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SYSTEMATIC REVIEW

Is There Evidence that Runners can Benefit from Wearing Compression Clothing?

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Abstract

Background Runners at various levels of performance and specializing in different events (from 800 m to marathons) wear compression socks, sleeves, shorts, and/or tights in attempt to improve their performance and facilitate recovery. Recently, a number of publications reporting contradictory results with regard to the influence of compression garments in this context have appeared.

Objectives To assess original research on the effects of compression clothing (socks, calf sleeves, shorts, and tights) on running performance and recovery.

Method A computerized research of the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science was performed in September of 2015, and the relevant articles published in peer-reviewed journals were thus identified rated using the Physiotherapy Evidence Database (PEDro) Scale. Studies examining effects on physiological, psychological, and/or biomechanical parameters during or after running were included, and means and measures of variability for the outcome employed to calculate Hedges'g effect size and associated 95 % confidence intervals for comparison of experimental (compression) and control (non-compression) trials.

Results Compression garments exerted no statistically significant mean effects on running performance (times for a (half) marathon, 15-km trail running, 5- and 10-km runs, and 400-m sprint), maximal and submaximal oxygen uptake, blood lactate concentrations, blood gas kinetics, cardiac parameters (including heart rate, cardiac output, cardiac index, and stroke volume), body and perceived temperature, or the performance of strength-related tasks after running. Small positive effect sizes were calculated for the time to exhaustion (in incremental or step tests), running economy (including biomechanical variables), clearance of blood lactate, perceived exertion, maximal voluntary isometric contraction and peak leg muscle power immediately after running, and markers of muscle damage and inflammation. The body core temperature was moderately affected by compression, while the effect size values for post-exercise leg soreness and the delay in onset of muscle fatigue indicated large positive effects.

Conclusion Our present findings suggest that by wearing compression clothing, runners may improve variables related to endurance performance (i.e., time to exhaustion) slightly, due to improvements in running economy, biomechanical variables, perception, and muscle temperature. They should also benefit from reduced muscle pain, damage, and inflammation.

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Key Points

Runners with varying levels of performance wear compression clothing to improve this performance and facilitate recovery, and the present systematic review summarizes relevant findings published to date.

The effect size values indicate that application of compression garments during running and/or recovery exerts no beneficial effect on racing performance (400-m sprint—marathon), various physiological parameters or the performance of strength-related tasks during recovery from running.

Small positive effects were observed with respect to the time to exhaustion (in connection with incremental or step tests), running economy, biomechanical variables, clearance of blood lactate, perceived exertion, maximal voluntary isometric contraction, and peak leg muscle power immediately after running, as well as markers of muscle damage and inflammation.

The effect size values for post-exercise pain, damage, and inflammation in muscles indicated large positive effects of compression.

1 Introduction

Runners at various levels of performance and specializing in different events (from 800 m to marathons) wear socks, sleeves, shorts, and/or tights with compression to improve their performance [1–3] and facilitate recovery [4, 5]. To date, the effects of compression clothing have been examined with a variety of running protocols, including short-term submaximal treadmill running [6–11], incremental treadmill tests to exhaustion [12–17], 10-km races [1], time to exhaustion at the pace used during a 10-km race [18], and 10-km submaximal running [14]. Few such investigations have involved real-life or simulated running competitions exceeding 1 hour in duration and conducted outdoors [2, 3, 19, 20], while others have applied compression garments only during recovery from running for 12 [21], 48 [4, 22], or 72 [5] h.

Recently, a number of publications concerning the influence of compression garments on running performance and perception of different intensities and durations of running have reported contradictory findings. In some cases, time-trial performance improved [23], but not in others [1, 3, 25]. Time to exhaustion was either unchanged [12, 18, 24], increased [16], or reduced [13]. In certain studies physiological parameters such as blood concentrations of lactate during [8, 15] and after [13] running and oxygen uptake [13, 18] were influenced to a considerable extent by compression clothing, whereas in others blood levels of lactate [1, 2] and oxygen uptake [12, 16, 26] were not altered.

Reviews of statistical findings in this field have summarized the multiple effects of compression clothing on exercise and recovery in various disciplines [27–30]. As pointed out earlier [29], assessment of effectiveness based on traditional deductive statistics may be prejudiced, since significance can be achieved either by increasing the number of participants and/or decreasing the variance of data comparing control and treatment conditions [31, 32]. Accordingly, as sometimes done [29, 33–35], calculation of effect sizes (ES; [36]) allows effectiveness to be compared and the practical relevance of the application of compression clothing assessed.

The aims of the present systematic review were as follows: (1) to review the available literature concerning compression garments and running, (2) to calculate the effect sizes associated with various markers related to performance and recovery; (3) to identify evidence-based application of compression in connection with distance running; and (4) to develop recommendations concerning the use of compression for distance runners.

2 Methods

2.1 Data Sources and Literature Searching

A comprehensive computerized search of the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science was performed during September of 2015 employing the following keywords: athlete, endurance, endurance running, blood flow, blood lactate, compression, compression clothing, compression garment, compression stockings, running, long distance running, exercise, fatigue, garments, heart rate, muscle damage, pain, swelling, oscillation, oxygenation, oxygen uptake, performance, perceived exertion, power, recovery, strength, stroke volume, textiles, thermoregulation, time to exhaustion, and time trial. In addition, the reference lists of the articles thus identified and from other relevant articles of which we were aware were examined for additional relevant titles.

