Effects of Compression Garments on Performance and Recovery in Endurance Athletes

Florian Engel, Christian Stockinger, Alexander Woll and Billy Sperlich

Abstract Athletes specializing in different endurance sports at various levels of performance wear compression garments to improve their performance and facilitate recovery. The purpose of this chapter is outline the effects of compression garments on performance and recovery in endurance disciplines. A computerized research of the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science (performed in December 2015) and articles published in peer-reviewed journals were analyzed. Studies examining effects on performance, recovery, physiological, and/or psychological parameters during or after endurance sports comparing experimental (compression) and control (non-compression) trials were investigated. A total of 55 articles involving 788 participants were included. Compression garments exerted no significant improvements on performance in running (400 m–42.195 km), triathlon, ice speed skating, cross country skiing, and kayaking. Maximal and submaximal oxygen uptake, blood lactate concentrations, blood gas analysis, cardiac parameters, and body temperature were not altered in most of the considered studies during endurance exercise. Also in most studies, perceived exertion as well as perceived temperature were not affected by compression. Compression clothing significantly increased cycling performance, post exercise blood lactate elimination and reductions in blood lactate concentration during running, cycling, and cross country skiing. Three studies observed improved muscular oxygenation following and during endurance exercise. Furthermore, compression garments reduced post-exercise muscle soreness following running and cycling in eight studies. We conclude that compression clothing has no

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significant impact on performance parameters during running, ice speed skating, triathlon, cross country skiing and kayaking. The wearing of compression clothing might improve cycling performance, reduce post-exercise muscle pain following running and cycling, and facilitate lactate elimination during recovery.

Keywords Blood flow · Compression clothing · Muscle damage · Oscillation · Performance · Recovery · Venous hemo-dynamics

Introduction

Elite endurance athletes specializing in different endurance sports e.g. cycling, running, or cross country skiing wear socks, sleeves, shorts, tights, and/or shirts or long sleeves shirts or whole body suits with compression to improve their performance and facilitate recovery. Companies promote the application of compression clothing and advertise ergogenic effects, improved recovery and perception. Accordingly, athletes and coaches consider compression clothing as an external aid to provide benefits for endurance performance and recovery.

Various mechanisms have been suggested to explain the ergogenic potential and improved recovery in endurance athletes including: diminished muscular micro-trauma due to reduced tissue vibrations during exercise (Friesenbichler et al. 2011; Valle et al. 2013); reduced muscle fiber recruitment causing less energy expenditure (Bringard et al. 2006; Kraemer et al. 1998); improved neuromechanics (i.e. reduced presynaptic inhibition) (Perlau et al. 1995; Bernhardt and Anderson 2005) and enhanced coordinative function (Birmingham et al. 1998). During recovery improved hemodynamics (venous return) (Ibegbuna et al. 2003; Lawrence and Kakkar 1980); arterial inflow (Bochmann et al. 2005) and lymphatic outflow (Kraemer et al. 2001) are thought to accelerate removal of metabolic waste products and reduce edema (Hirai et al. 2002; Partsch et al. 2008; Bovenschen et al. 2013). The improved perception by wearing compression clothing (Ali et al. 2007; Cipriani et al. 2014) increases the general comfort during exercise and reduces perceived exertion (Sperlich et al. 2010; Rugg and Sternlicht 2013).

However, to date most studies revealed no effects of compression clothing on performance variables (Del Coso et al. 2014; Barwood et al. 2013; Areces et al. 2015; Bieuzen et al. 2014; Born et al. 2014; Rider et al. 2014; Sperlich et al. 2014; MacRae et al. 2012; Ali et al. 2011), on oxygen uptake (Born et al. 2014; Rider et al. 2014; Sperlich et al. 2014; Dascombe et al. 2011; Rimaud et al. 2010), or on heart rate (Bieuzen et al. 2014; Vercruyssen et al. 2014; Rimaud et al. 2010) during or following endurance exercise.

The aims of this chapter is (i) to review the literature concerning compression garments applied during or following endurance dominated sports; (ii) to summarize the effects associated with various markers related to performance and recovery; (iii) to identify evidence-based application of compression in connection with endurance dominated disciplines; and (iv) to develop recommendations concerning the use of compression for endurance athletes and coaches.

