Sports Med
https://doi.org/10.1007/s40279-018-0927-z

SYSTEMATIC REVIEW

Association of Lower Limb Compression Garments During High-Intensity Exercise with Performance and Physiological Responses: A Systematic Review and Meta-analysis

César Augusto da Silva[1,2] · Lucas Helal[1,3] · Roberto Pacheco da Silva[1,4] · Karlyse Claudino Belli[1] · Daniel Umpierre[1,3,5] · Ricardo Stein[1,2,6,7]

Abstract

Background Although compression garments are used to improve sports performance, methodological approaches and the direction of evidence regarding garments for use in high-intensity exercise settings are diverse.

Objectives Our primary aim was to summarize the association between lower-limb compression garments (LLCGs) and changes in sports performance during high-intensity exercise. We also aimed to summarize evidence about the following physiological parameters related to sports performance: vertical jump height (VJ), maximal oxygen uptake (VO_2max), submaximal oxygen uptake (VO_2submax), blood lactate concentrations ([La]), and ratings of perceived exertion (RPE, 6–20 Borg scale).

Methods We searched electronic databases (PubMed, EMBASE, Cochrane Library, and ClinicalTrials.gov) and reference lists for previous reviews. Eligible studies included randomized controlled trials with athletes or physically active subjects ($\geq$ 18 years) using any type of LLCG during high-intensity exercise. The results were described as weighted mean difference (WMD) with a 95% confidence interval (95% CI).

Results The 23 included studies showed low statistical heterogeneity for the pooled outcomes. We found that LLCGs yielded similar running performance to controls (50–400 m: WMD 0.06 s [95% CI − 1.99 to 2.11]; 800–3000 m: WMD 6.10 s [95% CI − 7.23 to 19.43]; > 5000 m: WMD 1.01 s [95% CI − 84.80 to 86.82]). Likewise, we found no evidence that LLCGs were superior in secondary outcomes (VJ: WMD 2.25 cm [95% CI − 2.51 to 7.02]; VO_2max: WMD 0.24 $mL.kg^{-1}.min^{-1}$ [95% CI − 1.48 to 1.95]; VO_2submax: WMD − 0.26 $mL.kg^{-1}.min^{-1}$ [95% CI − 2.66 to 2.14]; [La]: WMD 0.19 mmol/L [95% CI − 0.22 to 0.60]; RPE: WMD − 0.20 points [95% CI − 0.48 to 0.08]).

Conclusions LLCGs were not associated with improved performance in VJ, VO_2max, VO_2submax, [La], or RPE during high-intensity exercise. Such evidence should be taken into account when considering using LLCGs to enhance running performance.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s40279-018-0927-z) contains supplementary material, which is available to authorized users.

✉ Ricardo Stein
rstein@cardiol.br

1 Graduate Program in Cardiology and Cardiovascular Sciences, School of Medicine, Hospital de Clínicas de Porto Alegre (HCPA), Universidade Federal do Rio Grande do Sul (UFRGS), Térreo, Ramiro Barcelos 2350, Largo Eduardo Zaccaro Faraco, Porto Alegre, RS CEP 90035-903, Brazil

2 Exercise Cardiology Research Group (CardioEx) HCPA/UFRGS, Porto Alegre, Brazil

3 Exercise Pathophysiology Laboratory (LaFiEx) HCPA/UFRGS, Porto Alegre, Brazil

4 Interdisciplinary Laboratory of Research on Sleep (LIPES) HCPA/UFRGS, Porto Alegre, Brazil

5 Institute for Health Technology Assessment (IATS), HCPA/UFRGS, Porto Alegre, Brazil

6 School of Medicine, HCPA/UFRGS, Porto Alegre, Brazil

7 Vitta Centro de Bem-Estar Físico, Porto Alegre, Brazil

Published online: 02 May 2018

Key Points

This systematic review and meta-analysis summarizes the association between lower-limb compression garments (LLCGs) during high-intensity efforts with changes in sports performance and physiological markers.

The use of LLCGs during high-intensity exercise was not associated with improved performance, oxygen uptake (maximal and submaximal) vertical jump height, blood lactate concentration, or ratings of perceived exertion compared with controls without compression.

The results were consistent regardless of sex, athletic status, types of LLCG, or test intensity.

1 Background

The compression garment (CG) is a non-invasive therapeutic strategy that applies mechanical pressure to the body surface by compressing and stabilizing the underlying tissues [1]. Typically used as a prophylactic method for patients with impaired hemodynamic function [2–5], lower-limb compression garments (LLCGs) have been increasingly used as ergogenic aids in sports, and the functional [6–10], metabolic [11], and perceptual parameters related to their use in athletic performance have been investigated.

While some studies have suggested improvement in sport performance variables under certain experimental conditions [6, 7, 12–14], solid conclusions have yet to be established. The inconsistency among the results may be due to the large methodological heterogeneity of the investigations, including the studied interventions or chosen outcomes [15]. Recently, the number of studies focusing on LLCG use during exercise has increased considerably, and systematic reviews have summarized the effects of LLCGs on varied outcomes [15–18]. However, the beneficial effects these reviews have found are mainly related to sport performance variables [16–18], such as vertical jump, motor control, oxygen uptake, muscle damage markers, and pain or comfort scales, and not sports performance directly. Therefore, it has been suggested that the positive evidence for CG in sports remains anecdotal [17], being influenced by indirect sports performance measures and inconsistent results for physiological parameters.

Ultimately, the time required to cover a given distance (or vice versa) is the standard performance measure for many sports modalities. However, there is little summarized evidence on direct changes in performance with LLCG use, since most available meta-analyses of the literature present the effect size as a standardized summary effect [16–18]. This approach does not preserve the real unit of measurement and makes it difficult to quantify the actual effect of LLCGs on performance.

The aforementioned effects of CGs on lower limb hemodynamics have been advocated as the rationale supporting their ergogenic effect in competitive sports performance, which is mostly performed at high intensity levels. For this reason and given the dearth of evidence concerning their effects at this intensity range, we aimed to conduct a systematic review and meta-analysis to summarize the effects of LLCG versus control groups without compression on performance as the primary outcome and on physiological and perceived exertion parameters as secondary outcomes during high-intensity exercise. We hypothesized that the LLCG group would be superior to controls for all measured outcomes.

2 Methods

This systematic review and meta-analysis was reported according to Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [19].

2.1 Search Strategies

Studies, without restrictions on date or type (e.g., original research, short communication, etc.), were identified through searches in the following databases: MEDLINE (PubMed), Cochrane Central Register of Controlled Trials, Excerpta Medica Database (EMBASE) and ClinicalTrials.gov, which were completed on May 2017. The main search terms were *athlete, adult, compression garment, compression clothing, elastic stocking, athletic performance, sport, physical exercise, time to exhaustion, time trial,* and associated terms, which were combined with a sensitive strategy to search for randomized controlled trials (RCTs). The complete MEDLINE search strategy is presented in Electronic Supplementary Material Appendix S1. The reference lists of relevant original articles and reviews, as well as the included original articles, were also hand searched to supplement the database searches.

2.2 Study Selection

Eligible studies were included if they fulfilled all the following criteria: (1) RCTs with a control group (wearing neither CG nor a placebo garment); (2) garments worn only on the lower limbs; (3) assessments performed during high-intensity exercise (maximal oxygen uptake

[VO_2max] ≥ 85%, maximal heart rate [HRmax] ≥ 85%, ratings of perceived exertion [RPE] > 16, blood lactate concentrations ([La]) > 4 mmol/L or all-out sprints); (4) participants over 18 years of age; (5) a study population including athletes and physically active subjects. To be classified as an athlete, a participant had to present one of the following characteristics: being deemed by the authors of the study as an athlete or highly trained in some sport, being a member of a college team or club, or having VO_2max > 60 $mL.kg^{-1}.min^{-1}$ in study assessments. The review included articles in English, Spanish, and Portuguese.

To avoid duplicate counting of individuals included in more than one study from the same group of researchers, sample size, baseline sample characteristics, and recruitment periods were evaluated for each article. When necessary, the authors were contacted for further information. We excluded trials that provided insufficient data to conduct the meta-analysis even after contact with authors, as well as studies of individuals with a history or diagnosis of cardiovascular, pulmonary or metabolic disease, peripheral vascular disease (whether arterial or venous), or who were taking medications. Duplicate references in different databases were identified and excluded.

The selection of potentially eligible studies began by analyzing the titles and abstracts, which was performed by two independent investigators (CAS and RPS) using a standardized reference manager. Disagreements were solved by consensus or by discussion with a third investigator (DU). Abstracts that did not provide sufficient information about at least one exclusion criterion were subsequently analyzed during full-text review.

