outcomes (type: variable; test and instrument used: and evaluation time). Intensity of training was classified as “low to moderate” if training sessions were performed at < 80% of maximal capacity, or high intensity if training sessions were performed at $\geq$80% of maximal capacity, similarly to previous studies.[15] If needed, corresponding authors of studies will be contacted to clarify raw data.

2.4. Qualitative synthesis: data analysis and synthesis

A qualitative analysis was undertaken to determine the strength of the relationship analysis between all variables and the aerobic/anaerobic programme with BFR application and to help interpret data from the meta-analysis. According to PRISMA guidelines, results were grouped according to the type of variable assessed: physiological parameters directly related with endurance performance and/or aerobic capacity (i.e. maximum oxygen consumption, onset blood lactate accumulation, cardiorespiratory capacity) and endurance performance tests (i.e. time to exhaustion, time trial). This classification was based on similar previous studies.[16]

To determine the strength of the associations between physiological parameters and endurance performance tests with the BFR exercise programmes, criteria similar to previous studies[17] were considered "strong evidence" when two or more low-risk-of-bias studies reported consistent results; "moderate evidence" was considered when one low-risk-of-bias study and one or more some concerns or high-risk-of-bias studies reported consistent results, or when two or more some concerns or high-risk-of-bias studies reported consistent results; "limited evidence" was considered when only one low, some concerns or high-risk-of-bias study reported results; "conflicting evidence" was considered when low, some concerns or high-risk-of-bias studies reported conflicting results, with 75% or more agreement among studies; and "very conflicting evidence" was considered when low, some concerns, or high-risk-of-bias studies reported results, with less than 75% agreement among studies.[17]

2.5. Quantitative synthesis: data analysis and synthesis

Sample size, mean and standard deviation (SD) were extracted from the selected studies for each group (experimental vs control) to estimate the effect size. For the interpretation of effect sizes, the following thresholds were considered: 0.1, small; 0.3, moderate; 0.5, large; 0.7, very large; and 0.9, extremely large.[18] Where at least three studies examined the effects of similar exercise programmes on comparable variables, meta-analysis was performed using the Meta-Essential tool for Excel 2013 and IBM SPSS 22 (IBM, Armonk, NY, USA).[19] For continuous data, standardised mean differences (SMDs) and 95% confidence intervals (CI) were calculated by dividing the means of the experimental and control groups by the pooled SD. The SMD in the means proposed by Cohen at each study were weighted by the inverse of their variance in order to obtain the pooled index of the magnitude of the effect. A random-effects model was used due to the heterogeneity of the selected studies. Heterogeneity was evaluated by using the inferential Q test proposed by Cochran, and the I^2 heterogeneity index with its 95% CI. High heterogeneity was established when $I^2 > 50\%$.[20] The asymmetries of the effect-size distribution due to publication or other types of bias were analysed using two different strategies: Begg's strategy and Egger's test. A sensitivity analysis was performed in order to test the influence of possible outliers and to visualise trends in the results. Data not suitable for meta-analysis were employed for determining the association between the effects of BFR exercise programmes and endurance performance tests and physiological parameters. Subgroup analyses were carried out based on training intensity (low-to-moderate or high intensity), similar to previous studies.[15] The primary analysis included all eligible studies. Statistical significance was set at $P < 0.05$.

3. Results

3.1. Search results

Three hundred and seventy-four articles underwent title and abstract screening after removing duplicated items. When applying eligibility criteria, 57 records were selected for further analysis after applying eligibility criteria. Full-text screening resulted in a final yield of 10 studies for systematic review and 6 for meta-analysis (Fig. 1).

Description of the included studies: From the selected studies, 207 athletes were included (sex: 77.8% men; age: 22.2 ± 2.2 years old). Among participants, 23.2% were collegiate athletes (n = 48),[21,22] 9.7% middle- or long-distance runners (n = 20),[23] 11.6% futsal players (n = 24),[24] 22.7% soccer players (n = 47),[25,26] 5.8% basketball players (n = 12),[27] 15.0% rowers (n = 23)[28] and 12.1% sprinters (n = 25).[29] Although all the selected studies had a control group, only 16.6% (n = 2) described details of randomisation procedures and allocation sequence.[24,25] The percentage of studies carried out in Asian countries (Iran, South Korea, and Taiwan) was 58.3% (n = 7),[22–27,30] with 41.7% (n = 5) of studies coming from Iran.[22,24–26,30] The main characteristics of the BFR exercise programmes and the rest of the properties of the selected studies are summarised in Supplemental Table S3 (https://figshare.com/s/2efacaafa2e3ab1d7c17 or https://doi.org/10.6084/m9.figshare.16553958).