Data Sources and Literature Searching

A comprehensive computerized search of the electronic databases PubMed, MEDLINE, SPORTDiscus, and Web of Science was performed during December of 2015 employing the following key words: *athlete, endurance, endurance running, endurance cycling, 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 as which we were previously aware were examined for additional relevant titles.

Study Selection and Quality Assessment

Original research articles in peer-reviewed journals that investigated any kind of compression garment (i.e., knee-high socks, sleeves, shorts, tights, shirts, long sleeve shirts or whole body compression garment) during and/or after endurance

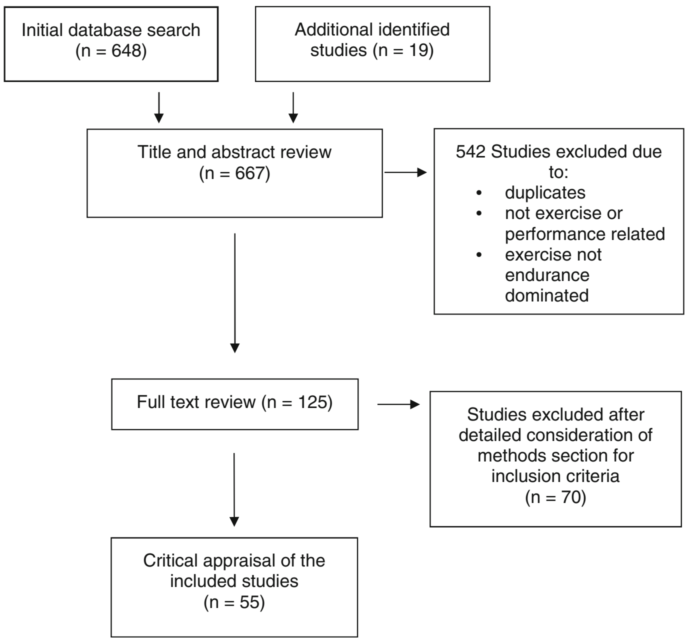

Fig. 1 Pathway of identified and subsequent excluded or reviewed articles

dominated exercise were included. These studies assessed physiological, psychological, and/or performance parameters. Only those articles presenting absolute values (means and measures of variability) of an experimental (compression) and a control group (non-compression) of participants at any level of performance (from untrained to elite) or where such missing data could be obtained from the authors were analyzed. Finally, only data concerning participants without any cardiovascular, metabolic, or musculoskeletal disorders were considered (Fig. 1).

Results

Characteristics of the Studies Analyzed

Of the 648 studies initially identified, 55 were examined in detail (Fig. 1). The participants as well as kind of compression clothing, parameters measured, and protocols of each study are summarized in Tables 1, 2 and 3.

The examined studies involved different protocols in following endurance dominated sports: running (n = 36), cycling (n = 15), triathlon (n = 1), kayak (n = 1), ice speed skating (n = 1), cross-country skiing (n = 1). Analyzed 55 studies involved a total of 788 participants (approx. 686 men and approx. 102 women (in two cases, the number of women was not reported)) (Ali et al. 2011; Cipriani et al. 2014). Forty-one studies included only male participants, one only woman, and the remaining 13 both sexes. The mean sample size was 14.3 ± 7.8 (mean ± SD, range: 6–36) and mean age was 28.7 ± 9.9 (19–63) years.

The compression garments applied included knee-high socks (n = 22), tights (n = 17), knee-high calf sleeves (n = 5), shorts (n = 4), shirt (n = 2), long sleeve shirt (n = 2), whole-body compression consisting of tights and a long-sleeve shirt (n = 2), respective whole body compression suit (n = 1), kind of compression garment not indicated (n = 1). Thirty studies included highly-trained (national/international level and $VO_{2max} > 65$ mL kg^{-1} min^{-1}) or well-trained subjects ($VO_{2max} \geq 50$ mL kg^{-1} min^{-1}), 22 moderately trained or recreational athletes, and three involved untrained participants. In 40 of these investigations graduated compression, i.e. pressure decreasing in the distal to proximal direction, was applied. Moreover, 44 investigations provided information concerning the level of pressure exerted (6–45 mm Hg), 11 included no such information, and 13 referred to the manufacturer's information (Tables 1, 2 and 3).