2.2 Study Selection and Quality Assessment

Original research articles in peer-reviewed journals that investigated any kind of lower-limb compression garment (i.e., knee-high socks, sleeves, shorts, or tights) or whole-body compression garments during and/or after long distance running were included. These studies assessed physiological (VO_{2max} (maximal oxygen uptake), VO_{2peak} (peak oxygen uptake), submaximal VO_2, blood lactate, post-exercise clearance of blood lactate, blood gases, cardiac parameters, inflammatory markers), biomechanical (ground contact time, step frequency, step length, swing time), psychological (rates of perceived exertion, perceived temperature, leg soreness), and/or performance parameters (running time, time to exhaustion, jump performance, maximal voluntary isometric contraction, peak leg muscle power). In the present analysis, we have only included data from investigations where (1) absolute values (means and measures of variability) were published or could be obtained from the authors and (2) both an experimental (compression) and a control group (non-compression) of runners at any level of performance (from untrained to elite) were included. Finally, only data concerning participants without any cardiovascular, metabolic, or musculoskeletal disorders were considered (Fig. 1).

Each study meeting our inclusion criteria was also evaluated by two independent reviewers according to the Physiotherapy Evidence Database (PEDro) Scale [37], where a "yes" answer adds 1 point, and "no" 0 points, and the maximal score is 10 points. This approach has been applied previously in connection with systematic reviews to assess methodological quality [38–40].

2.3 Statistical Analyses

To compare and quantify each parameter of performance and recovery, the ES (Hedges' g) and associated 95 % confidence interval were calculated as proposed by Glass [41]. Hedges' g was computed as the difference between the means of experimental (compression) and control (no compression) values divided by the average standard deviation for the population concerned [41]. To optimize the calculation of ES and estimate the standard deviation for Hedges' g, the standard deviations of the experimental and control groups at baseline were pooled [36]. In accordance with standard practice, the ES values obtained were then defined as trivial (<0.10), small (0.10–0.30), moderate (0.30–0.50), or large (>0.50) [32]. All statistical analyses were carried out in version 11.5.1.0 of the MedCalc software (MedCalc, Mariakerke, Belgium).

3 Results

3.1 Characteristics of the Studies Analyzed

Of the 643 studies initially identified, 32 (published between 1987 and 2015) were examined in detail (Fig. 1). Their average PEDro score was 6.5 (range 5–9). The participants and compression clothing, parameters measured, and protocols in each study are summarized in Table 1.

Thirty-two of these studies involved performance of different running protocols by a total of 494 participants (458 men and approximately 36 women (in one case, the number of women was not reported [1])). Twenty-four included only male participants, one only women, and the remaining seven included both. The mean sample size was 15.0 ± 7.7 (mean ± SD; range 6–36) and age 29.0 ± 7.2 (19–48) years.

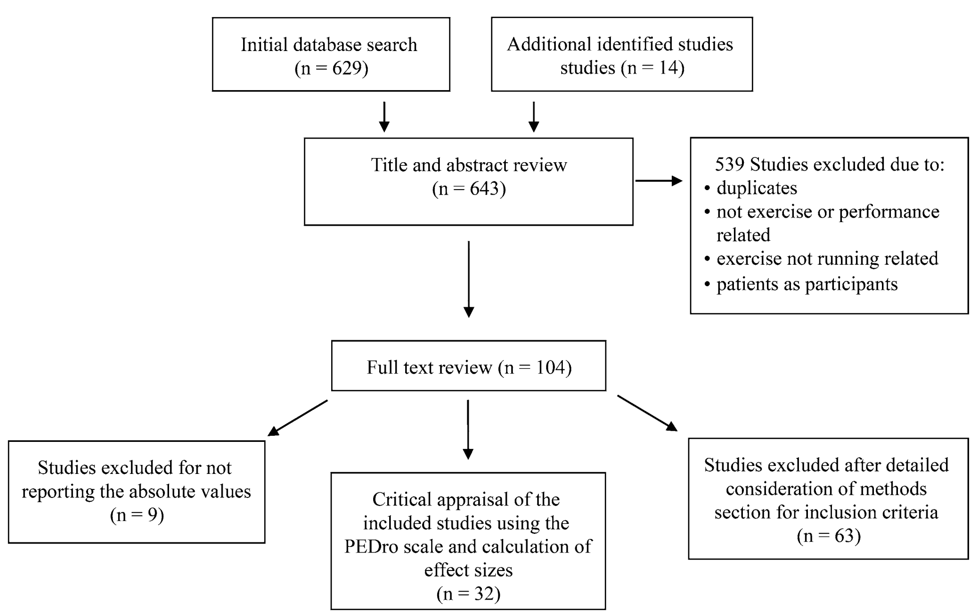

Fig. 1 Pathway of identified and subsequent excluded or reviewed articles. *PEDro* physiotherapy evidence database

Table 1 Summary of studies included in a systematic review of investigations into the effect of compression clothing on long-distance running performance and subsequent recovery