3.2. Qualitative analysis

Aerobic capacity and performance: We identified 3 variables regarding aerobic capacity (VO_{2max}, vVO_{2max}, and running economy) and 7 variables regarding aerobic/anaerobic sport performance tests (time to exhaustion; multistate fitness performance; 30-s Wingate test; sprint performance; change-of-direction performance; futsal-specific performance; soccer-specific performance) (Table 1). Minute ventilation (VE) and rate of perceived exertion (RPE) were identified as related variables. According to the USPSTF (U.S. Preventive Services Task Force).

4 variables (multistate fitness performance, 30-s Wingate test, change-of-direction performance, and soccer-specific performance) had limited evidence supporting better results from BFR training compared to NoBFR training, 1 variable (sprint performance) had moderate evidence supporting similar results from BFR compared NoBFR, and 2 variables (vVO_{2max} and futsal-specific performance) had limited evidence supporting similar results from BFR compared to NoBFR training. The remaining 5 variables reported very conflicting results. In reference to within-group results, BFR training showed moderate evidence to support improvements compared to the baseline in 7 variables (VO_{2max}, vVO_{2max}, time to exhaustion, 30-s Wingate test, sprint performance, VE, and RPE). The within-group change after NoBFR training showed improvements with moderate evidence compared to baseline in RPE, and no improvements with moderate evidence in time to exhaustion and VE. The rest of variables showed limited or very conflicting association for within-group results.

3.3. Quantitative analysis: meta-analysis

Aerobic capacity and performance: One meta-analysis was performed across the ten studies by including six studies.[21,23,24,26–28] More concretely, it included the effects of training with BFR in comparison with the same training without BFR on aerobic capacity (through VO_{2max}, evaluated with gold standard methods). High heterogeneity ($I^2 = 83.28\%$) and no statistical differences were found (df = 5; P = 0.064). Subgroups analysis according to the intensity of training (high intensity vs low-to-moderate intensity) was performed, with high heterogeneity ($I^2 = 64.5$ and 88.71%, respectively), and no statistical differences ($P > 0.05$). Forest plots for the overall and subgroups analyses are shown in Fig. 2.

3.4. Risk-of-bias assessment

"Some concerns" was identified as the overall risk of bias in all the selected studies. According to RoB 2 tool, the most consistent domains that decreased bias risk were *missing outcome data* and *measurement of the outcome,* while *selection of the reported result* and *randomisation process* were the domains that increased bias risk in most of the studies (Fig. 3).