2.3 Data Extraction

The data were extracted by two independent investigators (CAS and RPS) using standardized spreadsheets developed by the research group and previously tested at the beginning of the review. Disagreements were resolved by consensus or by discussion with a third investigator (DU). For any studies with incomplete data, the authors were contacted by e-mail. A total of 23 requests were made to clarify inaccurately described data required for meta-analysis. Of the authors contacted, nine (39.1%) replied with complete information, 10 (44.5%) did not answer, and four (17.4%) reported that they no longer had access to the requested data.

The information extracted from studies included the participants' characteristics (age, sex, body mass, height, aerobic capacity, and training routine), LLCG characteristics (type of garment, intensity of compression, pattern of compression distribution, and whether the garment was tailored), and outcomes, in which performance was considered as the time to cover a given distance, vertical jump height (VJ), VO_2max and VO_2submax measured directly by a respiratory gas exchange method, [La], and RPE assessed using the Borg scale, which is graded from 6 to 20 points.

2.4 Risk of Bias Assessment

The risk of bias was assessed using the Cochrane tool [20]. The assessment was performed independently by two investigators (CAS and RPS). Disagreements were solved by consensus or by discussion with a third investigator (DU). The risk of bias assessment was divided into four items: (a) control for placebo effect, (b) random sequence generation, (c) concealment of allocation sequence, and d) selective reporting of outcomes. The risk of bias was classified into three categories: low, unclear and high. Methodological quality was not used as an eligibility criterion.

2.5 Data Analysis

Stata 11.0 (Stata Inc., College Station, TX, USA) was used for all meta-analyses. Mean values and measures of central tendency and dispersion were extracted. Dispersion data expressed as standard error were converted into standard deviations in a standardized spreadsheet. Pooled estimates were calculated using the random effects model [21] and described as weighted mean difference (WMD), weighted by the inverse of the variance of each included study; precision was presented as 95% confidence intervals (95% CI). The main analyses compared the effects of LLCG versus control without compression on the following outcomes: (1) performance (evaluated by time), the primary outcome of this study; and (2) VJ, VO_2max, VO_2submax, [La], and RPE assessed by the Borg scale (6–20), which were secondary outcomes of this study [22]. Since some studies compared multiple interventions (different degrees of compression, types of LLCGs) with only one control group, we divided this group into smaller subgroups weighted by the different interventions [23]. Performance analysis was stratified according to sport and was performed only in groups of at least two studies, and, due to the low number of cycling studies, only running studies were analyzed for this outcome. We grouped running performance according to distances certified by the International Association of Athletics Federations (IAAF).

The possibility of publication bias was assessed by plotting the effect size found in each study versus standard error in a contour-enhanced funnel plot [24]. Funnel plot asymmetry was formally assessed using Begg and Egger's test [25] at a significance level of $p < 0.1$. The inconsistency test (I^2) was used to investigate the percentage of heterogeneity between the studies.

Sub-group and sensitivity analyses were defined a priori in order to explore the following characteristics: sex, athletic status, LLCG types (stocking/sleeve, shorts or a combination of stocking/sleeve + shorts or tights), and test intensity (maximal or submaximal). Additional information on subgroup and sensitivity analyses is provided in Electronic Supplementary Material Table S1.

3 Results

3.1 Study Selection

The database search resulted in 3107 potentially eligible references. After evaluation of the titles and abstracts, 92 references were chosen for full-text review, of which 23 RCTs were considered eligible and included in the study (Fig. 1). Two potentially eligible unpublished references (one abstract published in conference annals and one study registered in ClinicalTrials.gov) were not selected for full-text review, since we could not access the final version of the article or the results (data unavailable even after contact with authors). We excluded studies by design (any non-RCT, such as non-randomized controlled trials, uncontrolled trials etc., or RCTs whose test was rated as 'high intensity' by the aforementioned criterion), by outcome (any study not addressing performance by directly measuring VJ, VO_2max, VO_2submax, [La], and RPE, independent of sport as one of its outcomes), and by intervention (garments not used on lower limbs or a concomitant intervention, such as any other ergogenic aid).

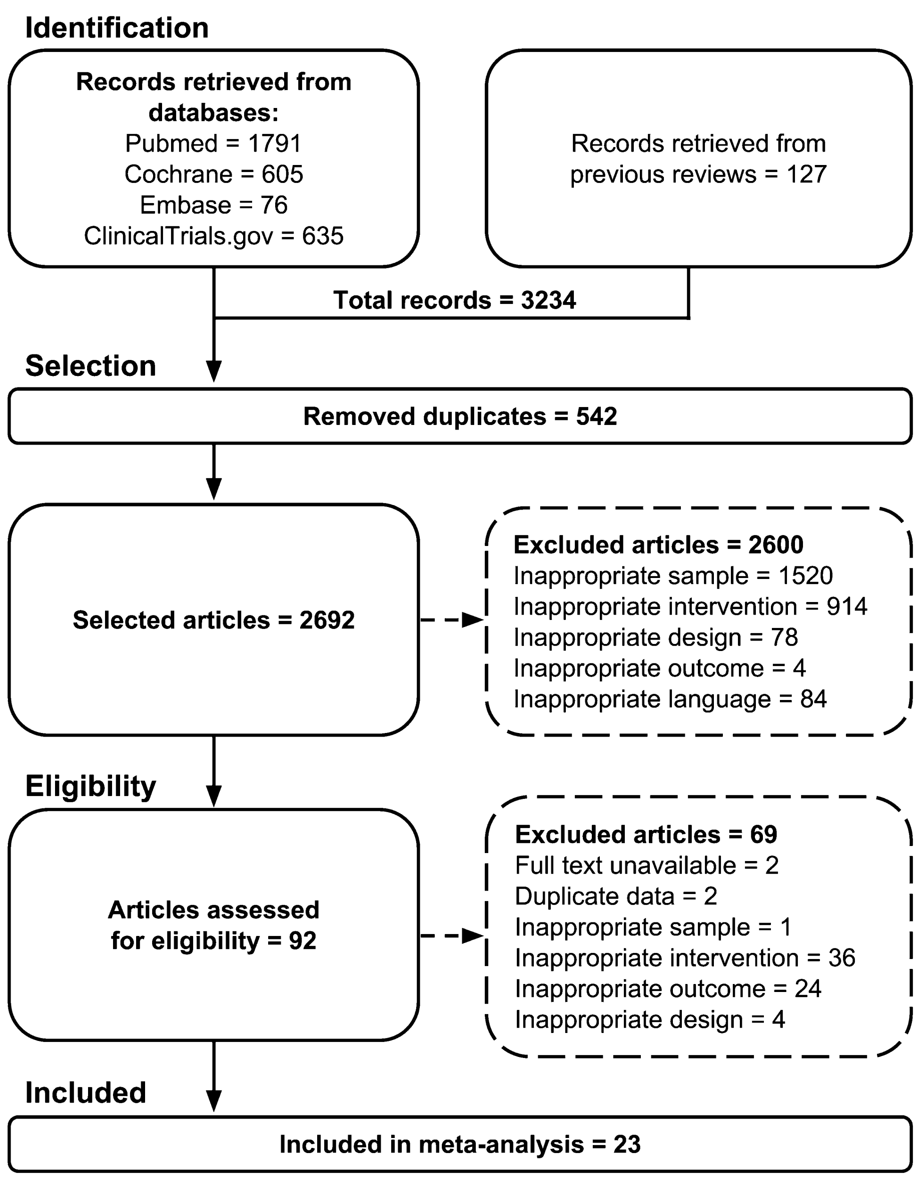


Fig. 1 Flowchart of study selection for inclusion in the systematic review and meta-analysis