Analysis of Endurance Performance

None of the considered studies revealed significant improvements of compression clothing on running performance (Areces et al. 2015; Zaleski et al. 2015; Bieuzen et al. 2014; Del Coso et al. 2014; Venckūnas et al. 2014; Vercruyssen et al. 2014;

Table 1 Summary of the studies included: investigations on the effect of compression clothing on performance during and recovery from long-distance running

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Areces et al. (2015)	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	Run time ↔, CMJ ↔, leg muscle power ↔, serum myoglobin ↔, CK ↔, RPE ↔, leg soreness 24 h postrace ↑, La ↔
Armstrong et al. (2015)	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)	P, R	Wearing compression socks for 48 h after a marathon, TTE treadmill test 14 days after marathon	TTE ↑, HR_{max} ↔, RPE ↔
Miyamoto and Kawakami (2015)	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)	n.i.	R	30 min submaximal treadmill running	(1) T2 ↔ (2, 3, 4) T2 ↑
Priego et al. (2015)	13, M, 7, F, 22 ± 5	Recreational runners (37 ± 9 km/week; VO_{2max}: n.i.)	Socks (G)	21–24 (manufacturer's information)	P	10 min warm-up, 30 min 80 % MAS on treadmill	VO_2 ↔, HR ↔, RPE ↔
Priego Quesada et al. (2015)	29, M, 15, F, 29 ± 6	Recreational runners (38.5 ± 16.3 km running training/week, VO_{2max}: n.i.)	Socks (G)	20–25 (manufacturer's information)	R	10 min warm-up, 20 min 75 % MAS, 3 min 60 % MAS, 1 min 5 km h^{-1} on treadmill	Skin temp ↑, HR ↔, RPE↔

(continued)

Table 1 (continued)

Reference	Size, gender, age (year)	Characteristics of participants Study population	Characteristics of compression clothing Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Stickford et al. (2015)	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)	RE ↔, running mechanics ↔
Zaleski et al. (2015)	10, M,10, F, 36 ± 8	Recreational marathon runners (VO_{2max}: n.i.)	Socks (G)	19–25 (manufacturer's information)	P, R	Marathon	Run time ↔, coagulatory factors ↔, fibrinolytic factors ↑
Bieuzen et al. (2014)	11, M, 35 ± 10	Well-trained runners (VO_{2max}: 60.1 ± 6.5 mL • kg^{-1} • 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 ↔
Ferguson et al. (2014)	21, M, 21 ± 1	Recreational active in intermittent sports (predicted VO_{2max}: 54 ± 5 mL • kg^{-1} • min^{-1})	Socks (G)	20–40 (manufacturer's information)	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}) without compression, subsequently wearing compression socks for 12 h	PMS ↑ (24 h post exercise), MVIC ↔, CK ↔, LDH↔, IL-6 ↔, CRP ↔, HR during exercise ↔

(continued)

Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Hill et al. (2014b)	17, M, 7, F, 48 ± 11	Marathon runners (VO_{2max}: 53.8 ± 10.2 mL • kg^{-1} • min^{-1}; marathon 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	PMS (24 h post) ↑, MVIC ↔, CK ↔, C-reactive protein ↔
Miyamoto and Kawakami (2014) (I)	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 and following the running exercise magnetic resonance images from the right thigh	(1) RPE ↑, T2 ↔ (2) RPE ↑, T2 ↑
Miyamoto and Kawakami (2014) (II)	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 and following the running exercise magnetic resonance images from the right thigh	(1) RPE ↔, T2 ↑ (2) RPE ↔, T2 ↑
Rider et al. (2014)	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, R	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 ↑

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Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Rugg and Sternlicht (2013)	8, M, 6, F, 28 ± 14	Competitive runners (VO_{2max}: n.i.)	Tights (G)	7–18 (manufacturer's information)	P, R	3 CMJ, 15 min continuous submaximal treadmill running (5 min at 50 %, 5 min at 70 %, 5 min at 85 % of HR reserve), 3 CMJ	Post-run CMJ ↑, RPE ↑, comfort level ↑
Venckūnas et al. (2014)	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	400-m sprint time ↔, HR ↔, orthoclinostatic test ↔, BF ↔, tissue SO_2 ↔, Leg BF during regeneration ↑, RPE ↔, perceived sweating ↔, perceived thermal sensation ↔, skin temp ↑ (higher), body core temp↔
Vercruyssen et al. (2014)	11, M, 34 ± 10	Well-trained runners (VO_{2max}: 60.1 ± 6.5 mL • kg^{-1} • min^{-1})	Socks	18	P, R	15.6 km trail run	P: Run time ↔, La ↔, HR ↔, RPE ↔, MVC ↔, CMJ ↔
Barwood et al. (2013)	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 h^{-1}, 5 min rest followed by a 5 km TT at 35 °C	TT ↔, split time ↔, pacing profile ↔, RPE ↔, thermal responses ↔, perceptual thermal responses ↔, sweat production ↔, volume of water intake ↔
Bovenschen et al. (2013)	13, M, 40 ± 16	Moderately trained runners (VO_{2max}: n.i.)	Socks (G)	25–35	R	10.000 m submaximal running	Lower leg volume after 10.000 m and treadmill