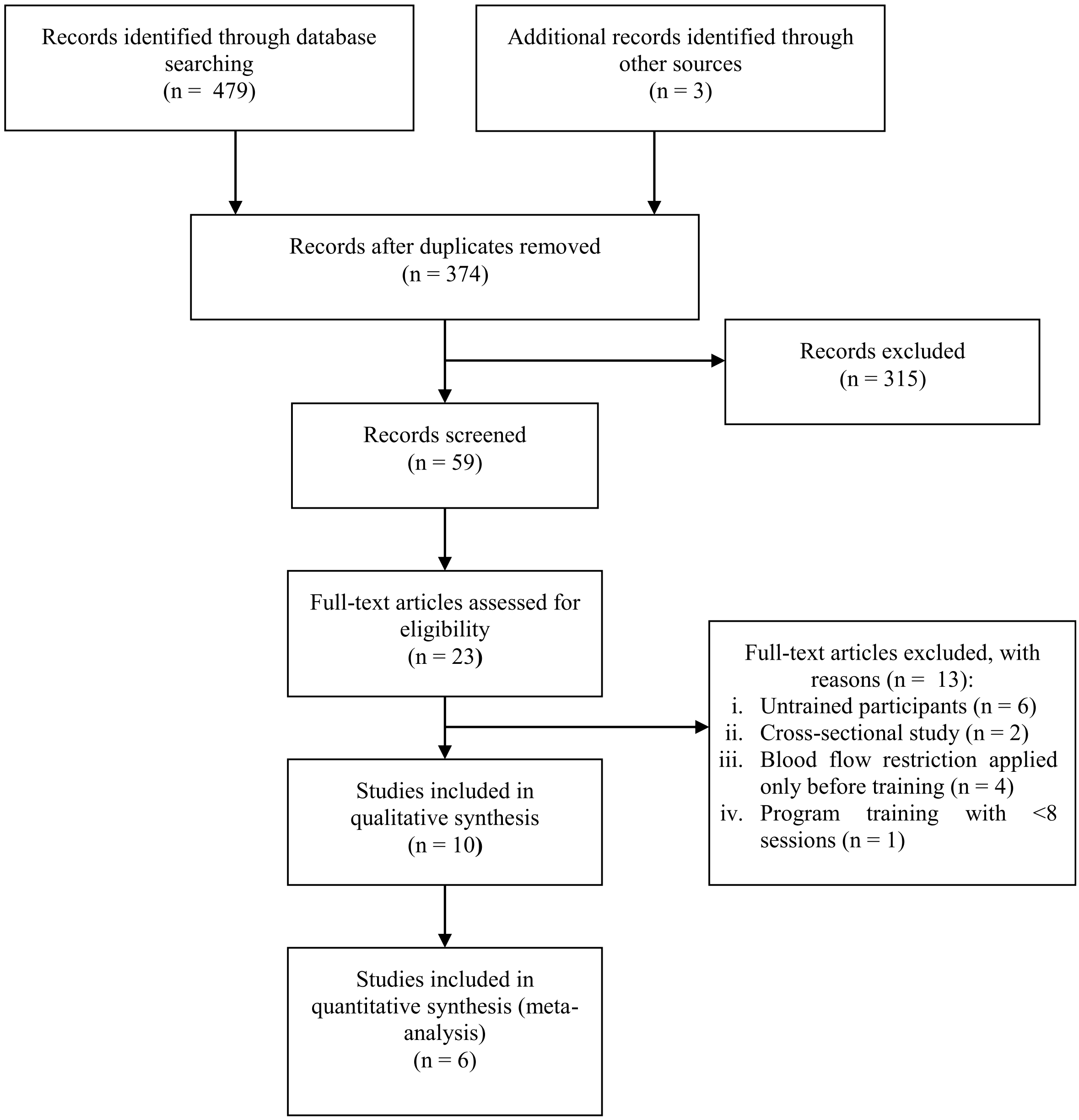

Fig. 1. Flow diagram.

4. Discussion

This systematic review with meta-analysis revealed that training with BFR did not add benefits in aerobic parameters compared with the same training without BFR in trained athletes. Although effect size from our quantitative analysis suggested slightly better results when BFR is added during training sessions, **no** variable reached statistical significance.

Athletes improved aerobic capacity and sport performance tests after most of the training programmes compared to baseline. These results were observed independently of the intensity of training and were more frequently reported when BFR was applied. We observed that athletes who trained with BFR showed significant improvements compared to baseline in the 14 variables identified, 7 of which were supported with moderate evidence. Meanwhile, athletes who performed the same training without BFR reported improvements compared to baseline in 4 variables, but only RPE showed moderate evidence.

Despite these results, between-group differences after training did not reach statistical significance in most of the variables and studies These results are in contrast with previous review studies, which reported significant differences after low-intensity BFR training in aerobic capacity and suggested potential benefits to various practitioners ranging from clinical to human performance applications.[15,31] To explain this, most of the studies included in these two review studies recruited physically active people or untrained athletes. We should highlight the physiological differences with trained athletes, who have experience in aerobic/anaerobic training and physiological adaptations. Also, although all participants from studies selected in the present systematic review met the minimum criteria to be considered trained athletes, the fitness level at baseline was not the same in all cases. This could explain some of the training effects observed.

If we focus on VO_{2max}, the 6 studies exploring this variable always reported higher percentage of change from baseline in athletes who trained with BFR. However, our quantitative analysis

Table 1
Qualitative results.