References (year)	Subjects (*n*), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing			Study protocol (occasion when compression was applied)	Effects of compression clothing
			Type of compression clothing	Pressure applied (mmHg)	Measure		
Areces et al. [2]	30 M, 41 ± 9 4 F, 41 ± 9	Experienced marathon runners (marathon PB: 03:20 ± 0:23 [h:min], VO_{2max}: n.i.)	Socks (G)	20–25 (manufacturer's information)	P, R	Marathon	P: Run time ↔, La ↔, RPE ↔ R: CMJ ↔, leg muscle power ↔, serum myoglobin ↔, CK ↔, leg soreness 24 h post-race ↑
Vercruyssen et al. [3]	11 M, 34 ± 10	Well-trained runners (VO_{2max}: 60.1 ± 6.5 $ml \cdot kg^{-1} \cdot min^{-1}$)	Socks	18	P, R	15.6-km trail run	P: Run time ↔, La ↔, HR ↔, RPE ↔, R: oxygenation profile VL ↔, MVC ↔, CMJ ↔
Bieuzen et al. (2014) [19]	11 M, 35 ± 10	Well-trained runners (VO_{2max}: 60.1 ± 6.5 $ml \cdot kg^{-1} \cdot min^{-1}$)	Calf compression sleeves (G)	P: 25/R: 20	P, R	15.6-km trail run	P: Run time ↔, HR ↔, RPE ↔ R: MVC ↑, CMJ ↑, perceived muscle soreness ↑, CK ↔, IL-6 ↔
Del Coso et al. [20]	36 M, 35 ± 5	Experienced triathletes (half Ironman PB: 303 ± 33 [min], VO_{2max}: n.i.)	Calf compression sleeves (G)	n.i.	P, R	Half Ironman triathlon (1.9 km swimming/75 km cycling/21.1 km running)	P: Race time ↔, velocity running ↔, RPE ↔, R: CMJ ↔, leg muscle power ↔, blood myoglobin ↔, CK ↔, serum LDH ↔, perceived muscle soreness ↔, temp ↔
Ali et al. [1]	12 M+F, 33 ± 10	Competitive runners (VO_{2max}: 68.7 ± 6.2 $ml \cdot kg^{-1} \cdot min^{-1}$)	Socks (G)	15, 21, 32	P, R	10 km TT	P: TT ↔, La ↔, CP ↔, RPE ↑↓, HR ↔ R: CMJ ↑↓
Barwood et al. (2013) [25]	8 M, 21 ± 2	Recreationally active individuals (VO_{2max}: n.i.)	(1) Correctly sized shorts (G) (2) Over-sized shorts (G)	(1) 11–20 (2) 10–17	P	15 min treadmill running at 35 °C and 10–12 $km \cdot h^{-1}$, 5 min rest followed by a 5-km TT at 35 °C	P: TT ↔, split time ↔, pacing profile ↔, RPE ↔, thermal responses ↔, perceptual thermal responses ↔, sweat production ↔, volume of water intake ↔
Ali et al. [23]	14 M, 22 ± 1	Amateur runners (1) VO_{2max}: 56.1 ± 0.4 $ml \cdot kg^{-1} \cdot min^{-1}$, (2) VO_{2max}: 55.0 ± 0.9 $ml \cdot kg^{-1} \cdot min^{-1}$	Socks (G)	18–22	P, R	2 × 20 m shuttle-runs (separated by 1 h) and 10-km TT	P: TT ↔, RPE ↔, HR ↔ R: DOMS ↑
Venckūnas et al. [42]	13 F, 25 ± 4	Recreationally physically active individuals (VO_{2max}: n.i.)	Tights	17–18	P, R	30-min (4-km) submaximal running followed by a 400-m sprint	P: 400-m sprint time ↔, HR ↔, RPE ↔, perceived sweating ↔, perceived thermal sensation ↔, skin temp ↑ (higher), body core temp↔ R: orthoclinostatic test ↔, BF ↔, tissue SO_2 ↔, leg BF during regeneration ↑

Table 1 continued

References (year)	Subjects (*n*), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing			Study protocol (occasion when compression was applied)	Effects of compression clothing
			Type of compression clothing	Pressure applied (mmHg)	Measure		
Varela-Sanz et al. [18]	13 M, 35 ± 7 3 F, 32 ± 5	Well-trained runners (VO_{2max} M: 65.9 ± 8.8; F: 59.5 ± 2.1 ml·kg^{-1}·min^{-1}; 10 km PB M: 37:14 ± 04:04; F: 43:09 ± 00:25 [min])	Socks (G)	15–22	P	TTE test: treadmill running at 105 % of a recent 10 km pace Running economy test: four consecutive trials of 6 min at recent half-marathon pace	P: TTE test: RE ↔, TTE ↔, La ↔, RPE ↔, VO_2 ↔, HR_{peak} ↔, $\%HR_{max}$ ↑, Kinematics ↔ Running economy test: TTE ↔, HR ↔, La ↔, RPE ↔, VO_2 ↔
Sperlich et al. [26]	15 M, 27 ± 5	Well-trained runners and triathletes (VO_{2max}: 63.7 ± 4.9 ml·kg^{-1}·min^{-1})	Socks, tights, WBC	20	P	15 min treadmill running at 70 % VO_{2max} followed by running to exhaustion at v_{max} of previous incremental test	P: VO_{2max} ↑, TTE ↔, VO_2 ↑↓, La ↔, pO_2 ↔, SO_2 ↔, RPE ↑
Dascombe et al. [15]	11 M, 28 ± 10	Well-trained runners and triathletes (VO_{2max}: 59.0 ± 6.7 ml·kg^{-1}·min^{-1})	Tights (G)	16–22, 14–19	P	Steptest and TTE test at 90 % VO_{2max}, $temp_{amb}$: 22°C ± 2 °C	P: VO_{2max} ↔, TTE ↔, VO_2 ↑↓, La ↔, HR ↔, RE ↔
Goh et al. [43]	10 M, 29 ± 10	Recreational runners (VO_{2max}: 58.7 ± 2.7 ml·kg^{-1}·min^{-1})	Tights (G)	9–14	P	20 min at 1st ventilatory threshold followed by run to exhaustion at VO_{2max} at 10 °C and 32 °C	P: TTE ↔
Ménétrier et al. [24]	11 M, 22 ± 1	Recreational endurance athletes (3.1 ± 0.3 h training per week, VO_{2max}: n.i.)	Calf compression sleeves (G)	15–27	P, R	Treadmill running: 15 min rest, 30 min at 60 % maximal aerobic velocity, 15 min passive recovery, running to exhaustion at 100 % maximal aerobic velocity and 30 min passive recovery	P: TTE ↔, HR ↔, RPE ↔ R: SO_2 calf during rest and recovery ↑
Kemmler et al. [16]	21 M, 39 ± 11	Moderately trained runners (VO_{2max}: 52.0 ± 6.1 ml·kg^{-1}·min^{-1})	Socks (G)	24	P	Incremental treadmill running test	P: TTE ↑, VO_{2max} ↔, La ↔, HR ↔