(continued)

Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
						Treadmill steptest until exhaustion	run ↑, leg volume 10 min and 30 min after 10.000 m and treadmill run ↔, leg soreness ↔
Valle et al. (2013)	15, M, 25 (SD n.i.)	Amateur soccer players (VO_{2max}: 44.0 ± 7.6 mL • kg^{-1} • min^{-1})	Shorts	n.i.	P	40 min submaximal treadmill running with 10 % decline	DOMS ↑
Wahl et al. (2012)	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	Erythrocyte deformability ↔, La ↔, HR ↔, pO2 ↔, VO_2 ↔, TTE ↔
Ali et al. (2011)	12, M + F, 33 ± 10	Competitive runners (VO_{2max}: 68.7 ± 6.2 mL • kg^{-1} • min^{-1})	Socks (G)	15, 21, 32	P, R	10.000 m TT	TT ↔, La ↔, CP ↔, CMJ ↑↓, RPE ↑↓, HR ↔
Dascombe et al. (2011)	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 ± 2 °C	VO_{2max} ↔, TTE ↔, VO_2 ↑↓, La ↔, HR ↔, RE ↔

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Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Goh et al. (2010)	10, M, 29 ± 10	Recreational runners (VO_{2max}: 58.7 ± 2.7 $mL \cdot kg^{-1} \cdot min^{-1}$)	Tights (G)	9–14	P	20 min at 1st ventilatory threshold followed by run to exhaustion at VO_{2max} at 10 and 32 °C	TTE ↔
Lovell et al. (2011)	25, M, 22 ± 2	Semi-professional Rugby league players (3–5 training sessions/week, VO_{2max}: n.i.)	Tights (G)	15–20	P, R	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 $h^{-1)}$	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}

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Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Ménétrier et al. (2011)	11, M, 22 ± 1	Recreational endurance athletes (3.1 ± 0.3 h training/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 ↑
Sperlich et al. (2011)	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}	VO_2 ↑↓, La ↔, CP ↑↓, SO_2 ↔, HR ↑
Varela-Sanz et al. (2011)	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 PB. Running economy test: 4 consecutive trials of 6 min at recent half marathon PB	TTE test: RE ↔, TTE ↔, La ↔, RPE ↔, VO_2 ↔, HR_{peak} ↔, % HR_{max} ↑, Kinematics ↔ Running economy test: TTE ↔, HR ↔, La ↔, RPE ↔, VO_2 ↔
Ali et al. (2010)	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}	VO_2 ↔, La ↔, HR ↔, CMJ ↔, RPE ↔
Cabri et al. (2010)	6, M, 31 ± 7	Trained runners (5000 m PB 1445 ± 233 s, VO_{2max}: n.i.)	Socks	n.i.	P, R	Submaximal running (5000 m) at a velocity of 85 % of 5000 m PB	La ↔, La removal post test ↔, HR ↑↓

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Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Sear et al. (2010)	8, M, 21 ± 1	Team amateur athletes (VO_{2max}: 57.5 ± 3.7 mL • kg^{-1} • min^{-1})	WBC	n.i.	P	45 min high-intensity interval treadmill running	TTE ↑, VO_2 ↑↓, La ↔
Sperlich et al. (2010)	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	VO_{2max} ↔, TTE ↔, VO_2 ↔, La ↔, pO_2 ↔, SO_2 ↔, RPE ↑, ↑, muscle soreness ↔
Kemmler et al. (2009)	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	TTE ↑, VO_{2max} ↔, La ↔, HR ↔
Ali et al. (2007)	14, M, 22 ± 1	Amateur runners (1) VO_{2max}: 56.1 ± 0.4 mL • kg^{-1} • min^{-1}, (2) VO_{2max}: 55.0 ± 0.9 mL • kg^{-1} • min^{-1}	Socks (G)	18–22	P, R	(1) 2 × 20 m shuttle-runs (separated by 1 h) (2) 10 km TT	(1) Performance ↔, physiological parameters ↔, (2) TT ↔, RPE ↔, DOMS ↑, HR ↔
Bringard et al. (2006)	6, M, 31 ± 5	Well-trained runners (VO_{2max}: 60.9 ± 4.4 mL • kg^{-1} • min^{-1})	Tights	n.i.	P, R	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	VO_{2max} ↓, RPE ↔, temp ↔