		Risk of bias			Results					
Variable	N	Low	Some Concerns	High	BFR compared to baseline	Association	NoBFR compared to baseline	Association	BFR compared to NoBFR	Association
Aerobic capacity										
VO_{2MAX} (ml/min/kg)	151		[21–24,26–28]		↑[21–24,26–28]	**Moderate**	↑[21,24] = [23,26–28]	**Very conflicting**	↑[23,27,28] = [21,24,26]	Very conflicting
Running economy (L/min)	28		[21,24]		↑[24] = [21]	Very conflicting	= [24]	Limited	↑[24] = [21]	Very conflicting
vVO_{2MAX} (km/h)	44		[22,24]		↑[22,24]	Moderate	↑[24] a22	Limited	= [24] a22	Limited
Sport performance										
Time to exhaustion at vVO_{2max} (s)	60		[21,22,24]		↑[21,22,24]	**Moderate**	= [21,24] a22	Moderate	↑[24] = [21] a22	Very conflicting
20-m multistate fitness test (m)	19		[25]		↑[25]	Limited	↑[25]	Limited	↑[25]	Limited
30-s Wingate test (W/kg)	44		[22,24]		↑[22,24]	Moderate	= [24] a22	Limited	↑[24] a22	Limited
Change of Direction performance (s)	19		[25]		↑[25]	Limited	= [25]	Limited	↑[25]	Limited
Futsal-specific performance test (s)	12		[30]		↑[30]	Limited	= [30]	Limited	= [30]	Limited
Soccer-specific performance test (m)	19		[25]		↑[25]	Limited	↑[25]	Limited	↑[25]	Limited
Sprint performance (m/s)	34		[25,29]		↑[25,29]	Moderate	↑[25] = [29]	Very conflicting	= [25,29]	Moderate
Other related variables										
RPE	72		[23,24,26,27]		↑[23,24,26,27]	**Moderate**	↑[23,24,26,27]	**Moderate**	↑[23,24] = [26,27]	Very conflicting
VE (L/min)	28		[21,27]		↑[21,27]	**Moderate**	↑[21] = [27]	**Very conflicting**	↑[27] = [21]	Very conflicting

BFR = blood flow restriction training; NoBFR = training without blood flow restriction; RPE = rated of perceived exertion; VO2max = maximal oxygen uptake; VE = ventilation; vVO2max = velocity at maximal oxygen uptake; [a] = this study had not control group that performed the same training session without BFR; ↑ association improving results after training; = no significant association for different results after training; ↓ association reducing results after training.

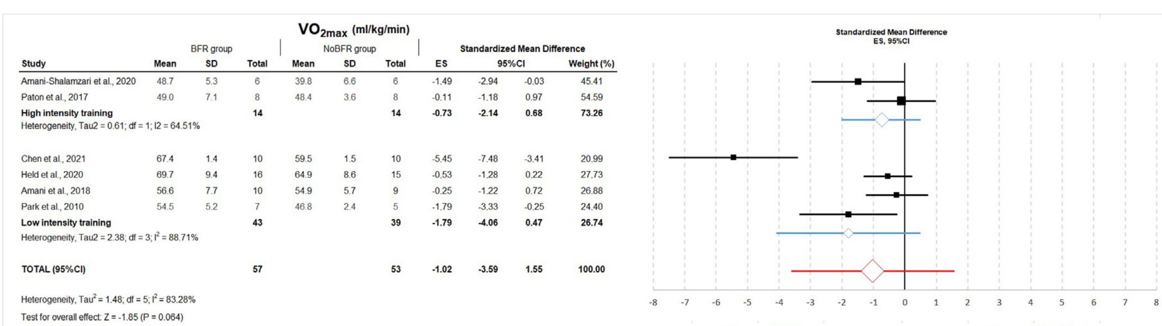

Fig. 2. Meta-analysis forest plot of aerobic capacity.

showed that the differences between groups did not reach the statistical significance, being a trend towards a greater VO_{2max} increase. Thus, it is important to consider effect-size data of our meta-analysis to interpret the practical relevance of the aerobic capacity results. The magnitude of the between-group differences obtained in our meta-analysis were extremely large effect sizes ($d > 0.9$), both in high-intensity and low-intensity training modalities. Based on this assumption, Formiga et al. highlighted increases of 3.4% in aerobic capacity as the minimal to be considered a difference with practical relevance in healthy participants.[15] Although this percentage cannot be applied to our population because they were trained athletes, we observed that increases in VO_{2max} were always higher in athletes who trained with BFR (with changes from baseline ranging from +3.7 to +11.6%) than in those who trained without BFR (with changes from baseline ranging from −1.3 to +6.8%). Therefore, the practical relevance of the aerobic capacity improvement in athletes who trained with BFR compared to those who performed the same training programme without BFR should be considered. Similarly, the review study by Bennet et al. also reported better results when adding BFR to sprint training sessions in trained individuals (+4.7% with BFR vs 0.7% without BFR).[6]