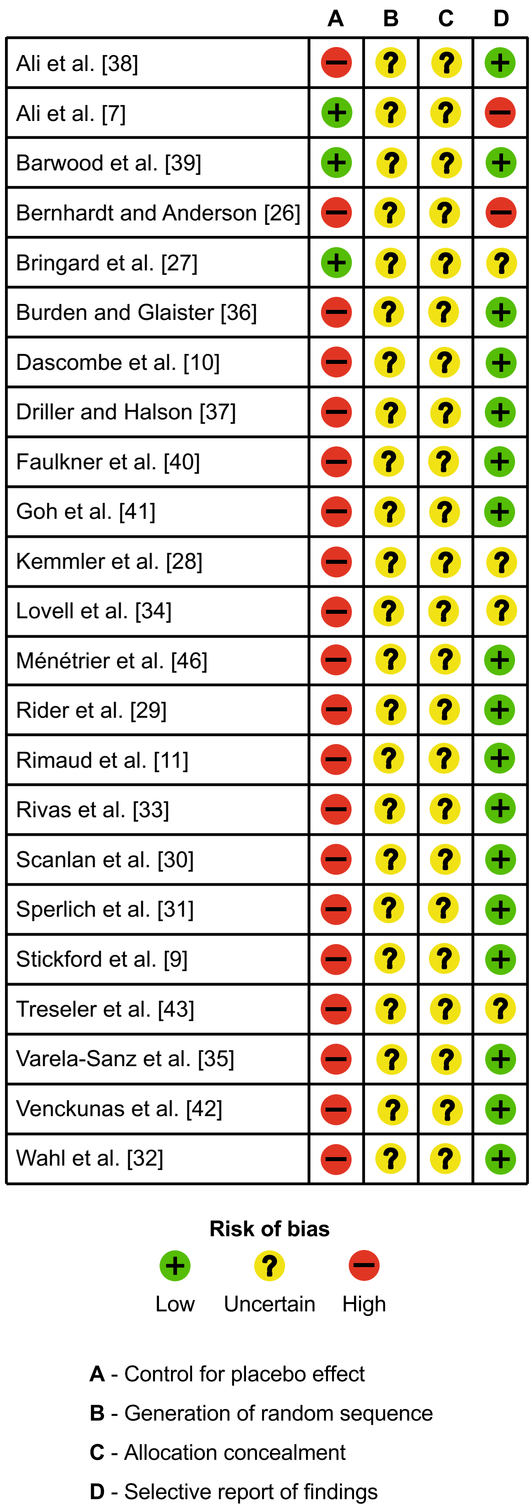


Fig. 2 Risk of bias classification according to the Cochrane tool for the studies included in the meta-analysis

3.2 Risk of Bias Assessment

Figure 2 shows the risk of bias classification for the 23 included studies. Of these, 74% (17 studies) had low risk of bias in terms of selective reporting of findings. Regarding the use of strategies to control or minimize the placebo effect, three studies (13%) had low risk of bias. Thus, all studies were classified as having uncertain risk of bias for random sequence generation and allocation concealment.

According to evaluation by funnel plot (Electronic Supplementary Material Figs. S1 to S5), only two of the 23 evaluated studies (9%) produced effect estimates outside the expected distribution for their size (or precision), suggesting a low risk of publication bias [24, 25].

3.3 Characteristics of the Included Studies

The characteristics of the studies are summarized in Table 1. The total sample included 294 participants aged 20–39 years, of which 85% (249) were men. In nine (39%) studies, the participants were described by the authors as athletes or met the criteria used to define an athlete, while in 14 (61%), the participants were rated as physically active. All 23 studies were published in English: ten (43%) were conducted in Europe, eight (35%) in Oceania and five (22%) in North America. Twenty-two (96%) trials were crossover studies. Regarding publication date, seven (30%) trials were carried out between 2005 and 2010 and 16 (70%) between 2011 and 2017.

In terms of exercise protocol, 12 (52%) studies involved treadmill running, seven (30%) involved indoor, track, or road running, and four (17%) involved a cycle ergometer. With respect to garment pressure range, 14 (61%) trials used ranges below 20 mmHg, four (17%) used 20–30 mmHg, two (9%) did not report this aspect, and three (13%) tested more than one range, varying from 12 to 45 mmHg.

Electronic Supplementary Material Table S2 shows the individual contribution of each study to the evaluated outcomes.

3.4 Performance

The performance results were subdivided according to distances covered in running tests, since only sufficient data were achieved for this modality (i.e., no sufficient data for cycling or any other modality) (Fig. 3). In the three analyses, LLCG group performance was not superior to that of the control group (50–400 m: WMD = − 0.06 s [95% CI − 1.99 to 2.11], $I^2 = 0.0\%$, $p = 0.922$; 800–3000 m: WMD = 6.10 s [95% CI − 7.23 to 19.43], $I^2 = 0.0\%$, $p = 0.991$; > 5000 m: WMD = 1.01 s [95% CI − 84.80 to 86.82], $I^2 = 0.0\%$, $p = 0.999$). Furthermore, these results did not change in any subgroup and sensitivity analyses (details in Electronic Supplementary Material Table S1).

Table 1 Summary of studies included in the systematic review and meta-analysis investigating lower-limb compression garment during high-intensity exercise in athletes and physically active subjects

Study	Participants		Clothing		Study protocol	Outcome variables included in meta-analysis[a,b]
	Sample size and sex; age (mean ± SD)	Athletic status (data are mean ± SD)	Type	Pressure range (mmHg)		
Ali et al. [38]	14 M; 22.5 ± 1.7[c]	Healthy males whose primary sport was based on running: (1) VO_2max 56 ± 2 mL.kg^{-1}.min^{-1c}, (2) VO_2max 55 ± 3 mL.kg^{-1}.min^{-1c}	Stockings (G)	18–22	2 × 20 shuttle-runs (separated by 1 h) and 10-km TT (road running)	TT, RPE
Ali et al. [7]	9 M/3 F; 33 ± 10	Well trained athletes (VO_2max 69 ± 6 mL.kg^{-1}.min^{-1})	Stockings (G)	12–15; 18–21; 23–32	10-km TT (track running)	TT, [La], VJ, RPE
Barwood et al. [39]	8 M; 21 ± 2	Recreationally active men (sport not specified)	Tights (G)	11–20	5-km TT (treadmill running in hot radiant conditions)	TT, RPE
Bernhardt and Anderson [26]	10 M/3 F; 25.7	Active young adults from a university population (sport not specified) (VO_2peak 50 ± 9 mL.kg^{-1}.min^{-1})	Shorts	NR	20-m shuttle run, 20-m sprint, VJ, joint-angle replication, agility and balance test, active range of motion	TT, VJ
Bringard et al. [27]	6 M; 31.2 ± 5.4	Well trained runners (VO_2max 60 ± 7 mL.kg^{-1}.min^{-1})	Tights	NR	Incremental test on indoor track at 10, 12, 14, 16 km/h (at 31 °C)	VO_2max, RPE
Burden and Glaister [36]	10 M; 34.6 ± 6.8	Well trained triathletes and cyclists (VO_2max 51 ± 7 mL.kg^{-1}.min^{-1})	Tights (G)	11–21	10-km TT on an electro-magnetically braked cycle ergometer and Wingate anaerobic test	[La]
Dascombe et al. [10]	11 M; 28.4 ± 10	Well trained runners and triathletes (VO_2max 59 ± 7 mL.kg^{-1}.min^{-1})	Tights (G)	14–22	Incremental maximal test and TTE at 90% VO_2max on treadmill (at 22 ± 2 °C)	TTE,VO_2max, VO_2submax, [La]
Driller and Halson [37]	12 M; 30 ± 6	Highly trained cyclists (VO_2peak 67 ± 3 mL.kg^{-1}.min^{-1})	Tights (G)	10–18	30-min cycling bout (15 min at constant workload + 15 min TT)	[La]
Faulkner et al. [40]	11 M; 23.7 ± 5.7	Velocity runners	Tights (G); shorts (G); stockings (G)	5–13; 4–8; 14–21	6 × 400-m TT (on an outdoor all-weather tartan running track)	TT, RPE
Goh et al. [41]	10 M; 29 ± 10	Recreational runners (VO_2max 59 ± 3 mL.kg^{-1}.min^{-1})	Tights (G)	9–14	20-min treadmill run at 1st ventilatory threshold followed by a run to exhaustion at VO_2max velocity (at 10 and 32 °C conditions)	TTE, RPE
Kemmler et al. [28]	21 M; 39.3 ± 10.9	Moderately trained runners (VO_2max 52 ± 6 mL.kg^{-1}.min^{-1})	Stockings (G)	18–24	Incremental maximal treadmill test until exhaustion (at 20–22 °C)	TTE, VO_2max, [La]
Lovell et al. [34]	25 M; 21.6 ± 2.5	Semiprofessional rugby players	Tights (G)	15–20	30-min treadmill runs comprising 5-min stages at three intensities: 6, 10 km/h and 85% VO_2max	VO_2submax, [La]
Ménétrier et al. [46]	14 M; 21.9 ± 0.7	Moderately trained in endurance sports	Sleeve (G)	15–27	15 min resting, 30 min at 60% MAV, 15 min of recovery, a running TTE at 100% MAV, and a final 30-min recovery period (12% treadmill slope at 22 ± 1 °C)	TTE
Rider et al. [29]	7 M/3 F; 20.3 ± 1.1	Division III cross-country runners (VO_2max 64 ± 7 mL.kg^{-1}.min^{-1})	Stockings (G)	15–20	Discontinuous ramped treadmill protocol until volitional exhaustion	TTE, VO_2max, RPE