(continued)

Table 1 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Trenell et al. (2006)	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)	DOMS ↔, damage marker ↑↓
Berry and McMurray (1987)	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, R	(1) Incremental treadmill test until exhaustion (2) 3 × 3 min cycling at 110 % VO_{2max}	(1) P: VO_{2max} ↔, TTE ↔ R: La ↑, VO_2 ↔ (2) R: VO_2 ↔, La ↑

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

↔ 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

Abbreviations: *BF* blood flow. *BW* body weight. *CK* creatine kinase. *CMJ* counter movement jump. *CP* cardiac parameters (HR, cardiac output, cardiac index, stroke volume). *CRP* c—reactive protein. *Damage marker* additional damage marker. *DOMS* delayed onset of muscle soreness. *F* female. *G* graduated. $HF_{wavelet}$ index of parasympathetic activity. *HR* heart rate. *IL-6* interleukin 6. *IL-1β* interleukin-1-beta. *jump* vertical jump exercise. *La* blood lactate concentration. *LDH* lactate dehydrogenase. $LF_{wavelet}$ sympathetic and parasympathetic activity. *LT* lactate threshold. *M* male. *MAS* maximal aerobic speed. *MPO* mean power output during TT. *MRI* magnetic resonance imaging. *MVC* maximal voluntary contraction. *MVIC* maximal voluntary isometric contraction. *n.i.* not indicated. pO_2 oxygen partial pressure. pVO_{2max} power output at VO_{2max}. *RE* running economy. *RER* respiratory exchange ratio. *RPE* rating of perceived exertion. *P* performance. *PB* personal best. *PMS* perceived muscle soreness. *PPO* peak power output in an incremental cycle ergometer test. *R* recovery. *temp* body temperature. *SJ* squat jump. SO_2 oxygen saturation. *sprint* short duration sprinting. *Swelling* muscle swelling. $temp_{amb}$ ambient temperature. *TT* time trial. *TTE* time to exhaustion. *T2* skeletal muscle proton transverse relaxation time. *TNF-α* tumor necrosis factor-alpha. VO_2 oxygen uptake. VO_{2max} maximal oxygen uptake. VO_{2peak} peak oxygen uptake. *WANT* wingate anaerobic test. *WBC* whole-body compression. W_{max} maximal external power reached in an ergocycle steptest. *y* years

Table 2 Summary of the Studies Included: Investigations on the Effect of Compression Clothing on Performance during and Recovery from Cycling exercise

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Leoz-Abaurrea et al. (2015)	12, M, 21 ± 6	Untrained individuals (VO_{2max}: 53.7 ± 5.0 mL • kg^{-1} • min^{-1})	Shirt	n.i.	P, R	4 × 14 min cycling at 50 % VO_{2peak} in hot conditions (40 °C, 35 % relative humidity), separated by one min active recovery (25 % VO_{2peak}); subsequently 1 min active cool down (25 % VO_{2peak})	P: body and skin temp ↔, weight loss ↔, sweat rate ↔, HR ↔, VO_2 ↔, RPE ↔ R: HR ↓, VO_2 ↓
Ménétrier et al. (2015)	15, M, 22 ± 0.7	Moderately endurance trained individuals (VO_{2max}: 56.6 ± 1.9 mL • kg^{-1} • min^{-1})	Socks (G)	14–27 (manufacturer's information)	R	45 min cycling. (9 × 5 min: 4 min 50 % PPO followed by 1 min 80 % PPO); followed by 12 min recovery	BF ↑
Argus et al. (2013)	11, M, 31 ± 6	Highly trained cyclists (VO_{2max}: n.i.)	Tight (G)	18–27	P, R	3 × WANT, 30 min recovery	MP WANT 1 to WANT 2 ↑, WANT 1 to WANT 3 ↑, La ↔, perceived quality of recovery ↔
Boucourt et al. (2014)	11, M	XYZ No Fulltext available	Calf sleeves	XYZ!	P, R	Submaximal 15 min incremental cycling exercise (40, 80, 120, 160, and 200 W)	Rest: tissue oxygen saturation ↑ Tissue oxygen saturation at 40 and 80 W ↑ R: Tissue oxygen saturation ↑