Since VO_{2max} is not the best indicator to predict performance in trained athletes, we also considered other related variables and direct sport performance tests, like time trials.[32,33] We found an high variability of data among studies that hampered pooling data in a meta-analysis. Apart from VO_{2max}, running economy or vVO_{2max} are considered good predictors for endurance performance.[33] Three of the 10 studies evaluated these variables and it is not clear that training with BFR demonstrated additional benefits when comparing with the same training without BFR. The limited number of studies that have evaluated these parameters and the very conflicting results make it difficult to draw conclusions.

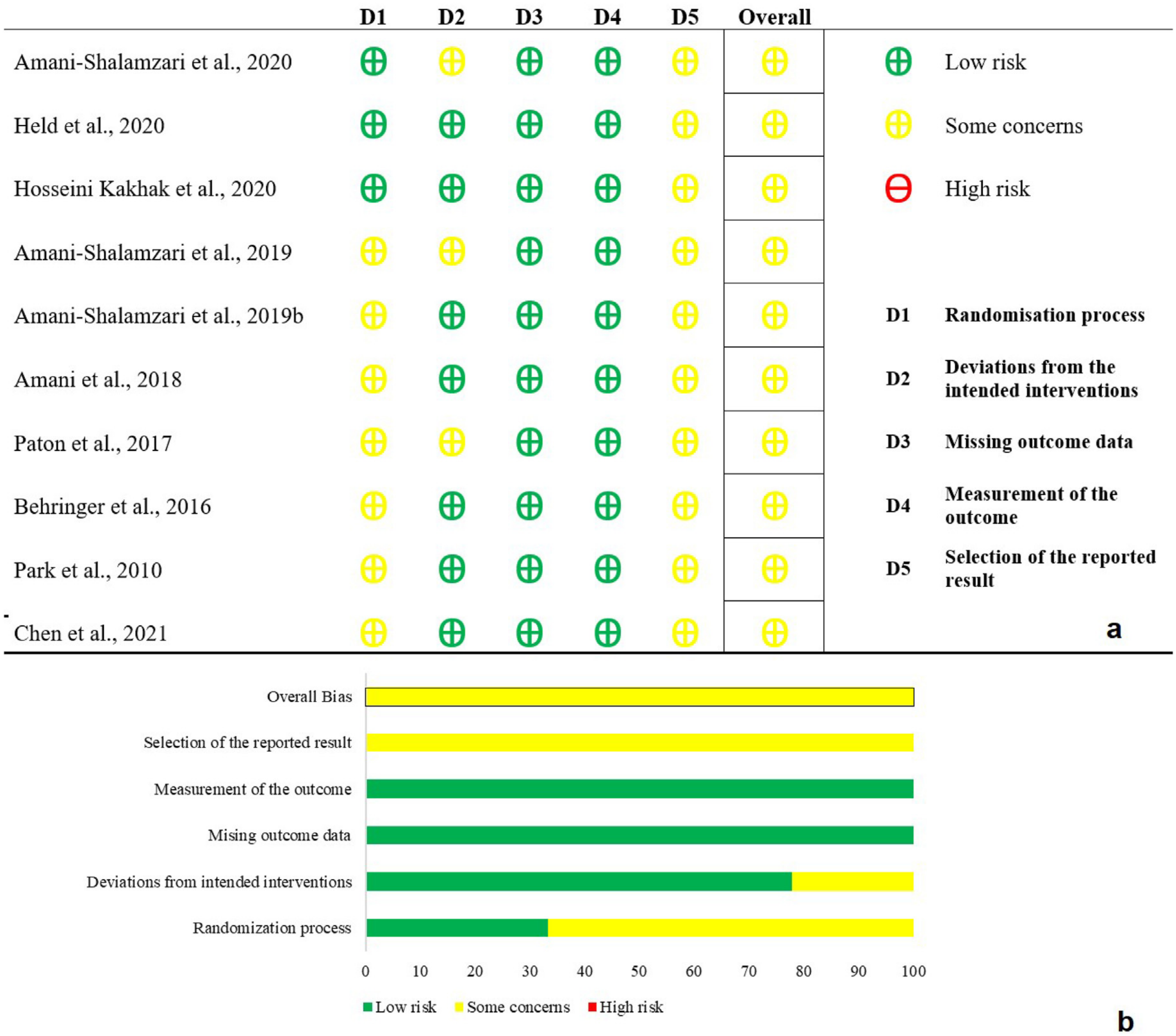

Fig. 3. Risk-of-bias assessment a) Overall risk of bias b) Risk of bias summary.

Regarding variables of sport performance, we also observed an extremely high variability among studies that prevents us from supporting BFR as a complement to training sessions. Six of the 10 studies evaluated sport performance through 7 different variables. The 6 studies demonstrated improvements compared to the baseline in athletes who trained with BFR, with moderate evidence in 3 variables. When these variables were analysed in athletes who performed the same training without BFR, no variable showed evidence enough to support improvements compared to baseline. Despite these within-group data, our qualitative analyses showed that no variable of sport performance had consistent results and evidence that supported additional benefits when comparing training with and without BFR. Therefore, the within-group improvements observed in sport performance could be a simple training effect or even a learning effect. As Bennet et al. reported in their review study, although some studies observed increases in aerobic capacity variables, it did not always correspond with an clear improvement in time-trial performance in trained athletes.[6]

In this systematic review, the level of evidence showed that all the selected studies had some concern risk of bias. *Randomisation process* and *selection of the reported results* were domains that increased the risk of bias. Only 2 of 10 studies specified the method of randomisation, while no studies reported a pre-specified analysis plan that was finalised before unblinded outcome data. This fact could facilitate bias related to the selection of the reported result. In the same line as previous systematic reviews, we found the very small simple size and sloppy method of reporting results to be the main limitations among the studies that investigated BFR training effects on aerobic capacity and performance.[15] We also observed that blinding and dropouts were not reported in any of the studies.[6] As a positive point, the domain referring to the *measurement of the main outcomes* was consistent among the included studies because all studies obtained VO_{2max} throughout an incremental test performed on a monitored treadmill with a breath-by-breath system. This fact allowed us to pool data and perform the meta-analysis.