Table 1 continued

Study	Participants		Clothing		Study protocol	Outcome variables included in meta-analysis[a,b]
	Sample size and sex; age (mean ± SD)	Athletic status (data are mean ± SD)	Type	Pressure range (mmHg)		
Rimaud et al. [11]	8 M; 27.1 ± 2.5[c]	Healthy trained subjects engaged in cycling, running or swimming activity (VO_2max 54 ± 8 $mL.kg^{-1}.min^{-1c}$)	Stockings (G)	12–22	Incremental cycling test until exhaustion	VO_2max, [La], RPE
Rivas et al. [33]	10 M/3F; 20.9 ± 2.5	Collegiate cross-country: male and female student athletes	Stockings (G)	9–15	4-min running stages (12.1, 12.9, 13.8 km/h), corresponding to 70 ± 6, 74 ± 7 and 85 ± 7% of VO_2max, respectively, followed by TTE ramp test on treadmill	VO_2max, [La]
Scanlan et al. [30]	12 M; 20.5 ± 3.6	Well trained cyclists (VO_2max 55 ± 7 $mL.kg^{-1}.min^{-1}$)	Tights (G)	9–20	1 h TT on cycle ergometer (between 90 and 100 RPM at 22 ± 2 °C)	VO_2max, [La]
Sperlich et al. [31]	15 M; 27.1 ± 4.8	Well trained runners and triathletes (VO_2max 64 ± 5 $mL.kg^{-1}.min^{-1}$)	Stockings and tights	20	15-min treadmill running at 70% VO_2max followed by TTE at maximal velocity of previous incremental test	TTE, VO_2max, [La], RPE
Stickford et al. [9]	16 M; 22.4 ± 3	Highly trained runners (VO_2max upper to 65 $mL.kg^{-1}.min^{-1}$ in last year)	Sleeve (G)	15–20	4-min stages at each of 3 constant submaximal speeds of 233, 268, and 300 m/min on a motorized treadmill	$VO_2submax$
Treseler et al. [43]	19 F; 20 ± 1	Recreationally active females	Stockings (G)	13–21	5-km time trial on an outdoor course	TT, RPE
Varela-Sanz et al. [35]	13 M/3 F; 34.7 ± 6.3	Experienced runners (VO_2max 63 ± 9 $mL.kg^{-1}.min^{-1}$)	Sleeve (G)	15–22	4 × 6 min at a recent half-marathon pace followed by TTE at 105% of a recent 10-km pace on treadmill	TTE, $VO_2submax$, [La]
Venckūnas et al. [42]	13 F; 25.1 ± 4.2	Healthy young adults	Tights	17–18	4 km at a 7 min 30 s per km pace immediately followed by 400-m TT on indoor 200-m athletic track	TT, RPE
Wahl et al. [32]	9 M; 25.8 ± 3.8	Well trained runners and triathletes (VO_2peak 58 ± 5 $mL.kg^{-1}.min^{-1}$)	Stockings (G)	13–21; 23–31; 39–46	30 min at 70% of VO_2peak followed by TTE ramp test on treadmill	TTE, VO_2max, [La]

F female, *G* gradual compression, *h* hour, *km* kilometer, *[La]* blood lactate concentrations, *M* male, *m* meter, *MAV* maximal aerobic velocity, *min* minutes, *NR* not reported, *RPE* ratings of perceived exertion, *RPM* revolutions per minute, *s* seconds, *SD* standard deviation, *TT* time trial, *TTE* time to exhaustion, *VJ* vertical jump height, *VO_2max* maximal oxygen uptake, *VO_2peak* peak oxygen uptake, *$VO_2submax$* submaximal oxygen uptake

[a]Baseline VO_2max or VO_2peak presented whenever available

[b]Cycling TT are presented in the table but were not included in the performance meta-analysis

[c]SD was obtained by multiplying the standard error of mean by the square root of the sample size

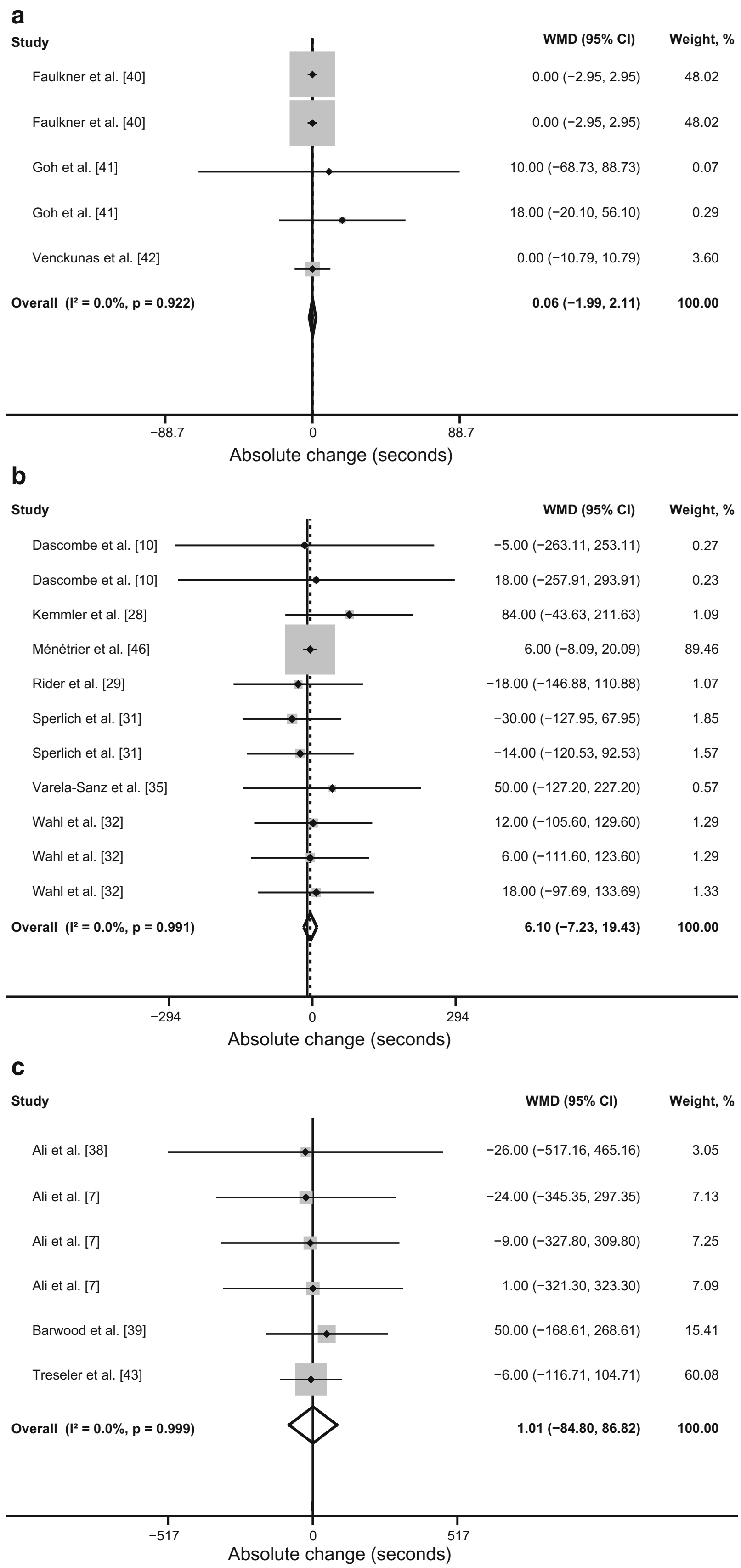
3.5 Vertical Jump Height

In the pooled analysis assessing VJ [7, 26], there was a difference between the LLCG and control groups (WMD = 2.25 cm [95% CI − 2.51 to 7.02], I^2 = 0.0%, p = 0.852) (Electronic Supplementary Material Fig. S6). These results did not change in any subgroup or sensitivity analysis (details in Electronic Supplementary Material Table S1).