Table 1 continued

References (year)	Subjects (*n*), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing			Study protocol (occasion when compression was applied)	Effects of compression clothing
			Type of compression clothing	Pressure applied (mmHg)	Measure		
Rider et al. [13]	7 M, 21 ± 1, 3 F, 19 ± 1	Well-trained cross-country runners (VO_{2max}: 63.1–64.9 ± 7.0 ml·kg^{-1}·min^{-1}; M 8 km PB: 26:37 ± 00:56; F 5 km PB: 19:04 ± 00:39 [min:s])	Socks (G)	15–20 (manufacturer's information)	P	Ramped treadmill test (stage 1 at 160 m·min^{-1}, stage 2 at 160 m·min^{-1} and a 5 % grade; each subsequent stage increased by 26.8 m·min^{-1} and 1 % grade·min^{-1} until exhaustion)	P: HR ↔, La ↔, La threshold ↔, VO_2 ↔, RER ↔, RPE ↔, TTE ↓ R: La ↑
Wahl et al. [12]	9 M, 22 ± 1	Well-trained endurance athletes (VO_{2peak}: 57.7 ± 4.5 ml·kg^{-1}·min^{-1})	Three different types of socks (G)	(1) 11–21 (2) 20–31 (3) 36–45	P	Treadmill test: 30 min at 70 % of VO_{2peak} followed by a ramp test (1 % increase in grade·min^{-1}) until exhaustion while wearing compression	P: TTE ↔, erythrocyte deformability ↔, La ↔, HR ↔, pO2 ↔, VO_2 ↔,
Berry et al. [17]	6 M, 23 ± 5	Well-trained runners (1) VO_{2max}: 52.8 ± 8.0 ml·kg^{-1}·min^{-1}, (2) VO_{2max}: 59.9 ± 6.8 ml·kg^{-1}·min^{-1}	Socks (G)	8–18	P	Incremental treadmill test until exhaustion	P: VO_{2max} ↔, TTE ↔
Bringard et al. [45]	6 M, 31 ± 5	Well-trained runners (VO_{2max}: 60.9 ± 4.4 ml·kg^{-1}·min^{-1})	Tights	n.i.	P	Energy cost at 10, 12, 14, 16 km·h^{-1} ($temp_{amb}$ 31 °C) and 15 min treadmill running at 80 % VO_{2max}. $temp_{amb}$ 23.6 °C	P: VO_{2max} ↓, RPE ↔, temp ↔, metabolic efficiency ↑
Stickford et al. [6]	16 M, 22 ± 3	Highly trained runners (10,000 m PB: 29:22 ± 0:35; 5,000 m PB: 14:47 ± 1:02 [min:s], VO_{2max}: n.i.)	Calf compression sleeves (G)	15–20 (manufacturer's information)	P	3 × 4 min submaximal treadmill running at 3 constant speeds (233, 268, 300 m/min)	P: RE ↔, running mechanics ↔
Miyamoto et al. (2014) (I) [46]	11 M, 26 ± 4	Healthy young individuals (VO_{2max}: n.i.)	(1) Shorts (G) (2) Shorts (G)	(1) 7–9 (2) 14–15	P	Submaximal treadmill running for 34.5 min at 6–12 km·h^{-1}. Prior to and following the running exercise magnetic resonance images from the right thigh	(1) P: RPE ↑, R: T2 ↔ (2) P: RPE ↑, R: T2 ↑

Table 1 continued

References (year)	Subjects (*n*), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing			Study protocol (occasion when compression was applied)	Effects of compression clothing
			Type of compression clothing	Pressure applied (mmHg)	Measure		
Miyamoto et al. (II) [46]	11 M, 27 ± 2	Healthy young individuals (VO_{2max}: n.i.)	(1) Shorts (G) (2) Shorts (G)	(1) 18–22 (2) 23–28	P	Submaximal treadmill running for 34.5 min at 6–12 km·h^{-1}. Prior to and following the running exercise magnetic resonance images from the right thigh	(1) P: RPE ↔, R: T2 ↑ (2) P: RPE ↔, R: T2 ↑
Sperlich et al. [9]	15 M, 22 ± 1	Well-trained runners and triathletes (VO_{2max}: 57.2 ± 4.0 ml·kg^{-1}·min^{-1})	Socks (G)	10, 20, 30, 40	P	45 min treadmill running at 70 % of VO_{2max}	P: VO_2 ↔, La ↔, CP ↔, SO_2 ↔, HR ↔
Lovell et al. [8]	25 M, 22 ± 2	Semi-professional Rugby league players (3–5 training sessions per week, VO_{2max}: n.i.)	Tights (G)	15–20	P	30 min treadmill running (5 min stages at 6 km·h^{-1}, 10 km·h^{-1}, 85 % VO_{2max}, 6 km·h^{-1}, 85 % VO_{2max}, 6 km·h$^{-1)}$	P: Physiological parameters ↔, except: La ↑, RER higher at 10 km·h^{-1} ↓ RER higher at 85 % VO_{2max} ↓ La ↑, HR at 6 km·h^{-1} ↓ RER higher at 85 % VO_{2max} ↓ La ↑, HR ↑ at 6 km·h^{-1}
Rugg et al. [7]	8 M, 6 F, 28 ± 14	Competitive runners (VO_{2max}: n.i.)	Tights (G)	7–18 (manufacturer's information)	P, R	Three CMJ, 15 min continuous submaximal treadmill running (5 min at 50 %, 5 min at 70 %, 5 min at 85 % of HR reserve), three CMJ	P: RPE ↑, comfort level ↑ R: Post-run CMJ ↑
Ali et al. [44]	10 M, 36 ± 10	Highly trained runners and triathletes (VO_{2max}: 70.4 ± 6.1 ml·kg^{-1}·min^{-1})	Socks (G)	12–15, 23–32	P, R	40 min treadmill running at 80 % VO_{2max}	P: VO_2 ↔, La ↔, HR ↔, RPE ↔ R: CMJ ↔,
Cabri et al. [10]	6 M, 31 ± 7	Trained runners (5,000 m PB 1445 ± 233 s, VO_{2max}: n.i.)	Socks	n.i.	P, R	Submaximal running (5000 m) at a velocity of 85 % of 5,000 m PB	P: La ↔, HR ↑↓ R: La removal ↔
Valle et al. [47]	15 M, 25 (SD n.i.)	Amateur soccer players (VO_{2max}: 44.0 ± 7.6 ml·kg^{-1}·min^{-1})	Shorts	n.i.	R	40 min submaximal treadmill running with 10% decline	R: DOMS ↑, damage marker ↑