(continued)

Table 2 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Cipriani et al. (2014)	20, M, F, 43 ± 11	Recreational and competitive cyclists (minimum 100 km/week and/or 8.0 h/week cycling, VO_{2max}: n.i.)	Shirt	n.i.	P, R	Two rides (minimum length of ride: 40 km); Post-ride recovery (minimum length of ride: 40 km); previous ride completed without compression garment	Perceived influence of shirt while riding ↑, perceived influence of shirt during recovery ↑
Driller and Halson (2013)	12, M, 30 ± 6	Highly trained cyclists (VO_{2max}: 66.6 ± 3.4 mL • kg^{-1} • min^{-1})	Tight (G)	~10–~18 (manufacturer's information)	P, R	10 min warm-up, 30 min cycling (15 min 70 % PPO + 15 min TT + 5 min cool down 40 % PPO)	P: MPO ↑, HR ↑, La ↔ R: calf girth ↔, thigh girth ↔, perceived leg soreness ↔
Ménétrier et al. (2013)	12, M, 21 ± 1	12 competitive cyclists (VO_{2max}: n.i.)	Tight (G)	14–27 (manufacturer's information)	P, R	Cycle ergometer: steptest until exhaustion followed by 15 min recovery with 12 min application of compression, respective cold water immersion or passive recovery; subsequently 5 min TT	Performance ↑, La ↑, HR ↔, muscle soreness ↑, RPE ↔
Sperlich et al. (2013)	6, M, 22 ± 2	Well-trained endurance individuals (VO_{2peak}: 54 ± 6 mL • kg^{-1} • min^{-1})	Shorts (G)	~37	R	10 min cycling at 100 W, ramp test until exhaustion, 1 min passive recovery followed by 10 min cycling at 75 % VO_{2peak}. After 10 min passive recovery compression short was applied	R: blood flow BCF ↔, blood flow QF ↓, glucose uptake BCF & QF ↔

(continued)

Table 2 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Burden and Glaister (2012)	10, M, 35 ± 7	Well-trained cyclists and triathletes (VO_{2max}: 50.9 ± 6.8 mL • kg^{-1} • min^{-1})	(1) Ionized tights (2) Non-ionized tights (3) Non-compression tights	(1) 11–21 (2) 11–21 (3) 6–11	P, R	Sprint trials: 5 min warm-up at 100 W, 30 s sprint at 150 % pVO_{2max} + 3 min recovery at 40 % pVO_{2max} + WANT + 3 min recovery at 40 % pVO_{2max} Endurance trials: 5 min warm-up at 100 W, 30 min at 60 % pVO_{2max} + 5 min rest + 10 km TT + 3 min recovery	Sprint trial: WANT performance ↔, La ↔ Endurance trial: TT ↔, VO_2 ↔, HR ↔, La ↑
de Glanville and Hamlin (2012)	14, M, 34 ± 7	Trained multisport athletes (40 km cycling PB: 66:11 ± 2:10 min)	Tight (G)	6–15	R	40 km TT on cycle ergometer (without compression), 24 h recovery with compression tight; Subsequently 40 km TT on cycle ergometer (without compression)	P: TT ↑, MPO ↑, RPE ↔, VO_2 ↔, La ↔, HR during recovery ↓, HR during TT ↔
MacRae et al. (2012)	12, M, 26 ± 7	Recreationally trained cyclists (VO_{2max}: 53 ± 8 mL • kg^{-1} • min^{-1})	(1) Correctly sized full-body suit (2) Over-sized full-body suit	(1) 11–15 (2) 8–13	P, R	60 min cycling at ~65 % VO_{2max} followed by 6 km TT	cardiac output ↑, stroke volume ↔, higher skin temperature ↓, core temperature ↔, TT ↔
de Pauw et al. (2011)	8, M, 21 ± 1	Recreationally trained individuals (VO_{2max}: 56.9 ± 3.8 mL • kg^{-1} • min^{-1})	n.i.	n.i.	P, R	30 min cycle exercise at 55 % W_{max}, followed by 30 min TT at 75 % W_{max}. Followed by a 20 min recovery intervention (cooling and compression),	TT ↔, La ↔, HR ↔, RPE ↔