3.6 Maximal Oxygen Uptake

There was no change in VO_2max between the LLCG and control groups in the nine included studies that assessed this outcome [10, 11, 27–33] (WMD = 0.24 $mL.kg^{-1}.min^{-1}$ [95% CI − 1.48 to 1.95], I^2 = 0.0%, p = 1.000) (Fig. 4). These results did not change in any subgroup or

Fig. 3 Forest plot illustrating the effect of LLCG use on performance during high-intensity exercise: **a** running test between 50 and 400 m; **b** running test between 800 and 3000 m; **c** running test > 5000 m. Weights are from random effects analysis. The center of the diamond represents the overall effect and the lateral tips of the diamond are the associated CI. The vertical line represents the null effect. *CI* confidence interval, *LLCG* lower-limb compression garment, *WMD* weighted mean difference



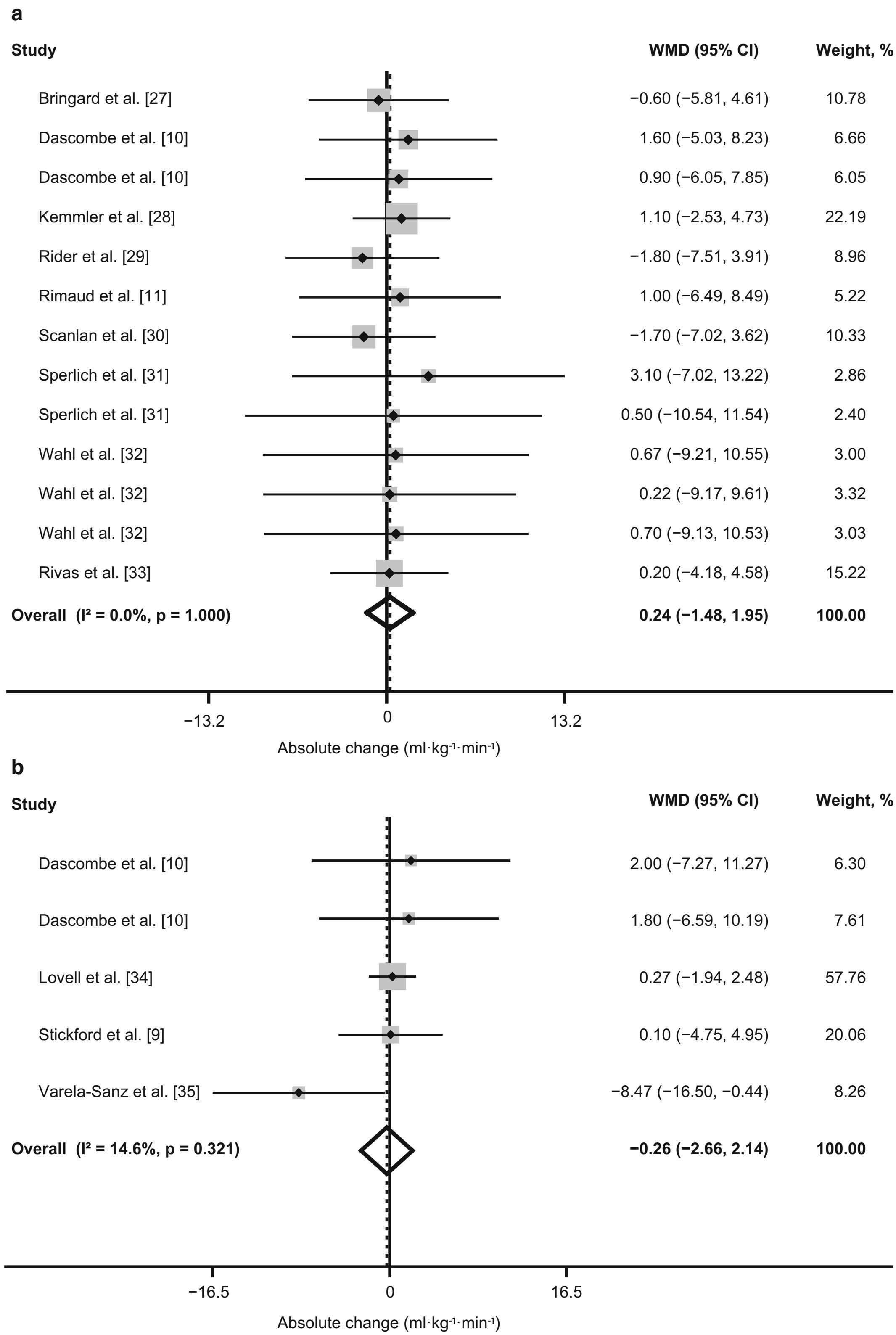


Fig. 4 Forest plot illustrating the effect of LLCG use on oxygen uptake during high-intensity exercise: **a** VO_2max; **b** VO_2submax. Weights are from random effects analysis. The center of the diamond represents the overall effect and the lateral tips of the diamond are the associated CI. The vertical line represents the null effect. *CI* confidence interval, *LLCG* lower-limb compression garment, *VO_2max* maximal oxygen uptake, *VO_2submax* submaximal oxygen uptake, *WMD* weighted mean difference

sensitivity analysis (details in Electronic Supplementary Material Table S1).

3.7 Submaximal Oxygen Uptake

There was no difference in VO_2submax between the LLCG and control groups according to the four included studies that assessed this outcome [9, 10, 34, 35] (WMD = − 0.26 mL.kg^{-1}.min^{-1} [95% CI − 2.66 to 2.14], I^2 = 14.6%, p = 0.321) (Fig. 4). Details of the subgroup and sensitivity analyses can be found in Electronic Supplementary Material Table S1.

3.8 Blood Lactate Concentration

Regarding [La] assessment, 12 studies were included in our review [7, 10, 11, 28, 30–37]. There was no difference in [La] between the LLCG and control groups (WMD = 0.19 mmol/L [95% CI − 0.22 to 0.60], I^2 = 0.0%, p = 0.961) (Electronic Supplementary Material Fig. S7). These results did not change in any subgroup or sensitivity analysis (details provided in Electronic Supplementary Material Table S1).

3.9 Ratings of Perceived Exertion

With respect to RPE assessment, 11 studies were included in our review [7, 11, 27, 29, 31, 38–43]. There was no difference in RPE between the LLCG and control groups (WMD = − 0.20 points [95% CI − 0.48 to 0.08], I^2 = 0.0%, p = 0.982) (Fig. 5). The results did not change in any subgroup or sensitivity analysis (details provided in Electronic Supplementary Material Table S1).

4 Discussion

Our systematic review and meta-analysis summarized the effects of RCTs with LLCGs on performance, VJ, VO_2max and VO_2submax, [La], and RPE during high-intensity exercise; that is, the intensity that best represents the competitive setting. We also sought to deal with inconclusive evidence among the primary studies. In an effort to preserve the variable units (i.e., weighted mean differences), pre-planned subgroup and sensitivity analyses were performed to address variables such as sex, athletic status, and even compression type. Finally, we targeted outcomes that would allow readers to judge the use of LLCGs more comprehensively, such as sports performance and related physiological variables.

We believe the present review offers a sound methodological approach for extending existing knowledge. We found no clear evidence that LLCGs enhanced sports performance or physiological markers. We also took sex, athletic status, and event distances (in three categories) into consideration. We will consider each of these aspects in the following subtopics.

4.1 Performance

The results of our meta-analyses did not confirm the superiority of LLCGs over non-compression comparators, which supports previous research [7, 8, 10, 13, 31, 32, 35, 36, 38–42, 44–46]. Performance has been assessed in previous meta-analyses [16–18], with Born et al. [16] and Engel et al. [18] stating that CG had a small effect size on performance, while Beliard et al. [17] reported that, in nine out of ten different protocols, athletic performance remained unchanged in a qualitative approach (i.e., systematic review), regardless of the compression level (pressure ranging from 16 to 45 mmHg at the ankle). We employed data synthesis to handle changes in direct units, and the present pooled analysis, unlike previous systematic reviews and meta-analyses, did not confirm small effects. Such divergent results may be partially influenced by different meta-analytic approaches, since previous reviews presented standardized effect sizes, whereas we generated mean differences that retained the original units of change for each variable. Since physiological responses are greatly dependent upon the duration of exercise, we conducted a sensitivity analysis that stratified events according to distance. However, the hypothesized improvement with LLCG use could not be confirmed for events of 50–400 m, 800–3000 m, or > 5000 m. Although we are not aware of previous reviews with stratified analyses comparable to ours, we do not discount the need for cumulative evidence to confirm these subgroup results.

Given the presence of bias, it is very difficult to adequately judge the validity and reliability of the findings of trials, and consequently, of systematic reviews [47]. According to our review, which followed PRISMA risk of bias assessment guidelines [20], many trials presented a high or uncertain risk of bias related to control for placebo effect, random sequence generation, and/or allocation concealment (Fig. 2). Among the studies that found positive results for compression garments [15, 16, 18], only MacRae et al. [15] discussed the potential placebo effect. Since many of the studies in our review had been included in previous reviews and did not control for a potential placebo effect, we believe, in addition to our statistical conclusions, that there is insufficient causal evidence to support recommending LLCGs to improve performance.