Table 1 continued

References (year)	Subjects (*n*), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing			Study protocol (occasion when compression was applied)	Effects of compression clothing
			Type of compression clothing	Pressure applied (mmHg)	Measure		
Miyamoto et al. [11]	15 M, 26 ± 3	Healthy young individuals (VO_{2max}: n.i.)	(1) Socks (G, low pressure) (2) Socks (G, high pressure) (3) Socks (uniform pressure distribution) (4) Socks (localized pressure)	(1) 14–18 (2) 21–27 (3) 21 (4) 10–21	R	30 min submaximal treadmill running	R: (2, 3, 4) T2 ↑
Bovenschen et al. [14]	13 M, 40 ± 16	Moderately trained runners (VO_{2max}: n.i.)	Socks (G)	25–35	R	10,000 m submaximal running Treadmill steptest until exhaustion	R: Lower leg volume after 10,000 m and treadmill run ↑, leg volume 10 min and 30 min after 10,000 m and treadmill run ↔, leg soreness ↔
Ferguson et al. [21]	21 M, 21 ± 1	Recreational active in intermittent sports (predicted VO_{2max}: 54 ± 5 $ml \cdot kg^{-1} \cdot min^{-1}$)	Socks (G)	20–40 (manufacturer's information)	P, R	90-min intermittent shuttle run test (3 × 20 m walking, 1 × 20 m sprint, 4 s recovery, 3 × 20 m at 75 % VO_{2max}, 3 × 20 m at 100 % VO_{2max}), subsequently wearing compression socks for 12 h	P: HR during exercise ↔ R: PMS ↑ (24 h post exercise), MVIC ↔, CK ↔, LDH↔, IL-6 ↔, CRP ↔
Armstrong et al. [4]	23 M, 10 F, 38 ± 7	Experienced marathon runners (marathon time: 03:58 ± 0:23 [h:min], VO_{2max}: n.i.)	Socks (G)	30–40 (manufacturer's information)	R, P	Wearing compression socks for 48 h after a marathon, TTE treadmill test 14 days after marathon	P: TTE ↑, HR_{max} ↔, RPE ↔
Hill et al. [5]	17 M, 7 F, 48 ± 11	Marathon runners (VO_{2max}: 53.8 ± 10.2 $ml \cdot kg^{-1} \cdot min^{-1}$; finish time: 03:46:45 ± 00:22:30 [h:min:s])	Tights	9.3–9.9	R	Wearing compression tights for 72 h after a marathon	R: PMS (24 h post) ↑, MVIC ↔, CK ↔, C-reactive protein ↔

Table 1 continued

References (year)	Subjects (n), sex, age (y) [mean ± SD]	Characteristics of participants[a] Study population	Characteristics of compression clothing: Type of compression clothing	Pressure applied (mmHg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Trenell et al. [22]	11 M, 21 ± 3	Recreational athletes (type of sport not specified, VO_{2max}: n.i.)	Tights (G)	10–17	R	30-min downhill treadmill walking (6 km·h^{-1}, 25 % grade; compression 48 h after exercise)	R: DOMS ↔, damage marker ↑↓

↔ no significant effect of compression, ↑ significant positive effect of compression, ↓ significant negative effect of compression, ↑↓ contradictory results: positive, as well as negative effects of compression, *BF* blood flow, *CK* creatine kinase, *CMJ* counter movement jump, *CP* cardiac parameters (HR, cardiac output, cardiac index, stroke volume), *CRP* c—reactive protein, *DOMS* delayed onset of muscle soreness, *F* female, *G* graduated, *HR* heart rate, HR_{max} maximum heart rate, HR_{peak} peak heart rate, *IL-6* interleukin 6, *La* blood lactate concentration, *LDH* lactate dehydrogenase, *M* male, *MVC* maximal voluntary contraction, *MVIC* maximal voluntary isometric contraction, *n.i.* not indicated, *P* performance, *PB* personal best, *PMS* perceived muscle soreness, pO_2 oxygen partial pressure, *R* recovery, *RE* running economy, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, SO_2 oxygen saturation, *T2* skeletal muscle proton transverse relaxation time, *TT* time trial, $temp_{amb}$ ambient temperature, *temp* body temperature, *TTE* time to exhaustion, V_{max} maximum running velocity, *VL* vastus lateralis, VO_2 oxygen uptake, VO_{2max} maximal oxygen uptake, VO_{2peak} peak oxygen uptake, *WBC* whole-body compression