As an additional aspect to take into account, 4 of 10 studies registered RPE during training with and without BFR in order to monitor training load[34] due to the strong relationship with parameters like the lactate threshold and heart rate.[35] Two of the studies reported higher values of RPE when athletes trained with BFR compared to those who trained without BFR, while 2 studies demonstrated similar RPE values. This controversial finding did not allow us to confirm that including BFR leads to higher perceived exertion among athletes.

This systematic review with meta-analysis has limitations. Firstly, we observed a high variety of training programmes to combine with BFR, with only 2 studies considering a high-intensity training regimen. As an important limitation related to this, only 6 studies could be included in our meta-analysis for the overall analysis. Secondly, there was inconsistency in the test included for evaluating sport performance, which ended up reporting limited or controversial evidence for all sport performance variables registered. Lastly, we did not analyse sex differences because most studies recruited male athletes. This hampers the extraction of specific results according to sex differences. For future studies, we recommend including a consistent training regime and female athletes as the recruited population.

As practical applications, practitioners should consider that the inclusion of BFR during training sessions does not add additional benefits in aerobic capacity and sport performance, although improvements from baseline are always observed even in trained athletes. Although findings are very controversial, it is more appropriate to include this complement during transitory periods (i.e. pre-session) due to a possibly higher rate of perceived exertion observed in some studies.

The results of this systematic review with meta-analysis demonstrated that including BFR in the training sessions always produce benefits from baseline in aerobic capacity and sport performance of trained athletes. However, these results are not better than those observed after the same training sessions without BFR. These results are observed independently of the intensity of training. The reduced number of studies, the some-concerns risk of bias and the high variability with respect to the evaluation of sport performance should be taken into account as a limitations to extracting firm conclusions.

Declaration of interest statement

None.

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Declaration of competing interest

The author(s) have no conflicts of interest relevant to this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jesf.2022.03.004.

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