Another important issue regarding previous reviews [16, 18] with results that diverge from ours is the use of a meta-analysis outcome that depends on reporting an overall

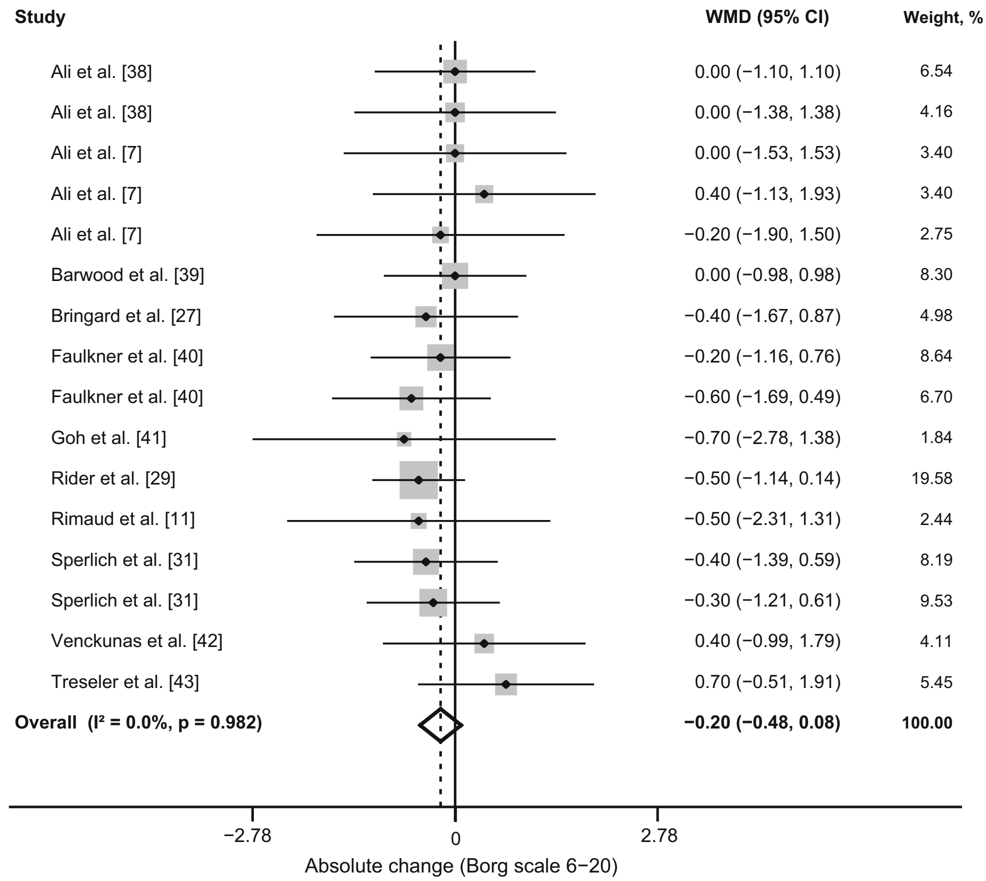


Fig. 5 Forest plot illustrating the effect of LLCG use on RPE during high-intensity exercise. Weights are from random effects analysis. The center of the diamond represents the overall effect and the lateral tips of the diamond are the associated CI. The vertical line represents the null effect. *CI* confidence interval, *LLCG* lower-limb compression garment, *RPE* ratings of perceived exertion, *WMD* weighted mean difference

effect based on a standardized effect size metric (Hedges' *g*). While recommended for better understanding of the magnitude of an outcome [48], the use of an effect size alone does not provide adequate understanding of 'clinical' applicability, and has led readers to conclude that LLCGs have apparent benefits on performance and physiological markers [16]. Its use, however, should be accompanied by an inference-based statistical approach to avoid misinterpretation of the true effect of an intervention (i.e., the probability that it is a true difference rather than a random variation). On the other hand, when we summarized the data using WMD, which is based on a real outcome metric, the benefit became irrelevant and without statistical significance, even when stratified by sex, athletic status, garment compression type, or intensity ranges, which are some potential moderating factors.

It is clear that translating the previously claimed small-to-moderate standardized effect into a more robust unit changed the direction of the LLCG performance benefit, especially for high-intensity events. Nonetheless, it is important to point out that most of the studies included in this systematic review and meta-analysis, which were also included in previous reviews [16–18], had small sample sizes, were uncontrolled for placebo effect, and had imprecise effect sizes (i.e., wide confidence intervals). Thus, more reliable evidence about the effects of this type of ergogenic aid on sports performance is now available from pooled data obtained from our results, which partially address these caveats.

4.2 Vertical Jump Height

The results of our meta-analysis indicated no significant difference in VJ between groups in either the pooled analysis or any sensitivity analyses. MacRae et al. [15] concluded in their systematic review that the use of CG had limited effects on physiological and performance aspects, pointing out that any positive results were isolated and conflicting. The meta-analysis by Born et al. [16] found a slightly positive effect size (Hedges' $g = 0.10$) on VJ performance in the CG group. Again, this slightly positive standardized effect size does not seem to translate into any relevant improvement in vertical jump height, since we found a non-significant improvement of 2.25 cm (− 2.51 to 7.02).

Similarly, at the primary study level, there were divergent results among RCTs. Bernhardt and Anderson [26] observed no significant difference in results between groups for VJ. Another RCT that exposed skiers to a fatigue protocol on a vibration platform found similar results for jump performance, regardless of compression tights [6]. Additionally, in Doan et al. [13], maximum VJ increased only for individuals who wore compression shorts. Although this review was not focused on clarifying which mechanisms are potentially involved in jump performance and how they may alter this outcome, the type of LLCG did not improve VJ based on one of our sensitivity analyses (see Electronic Supplementary Material Table S1).

Considering that all studies included in our meta-analyses investigated VJ after long-duration continuous protocols, predominantly based on running, our findings suggest that, at least under these conditions, the use of LLCGs does not change jump performance. However, given the wide variety of sports and the fact that muscle action is affected by different fatigue manifestations [49, 50], it would be interesting to determine whether the results found in the present investigation could be confirmed in other forms of exercise, such as those involving muscle power and jumping movements (e.g., volleyball, basketball, pole vault, high jump, etc.).

4.3 Maximal and Submaximal Oxygen Uptake

Improved hemodynamics due to increased venous return pump pressure [2, 3, 51] is one of the most widely purported physiological effects of LLCGs as an ergogenic aid. It has been suggested as a potential mediator of benefits during exercise [10, 37, 52], which could occur by increasing muscle oxygen saturation [53], improving cardiac preload, and enhancing local blood flow [54].

Despite such a physiologically based rationale that LLCGs improve oxygen uptake during exercise, there is extensive debate in the literature over whether such increments reduce cardiorespiratory overload and positively impact VO_2, especially the unsolved question of central or peripheral limiting factors of VO_2max [55] and oxygen uptake kinetics [56–60]. In this context, our results agree with the findings of the original trials, in which some studies found innocuous or only minor effects [9–11, 26, 28–32, 34, 35, 61] in terms of LLCG-related improvements in VO_2max and VO_2submax.

Interestingly, contrary results were found in well trained runners undergoing a 15-min high-intensity test [27]. In this study, individuals wearing compression tights showed a significant reduction in the slow component of VO_2 compared with those wearing conventional shorts [27]. It is not clear how a reduction in VO_2 slow component amplitude could be caused by improved tissue blood flow, given its relation to the inherent fatigue process induced by additional type II fiber recruitment [62].

In sum, the results of our meta-analysis of oxygen uptake data demonstrate that LLCGs have no effect on VO_2max or VO_2submax, both well recognized physiological parameters involved in endurance performance, strengthening the findings of individual studies through application of increased statistical power in our analysis.

4.4 Blood Lactate Concentration

Our meta-analysis found no significant difference in [La] between groups in either the pooled analysis or sensitivity analyses, which also agrees with previous reviews [16, 18] and some trials [7, 10, 28, 30–32, 34, 35, 37, 45, 61]. Born et al. [16] confirmed these findings and showed that this physiological marker was not affected by CGs when used during continuous exercise. Unlike the other outcomes, our results here agree with previous studies, showing that LLCGs have no effect on [La] during exercise.

Although many trials have demonstrated null effects for LLCGs on [La] during exercise, other studies have reported contradictory findings. While Burden and Glaister [36] observed better lactate clearance in the compression group than in the control group (no compression) immediately after exercise, Berry and McMurray [63] concluded that LLCGs may cause cellular retention of lactate, proposing that lower [La] was caused by reduced diffusion of lactate from the muscle bed to the blood stream. In this regard, previous studies have shown that applying pressure on the lower limbs during dynamic exercise may reduce blood flow in the compressed area [64–66], consequently increasing [La] [67]. Future studies are needed to clarify the influence of compression on muscle metabolism during exercise, especially on lactate kinetics, since [La] has been acknowledged as a physiological marker of exercise tolerance [68].