[a] Highly trained—national/international level and VO_{2max} >65 mL·kg^{-1}·min^{-1}; well trained—VO_{2max} ≥50 mL·kg^{-1}·min^{-1}; moderately trained—VO_{2max} ≥45 mL·kg^{-1}·min^{-1} or running volume >30 km/week; recreational—running volume <30 km/week

The compression garments employed included knee-high socks ($n = 17$), tights ($n = 10$), knee-high calf sleeves ($n = 4$), shorts ($n = 3$), and tights and a long-sleeve shirt providing whole-body compression ($n = 1$). Sixteen studies included elite or well-trained subjects, 13 recreational athletes or participants competing at a regional level, and three involved untrained participants. In 26 of these investigations graduated compression, with pressure decreasing in the distal to proximal direction, was applied. Moreover, 27 provided information concerning the level of pressure exerted (7–40 mmHg), six included no such information, and five referred to information from the manufacturer on this matter (Table 1).

The various ESs relating to the effects of applying compression clothing during running and recovery are illustrated in Fig. 2.

3.2 Analysis of Performance

Altogether, the findings indicate that compression clothing has little or no positive effect (mean $g = 0.03 \pm 0.15$; range −0.23 to 0.23 [1–3, 19, 20, 23, 25, 42]) on running performance (Table 1), as reflected in the times for a (half) marathon, 15-km trail running, 5- and 10-km runs and 400-m sprint. Of the 11 studies in which the time to exhaustion in incremental or step tests or runs until exhaustion were examined, seven reported small mean effects of compression garments on variables related to performance (mean $g = 0.27 \pm 0.33$; range 0.01–0.96 [4, 13, 15–17, 26, 43]). Three studies documented a moderate-to-large effect of compression garments ($g = 0.39$ [16]; $g = 0.41$ [43]; $g = 0.96$ [4]), whereas four found small negative effects on the time to exhaustion (mean g −0.22 ± 0.11; range −0.31 to −0.07 [12, 15, 18, 24]).

3.3 Running Economy

In the four investigations that evaluated the influence of calf compression sleeves [6], compression socks [18], compression tights [15], or three different compression garments (socks, tights, whole-body compression) [26] on the running economy of well-trained and highly trained runners, a small positive effect was observed (mean $g = 0.21 \pm 0.38$; range 0.00–0.88).

3.4 Biomechanical Parameters

Compression sleeves [6] and stockings [18] exerted a small positive effect (mean $g = 0.21 \pm 0.38$; range −0.33 to 0.72 [6, 18]) on biomechanical parameters (i.e., ground contact time, step frequency, step length, and swing time).

3.5 Physiological Parameters During Running

Whereas maximal oxygen uptake was not affected in most cases (mean $g = 0.05 \pm 0.35$; range −0.28 to 1.16 [9, 12, 13, 15–18, 26]), one study found a large positive effect on this parameter in well-trained runners performing a test to exhaustion (best $g = 1.16$ [18]). In the case of parameters related to endurance, such as submaximal oxygen uptake (mean $g = -0.01 \pm 0.10$; range −0.21 to 0.16 [6, 8, 15, 26, 44]), compression clothing had no effects. In most cases there were no effects on blood lactate concentrations either (mean $g = -0.04 \pm 0.33$; range −0.96 to 0.54 [1–3, 8–10, 12, 15, 16, 18, 26, 44]), although two studies reported moderate positive effects on this parameter (mean $g = 0.49 \pm 0.33$; range 0.46–0.54 [8, 15]).

Neither blood saturation and partial pressure of oxygen (mean $g = -0.05 \pm 0.20$; range −0.37 to 0.31 [9, 12, 26] nor cardiac parameters, including heart rate, cardiac output, cardiac index, and stroke volume, were influenced to any great extent by the compression garments (mean $g = 0.08 \pm 0.37$; range −0.48 to 1.77 [1, 3, 8–10, 12, 13, 15, 16, 18, 19, 21, 24, 42, 44]), although two studies did observe moderate-to-large positive effects on maximal heart rate ($g = 1.77$ [18]) and heart rate during submaximal running ($g = 0.53$ [10]).