Our findings on [La] are of great importance and should be included in discussion of LLCGs, particularly because we included only studies with efforts near 85% VO_2max, an intensity well recognized as the boundary of the second lactate threshold [69, 70]. These findings, together with those for running performance (Sect. 3.4) and maximal and submaximal oxygen uptake (Sects. 3.6 and 3.7), point to the uncertain benefits of the use of LLCGs.

4.5 Ratings of Perceived Exertion

Our meta-analysis of LLCGs during high-intensity exercise found no significant difference in RPE between the LLCG and control groups. Sensitivity analyses also showed no significant difference. Previous reviews [16, 18] have found a small positive effect size (Hedges' $g = 0.05$) on RPE in the CG group compared with the control group.

RPE does not appear to be affected by LLCGs, especially during prolonged exercise. It should be noted that it is difficult to control for the placebo effect; thus, conclusions about outcomes vulnerable to this type of influence should be drawn cautiously when this effect is not effectively controlled for. Strategies for overcoming this bias are needed in future studies to enable accurate interpretations of results, particularly those depending on perceptual and motivational aspects.

4.6 Limitations

Few of the analyzed studies used strategies to minimize or control for the placebo effect, and their results were obtained through exercise tests susceptible to the influence of psychological factors [71–73]. Since perceptual and motivational aspects are present in the sports environment, conclusions on outcomes vulnerable to this type of influence are impaired. The lack of description of random sequence generation methods and allocation sequence concealment imposes RCT selection bias limitations [20], which have a consequent impact on the interpretation of results.

Readers should be aware that, in our intent to use WMD instead of SMD (standard mean difference), the estimated effect of LLCGs on performance for 800–3000 m should be interpreted according to its relevance for each distance. Although not reaching statistical significance, a potential 6-s improvement could distinctly impact an 800 or 3000 m race. Moreover, our review does not cover all aspects of sports performance, since numerous physiological, biomechanical, and psychological aspects are involved. Thus, further research could yield more comprehensive understanding.

Also, only running studies had sufficient data to be included in the performance analysis. This means that our overview of LLCG effects on overall performance lacked RCTs on cycling and our results were therefore restricted to only one type of exercise. Therefore, more information is needed for other exercise modalities, as well as long-distance and lower intensity events.

Another potential limitation of our study is that some of the primary studies compared multiple interventions with only one control group. We divided this group into smaller subgroups weighted by the different interventions. Both methodological approaches may have influenced the divergent results from some original studies [7, 28, 34, 35, 40], as well as those indicated in our meta-analysis. However, the decision to use only data related to high-intensity exercise allowed us to demonstrate the effect of LLCGs when used under conditions similar to those of training and competition scenarios. Finally, regarding the separation of the control group, this approach was taken to obtain reasonably independent comparisons and overcome unit-of-analysis error [23].

5 Conclusion

Our systematic review and meta-analysis found that use of LLCGs during high-intensity exercise did not change performance, VJ, VO_2max, VO_2submax, [La], or RPE, regardless of sex, athletic status, garment type, and test intensity. These findings suggest that LLCG use during exercise is not an evidence-based practice and the use of such garments should be reconsidered.

Compliance with Ethical Standards

Funding This study was supported by the Fundo de Incentivo à Pesquisa e Eventos from the Hospital de Clínicas de Porto Alegre (FIPE/HCPA). Ricardo Stein and Daniel Umpierre receive research productivity funding from the Brazilian National Council for Scientific and Technological Development (CNPq). Lucas Helal receives PhD funding support from the CAPES (Coordination for the Improvement of Higher Education Personnel) Foundation.

Conflict of interest César Augusto da Silva, Lucas Helal, Roberto Pacheco da Silva, Karlyse Claudino Belli, Daniel Umpierre, and Ricardo Stein declare that they have no conflicts of interest relevant to the content of this review.

References

1. Partsch H. The static stiffness index: a simple method to assess the elastic property of compression material in vivo. Dermatol Surg. 2006;31:625–30.
2. O'Meara S, Cullum NA, Nelson EA, et al. Compression for venous leg ulcers. Cochrane Libr. 2009;11:1–3.
3. Moseley AL, Carati CJ, Piller NB. A systematic review of common conservative therapies for arm lymphoedema secondary to breast cancer treatment. Ann Oncol. 2007;18:639–46.
4. Rinehart-Ayres ME. Conservative approaches to lymphedema treatment. Cancer. 1998;83:2828–32.
5. Qaseem A. Venous thromboembolism prophylaxis in hospitalized patients: a clinical practice guideline from the American College of Physicians. Ann Intern Med. 2011;155:625.
6. Sperlich B, Born DP, Swarén M, Kilian Y, Geesmann B, Kohl-Bareis M, et al. Is leg compression beneficial for alpine skiers? BMC Sports Sci Med Rehabil. 2013;5:18.
7. Ali A, Creasy RH, Edge JA. The effect of graduated compression stockings on running performance. J Strength Cond Res. 2011;25:1385–92.
8. Gupta A, Bryers JJ, Clothier PJ. The effect of leg compression garments on the mechanical characteristics and performance of single-leg hopping in healthy male volunteers. BMC Sports Sci Med Rehabil. 2015;7:10.
9. Stickford AS, Chapman RF, Johnston JD, Stager JM. Lower leg compression, running mechanics and economy in trained distance runners. Int J Sports Physiol Perform. 2014;10:76–83.
10. Dascombe BJ, Hoare TK, Sear JA, Reaburn PR, Scanlan AT. The effects of wearing undersized lower-body compression garments