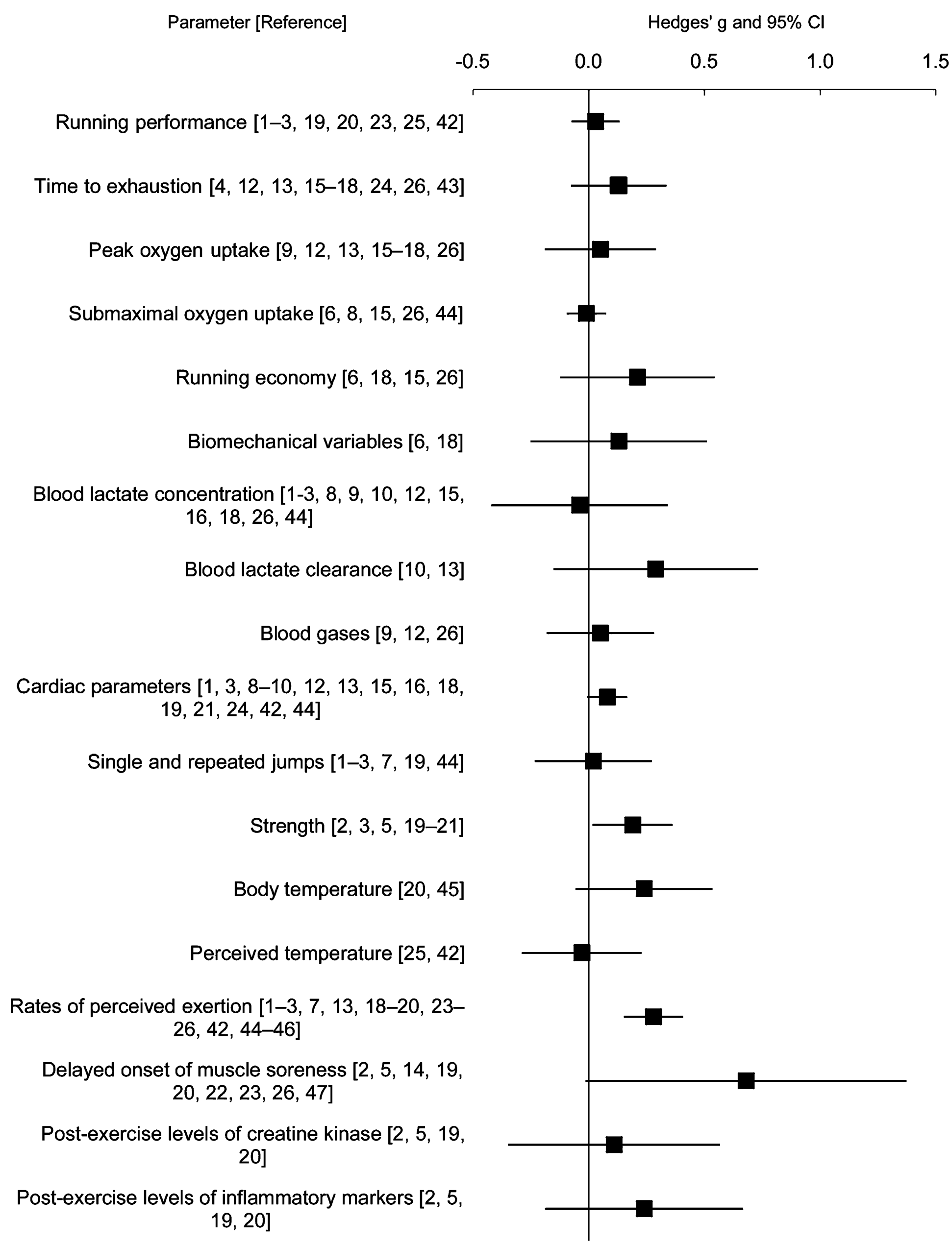

Fig. 2 Hedges' g effect sizes (*square*) and associated 95 % confidence interval (*lines*) of the application of compression clothing according to various markers of performance and recovery during and after running

3.6 Body and Perceived Temperature

Body core temperature during and after running was affected to small and moderate extents by compression clothing in two studies [20, 45], with no effect on body temperature ($p = 0.00$) (mean $g = 0.24 \pm 0.21$; range 0.00–0.41 [20, 45]). Although in one case the perceived temperature during running with compression was not altered ($g = 0.00$ [25]), Venckūnas and colleagues [42] detected a moderate negative effect on perceived body temperature during 30 min of submaximal running ($g = -0.32$).

3.7 Psychological Variables While Running

The overall effect of compression clothing on perceived exertion during running was small but positive (mean $g = 0.28 \pm 0.38$; range −0.31 to 1.21 [1–3, 7, 13, 18–20, 23–26, 42, 44–46]), although certain investigations showed moderate-to-large positive effects [2, 23, 26, 45] and others small-to-moderate negative [19, 20] or no effects [7, 13, 18, 24, 25, 42].

3.8 Responses After Running

3.8.1 Recovery of Parameters Related to Performance

The present analysis revealed trivial, small, moderate, and large positive, as well as small and large negative effects on recovery in strength-related tasks such as jumping after running (mean $g = 0.02 \pm 0.33$; range −0.64–0.53 [1–3, 7, 19, 44]). Single and repeated jumping performance (counter movement jump) following different running protocols was associated with small to large negative effects [1], as well as small [7, 20], moderate [19], and large [3] positive effects.

Maximal voluntary isometric contraction and peak leg muscle power immediately after running were somewhat greater with than without compression garments (mean $g = 0.19 \pm 0.22$; range −0.05 to 0.53 [2, 3, 5, 19–21]). Leg strength following running protocols as reflected in maximal voluntary (isometric) contractions and isometric knee extensor torque, showed trivial negative effects [3, 21], as well as trivial [2], small [19, 20], moderate [5], and large [3] positive effects.

3.8.2 Clearance of Blood Lactate

Clearance of blood lactate following running exhibited a small positive effect (mean $g = 0.29 \pm 0.32$; range −0.02 to 0.62 [10, 13]).

3.8.3 Markers of Muscle Damage

On average, compression clothing exerted a small effect on post-exercise levels of creatine kinase, a marker for muscle-damage (mean $g = 0.11 \pm 0.47$; range −0.42 to 0.73 [2, 5, 19, 20]. In three studies this effect was moderate-to-large and positive (range 0.35–0.73 [2, 5, 20] and in another small-to-moderate negative at three different time-points (1, 24, and 48 h) after exercise [19]. For other markers of muscle damage, such as serum levels of myoglobin, interleukin 6, and C-reactive protein, both trivial negative [19] as well as trivial, moderate, and large positive effects were detected [2, 5, 19, 20]. The overall average ES for different inflammatory markers was small and positive (mean $g = 0.24 \pm 0.44$; range −0.09 to 1.14 [2, 5, 19, 20]).