on endurance running performance. Int J Sports Physiol Perform. 2011;6:160–73.
11. Rimaud D, Messonnier L, Castells J, Devillard X, Calmels P. Effects of compression stockings during exercise and recovery on blood lactate kinetics. Eur J Appl Physiol. 2010;110:425–33.
12. Kraemer WJ, Bush JA, Bauer JA, Triplett-McBride NT, Paxton NJ, Clemson A, et al. Influence of compression garments on vertical jump performance in NCAA Division I volleyball players. J Strength Cond Res. 1996;10:180–3.
13. Doan BK, Kwon YH, Newton RU, Shim J, Popper EM, Rogers RA, et al. Evaluation of a lower-body compression garment. J Sports Sci. 2003;21:601–10.
14. Born DP, Holmberg HC, Goernert F, Sperlich B. A novel compression garment with adhesive silicone stripes improves repeated sprint performance—a multi-experimental approach on the underlying mechanisms. BMC Sports Sci Med Rehabil. 2014;6:21.
15. MacRae BA, Cotter JD, Laing RM. Compression garments and exercise: garment considerations, physiology and performance. Sports Med. 2011;41:815–43.
16. Born DP, Sperlich B, Holmberg HC. Bringing light into the dark: effects of compression clothing on performance and recovery. Int J Sports Physiol Perform. 2013;8:4–18.
17. Beliard S, Chauveau M, Moscatiello T, Cros F, Ecarnot F, Becker F. Compression garments and exercise: no influence of pressure applied. J Sports Sci Med. 2015;14:75–83.
18. Engel FA, Holmberg HC, Sperlich B. Is there evidence that runners can benefit from wearing compression clothing? Sports Med. 2016;46:1939–52.
19. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med. 2009;151:264–9.
20. Higgins JPT, Altman DG, Gøtzsche PC, Jüni P, Moher D, Oxman AD, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. BMJ. 2011;343:d5928.
21. Riley RD, Higgins JPT, Deeks JJ. Interpretation of random effects meta-analyses. BMJ. 2011;342:d549.
22. Borg GA. Perceived exertion. Exerc Sport Sci Rev. 1974;2:131–53.
23. Higgins JPT, Green S (editors). Cochrane handbook for systematic reviews of interventions version 5.1.0 [updated March 2011]. The Cochrane Collaboration, 2011. http://handbook.cochrane.org.
24. Peters JL, Sutton AJ, Jones DR, Abrams KR, Rushton L. Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. J Clin Epidemiol. 2008;61:991–6.
25. Egger M, Smith GD, Schneider M, Minder C, Mulrow C, Egger M, et al. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315:597–9.
26. Bernhardt T, Anderson GS. Influence of moderate prophylactic compression on sport performance. J Strength Cond Res. 2005;19:292–7.
27. Bringard A, Perrey S, Belluye N. Aerobic energy cost and sensation responses during submaximal running exercise-positive effects of wearing compression tights. Int J Sports Med. 2006;27:373–8.
28. Kemmler W, von Stengel S, Köckritz C, Mayhew J, Wassermann A, Zapf J. Effect of compression stockings on running performance in men runners. J Strength Cond Res. 2009;23:101–5.
29. Rider BC, Coughlin AM, Hew-Butler TD, Goslin BR. Effect of compression stockings on physiological responses and running performance in Division III collegiate cross-country runners during a maximal treadmill test. J Strength Cond Res. 2014;28:1732–8.
30. Scanlan AT, Dascombe BJ, Reaburn PRJ, Osborne M. The effects of wearing lower-body compression garments during endurance cycling. Int J Sports Physiol Perform. 2008;3:424–38.
31. Sperlich B, Haegele M, Achtzehn S, Linville J, Holmberg HC, Mester J. Different types of compression clothing do not increase sub-maximal and maximal endurance performance in well-trained athletes. J Sports Sci. 2010;28:609–14.
32. Wahl P, Bloch W, Mester J, Born DP, Sperlich B. Effects of different levels of compression during sub-maximal and high-intensity exercise on erythrocyte deformability. Eur J Appl Physiol. 2012;112:2163–9.
33. Rivas E, Smith JD, Sherman NW. Leg compressions improve ventilatory efficiency while reducing peak and post exercise blood lactate, but does not improve perceived exertion, exercise economy or aerobic exercise capacity in endurance-trained runners. Respir Physiol Neurobiol. 2017;237:1–6.
34. Lovell DI, Mason DG, Delphinus EM, McLellan CP. Do compression garments enhance the active recovery process after high-intensity running? J Strength Cond Res. 2011;25:3264–8.
35. Varela-Sanz A, España J, Carr N, Boullosa DA, Esteve-Lanao J. Effects of gradual-elastic compression stockings on running economy, kinematics, and performance in runners. J Strength Cond Res. 2011;25:2902–10.
36. Burden RJ, Glaister M. The effects of ionized and nonionized compression garments on sprint and endurance cycling. J Strength Cond Res. 2012;26:2837–43.
37. Driller MW, Halson SL. The effects of wearing lower body compression garments during a cycling performance test. Int J Sports Physiol Perform. 2013;8:300–6.
38. Ali A, Caine MP, Snow BG. Graduated compression stockings: physiological and perceptual responses during and after exercise. J Sports Sci. 2007;25:413–9.
39. Barwood MJ, Corbett J, Feeney J, Hannaford P, Henderson D, Jones I, et al. Compression garments: no enhancement of high-intensity exercise in hot radiant conditions. Int J Sports Physiol Perform. 2013;8:527–35.
40. Faulkner JA, Gleadon D, McLaren J, Jakeman JR. Effect of lower limb compression clothing on 400-m sprint performance. J Strength Cond Res. 2013;27:669–76.
41. Goh SS, Laursen PB, Dascombe B, Nosaka K. Effect of lower body compression garments on submaximal and maximal running performance in cold (10 °C) and hot (32 °C) environments. Eur J Appl Physiol. 2011;111:819–26.
42. Venckūnas T, Trinkūnas E, Kamandulis S, Poderys J, Grūnovas A, Brazaitis M. Effect of lower body compression garments on hemodynamics in response to running session. Sci World J. 2014;2014:1–10.
43. Treseler C, Bixby WR, Nepocatych S. The effect of compression stockings on physiological and psychological responses after 5-km performance in recreationally active females. J Strength Cond Res. 2016;30:1985–91.
44. Del Coso J, Areces F, Salinero JJ, González-Millán C, Abián-Vicén J, Soriano L, et al. Compression stockings do not improve muscular performance during a half-ironman triathlon race. Eur J Appl Physiol. 2014;114:587–95.
45. Areces F, Salinero JJ, Abian-Vicen J, González-Millán C, Ruiz-Vicente D, Lara B, et al. The use of compression stockings during a marathon competition to reduce exercise-induced muscle damage: are they really useful? J Orthop Sports Phys Ther. 2015;45:462–70.
46. Ménétrier A, Mourot L, Bouhaddi M, Regnard J, Tordi N. Compression sleeves increase tissue oxygen saturation but not running performance. Int J Sports Med. 2011;32:864–8.
47. Moher D, Hopewell S, Schulz KF, Montori V, Gøtzsche PC, Devereaux PJ, et al. CONSORT 2010 explanation and

elaboration: updated guidelines for reporting parallel group randomised trials. J Clin Epidemiol. 2010;10:28–55.
48. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol. 2013;4:863.
49. Knicker AJ, Renshaw I, Oldham ARH, Cairns SP. Interactive processes link the multiple symptoms of fatigue in sport competition. Sports Med. 2011;41:307–28.
50. Millet GY, Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. Sports Med. 2004;34:105–16.
51. Lattimer CR, Kalodiki E, Kafeza M, Azzam M, Geroulakos G. Quantifying the degree graduated elastic compression stockings enhance venous emptying. Eur J Vasc Endovasc Surg. 2014;47:75–80.
52. Ibegbuna V, Delis KT, Nicolaides AN, Aina O. Effect of elastic compression stockings on venous hemodynamics during walking. J Vasc Surg. 2003;37:420–5.
53. Dermont T, Morizot L, Bouhaddi M, Ménétrier A. Changes in tissue oxygen saturation in response to different calf compression sleeves. J Sport Med. 2015;2015:857904.
54. Liu R, Lao TT, Kwok YL, Li Y, Ying MTC. Effects of graduated compression stockings with different pressure profiles on lower-limb venous structures and haemodynamics. Adv Ther. 2008;25:465–78.
55. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc. 2000;32:70–84.
56. Poole DC, Jones AM. Oxygen uptake kinetics. Compr Physiol. 2012;2:933–96.
57. Faisal A, Dyson KS, Hughson RL. Prolonged ischaemia impairs muscle blood flow and oxygen uptake dynamics during subsequent heavy exercise. J Physiol. 2010;588:3785–97.
58. Grassi B, Gladden LB, Stary CM, Wagner PD, Hogan MC. Peripheral O_2 diffusion does not affect $V(O_2)$ on-kinetics in isolated insitu canine muscle. J Appl Physiol. 1998;85:1404–12.
59. Grassi B, Gladden LB, Samaja M, Stary CM, Hogan MC. Faster adjustment of O_2 delivery does not affect $V(O_2)$ on-kinetics in isolated in situ canine muscle. J Appl Physiol. 1998;85:1394–403.
60. Wilkerson DP, Rittweger J, Berger NJA, Naish PF, Jones AM. Influence of recombinant human erythropoietin treatment on pulmonary O_2 uptake kinetics during exercise in humans. J Physiol. 2005;568:639–52.
61. Ali A, Creasy RH, Edge JA. Physiological effects of wearing graduated compression stockings during running. Eur J Appl Physiol. 2010;109:1017–25.
62. Jones AM, Grassi B, Christensen PM, Krustrup P, Bangsbo J, Poole DC. Slow component of VO_2 kinetics: mechanistic bases and practical applications. Med Sci Sports Exerc. 2011;43:2046–62.
63. Berry MJ, McMurray RG. Effects of graduated compression stockings on blood lactate following an exhaustive bout of exercise. Am J Phys Med. 1987;66:121–32.
64. Nielsen HV. External pressure-blood flow relations during limb compression in man. Acta Physiol Scand. 1983;119:253–60.
65. Styf J. The influence of external compression on muscle blood flow during exercise. Am J Sports Med. 1990;18:92–5.
66. Sperlich B, Born DP, Kaskinoro K, Kalliokoski KK, Laaksonen MS. Squeezing the muscle: compression clothing and muscle metabolism during recovery from high intensity exercise. PLoS One. 2013;8:e60923.
67. Nishiyasu T, Nagashima K, Nadel ER, Mack GW. Human cardiovascular and humoral responses to moderate muscle activation during dynamic exercise. J Appl Physiol. 2000;88:300–7.
68. Billat LV. Use of blood lactate measurements for prediction of exercise performance and for control of training. recommendations for long-distance running. Sports Med. 1996;22:157–75.
69. Faude O, Kindermann W, Meyer T. Lactate threshold concepts: how valid are they? Sports Med. 2009;39:469–90.
70. Dittrich N, de Lucas RD, Maioral MF, Diefenthaeler F, Guglielmo LGA. Continuous and intermittent running to exhaustion at maximal lactate steady state: neuromuscular, biochemical and endocrinal responses. J Sci Med Sport. 2013;16:545–9.
71. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106:857–64.
72. Marcora SM, Staiano W. The limit to exercise tolerance in humans: mind over muscle? Eur J Appl Physiol. 2010;109:763–70.
73. Blanchfield AW, Hardy J, De Morree HM, Staiano W, Marcora SM. Talking yourself out of exhaustion: the effects of self-talk on endurance performance. Med Sci Sports Exerc. 2014;46:998–1007.