3.8.4 Perceived Muscle Soreness

Compression exerted a large positive effect on post-exercise leg soreness and delay in the onset of muscle fatigue (mean $g = 0.67 \pm 1.06$; range −0.44 to 3.80 [2, 5, 14, 19, 20, 22, 23, 26, 47]).

4 Discussion

Compression clothing led to trivial [1, 3, 19, 20, 25, 42] and small [1, 2, 20, 23] ES values in connection with running performance (400 m to 42,195 km). Comparable ES values for improving time to exhaustion were obtained in eight studies [12, 13, 15, 18, 24, 43], whereas three others reported moderate-to-large values [4, 16, 43]. This degree of improvement is in line with that reported by Born and colleges [29], as well as with the influence of compression garments on performance in other disciplines such as cycling and repeated sprinting.

From a physiological point of view and depending on the duration and environmental conditions, performance during running is determined mainly (although not exclusively) by the athlete's peak oxygen uptake, fractional utilization of VO_{2peak}, velocity at the lactate threshold, running economy (including biomechanical factors [48], and heat exchange processes [49]). Other physiological mechanisms of relevance in this context include enhanced hemodynamics, i.e., elevated venous return [50, 51], arterial inflow [52], and lymphatic outflow [53]. Since our statistical analysis revealed that the ES between compression and non-compression running for peak oxygen uptake, oxygen uptake, and blood lactate was trivial, a runner will most probably not benefit from compression in these respects.

However, the small positive ES for body temperature, running economy, and biomechanical variables during running indicate a potential (small) benefit of compression with regard to running economy (due potentially to altered biomechanics). This is consistent with previous reports [28, 29] that compression clothing improves neuro-mechanical parameters, including lower presynaptic inhibition [54, 55] and coordinative function [56], as well as recruitment of fewer muscle fibers [45, 57].

In contrast to performance and physio-biomechanics, compression appears to exert positive effects on the psychological parameters examined, i.e., a small positive effect on perceived exertion [1–3, 7, 13, 18–20, 23–26, 42, 44–46], as well as a large positive effect regarding leg soreness [2, 5, 14, 19, 20, 22, 23, 26, 47] both during running and recovery. As described previously [29], this psychological improvement may be a result of (1) attenuated oscillatory displacement of the leg muscles [57, 58], (2) a reduction in the number of muscle fibers recruited [59], (3) less structural damage to muscles [47, 60], and/or (4) improved lymphatic outflow leading to less muscle swelling and, thereby, greater comfort [53]. Since it is difficult to design an appropriate placebo condition for wearing compression garments, the possibility that the improvement in psychological parameters is influenced by more positive perceptions and the participants' intuitions concerning the results to be expected cannot be excluded.

The mean serum levels of creatine kinase were reduced in all of the studies (small ES), indicating that compression may help diminish structural damage to muscle and facilitate the clearance of metabolites through improved lymphatic outflow. The analytical review by Hill and colleagues [30] found higher (moderate) ES values for post-exercise levels of creatine kinase, but their investigation involved vertical jumping, repeated sprinting, and resistance training, rather than running. These effects have been attributed to attenuated release of creatine kinase into the blood and improved clearance of metabolites [61], as well as better muscle repair [62]. Furthermore, improvement of the pump function of muscles by compression clothing (described in detail by Born et al. 2013 [29]) may enhance circulation and thereby removal of creatine kinase. In this connection it is important to note that we also calculated increases (small ES) in the temperatures of both muscles and the whole body [20, 45] with compression. Since biochemical processes are controlled by temperature, these changes may also contribute to the differences in physiological and psychological variables.

The various hemodynamic (venous return and arterial inflow) and neural mechanisms and mechanical properties by which compression enhances performance and recovery have been described in detail previously [28, 29]. Since the methods (apparatus, study design, intensity and duration of running, range of compression) employed in the different studies examined here varied, we have refrained from meta-analysis. However, unlike Born [29], we have focused on running only and the reasonably large number of studies ($n = 32$) involving 494 participants analyzed here provides an adequate overview (Fig. 2) of the responses of various parameters of importance for running performance and recovery to compression.

5 Conclusions

On the basis of the mean ES-values for variables related to performance and recovery calculated from 32 studies, we conclude that compression exerts a trivial mean effect on running performance (times for a (half) marathon, 15-km trail running, 5- and 10-km runs and 400-m sprint), maximal and submaximal oxygen uptake, blood lactate concentrations, blood gas kinetics, cardiac parameters (including heart rate, cardiac output, cardiac index, and stroke volume), and body and perceived temperature, or on the performance of strength-related tasks after running. Small positive effects were observed for the time to exhaustion (in incremental or step tests), running economy (including the biomechanical variables ground contact time, step frequency, step length, and swing time), clearance of blood lactate, perceived exertion, maximal voluntary isometric contraction and peak leg muscle power immediately after running, and markers of muscle damage and inflammation. Body core temperature was calculated to be moderately affected by compression. The ES values for post-exercise leg soreness and the delay in onset of muscle fatigue indicated large positive effects of compression.

Apparently, by wearing compression garments runners might slightly improve variables related to endurance performance (i.e., time to exhaustion), due to improvements in running economy, biomechanical variables, perception, and muscle temperature. They should also benefit from reduced muscle pain, damage, and inflammation during recovery.

Compliance with Ethical Standards

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Conflict of interest Florian Engel, Hans-Christer Holmberg, and Billy Sperlich declare that they have no conflicts of interest relevant to the content of this review.

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