(continued)

Table 2 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
						with subsequent passive rest for 100 min + TT at 75 % W_{max}	
Rimaud et al. (2010)	8, M, 27 ± 1	Trained athletes (VO_{2max}: 53.3 ± 2.7 mL • kg^{-1} • min^{-1})	Tights (G)	12–22	P	Incremental cycling test until exhaustion	La production ↓, La elimination ↑, RPE ↔, HR ↔
Scalan et al. (2008)	12, M, 21 ± 4	Amateur cyclists (VO_{2max}: 55.2 ± 6.8 mL • kg^{-1} • min^{-1})	Tights (G)	9–20	P	Incremental cycling test, 1 h TT on cycling ergometer	Incremental cycling test: VO_{2max} ↔, La ↔, HR ↔, power output ↔, 1 h TT: MPO ↔, PPO↔, VO_2 ↔, La ↔, HR↔, SO_2 ↑
Chatard et al. (2004)	12, M, 63 ± 3,	Recreationally trained cyclists (5108 km/year; VO_{2max}: 49 ± 6 mL • kg^{-1} • min^{-1})	Socks (G)	24–44 (manufacturer's information)	P, R	Two 5 min maximum effort cycling bouts (without compression) separated by 80 min passive recovery while wearing compression	Performance ↑, La ↑, hematocrit ↑, plasma volume ↔, leg pain ↑

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

↔ 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

Abbreviations: *BF* blood flow. *BCF* biceps femoris. *F* female. *G* graduated. *HR* heart rate. *La* blood lactate concentration. *M* male. *MP* mean power wingate anaerobic test. *MPO* mean power output during TT. *n.i.* not indicated. *P* performance. *PB* personal best. *PPO* peak power output. pVO_{2max} power output at VO_{2max}. *QF* quadriceps femoris. *R* recovery. *RPE* rating of perceived exertion. *temp* body temperature. *TT* time trial. VO_2 oxygen uptake. VO_{2max} maximal oxygen uptake. VO_{2peak} peak oxygen uptake. *WANT* wingate anaerobic test. W_{max} maximal external power reached in an ergocycle steptest. *y* years

Table 3 Summary of the Studies Included: Investigations on the Effect of Compression Clothing on Performance during and Recovery from other endurance dominated exercise

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Born et al. (2014)	4, M, 6, F, 23 ± 7	Highly trained ice speed skaters (VO_{2peak}: 58.0 ± 5.2 mL kg^{-1} min^{-1})	Tight (G)	20.3– 24.4	P, R	3000 m ice speed skating race simulation	race time ↔, lap times ↔, tissue oxygenation (vastus lateralis) ↔, local blood volume ↔, VO_2 ↔, HR ↔, La ↔, RPE ↔
Del Coso et al. (2014)	36, M, 35 ± 5	Experienced triathletes (half Ironman PB: 303 ± 33 [min], VO_{2max}: n.i.)	Calf compression sleeves (G)	n.i.	P	Half Ironman triathlon (1.9 km swimming/75 km cycling/21.1 km running)	Race time ↔, velocity cycling ↔,velocity running ↔, CMJ ↔, leg muscle power ↔, blood myoglobin ↔, CK ↔, serum LDH ↔, RPE ↔, perceived muscle soreness ↔, temp ↔
Sperlich et al. (2014)	10, M, 25 ± 4	Well-trained endurance athletes (VO_{2peak}: 4.7 ± 5.4 L min^{1})	Long sleeve shirt (G)	9–21	P	3 × 3 min double poling sprint on cross-country ski ergometer (submaximal and maximal intensity)	MPO ↔, La ↑, oxygenation profile ↔, blood pH ↔, VO_2 ↔, HR ↔, stroke volume ↔, RPE ↔

(continued)

Table 3 (continued)

		Characteristics of participants	Characteristics of compression clothing				
Reference	Size, gender, age (year)	Study population	Type of compression clothing	Pressure applied (mm Hg)	Measure	Study protocol (occasion when compression was applied)	Effects of compression clothing
Dascombe et al. (2013)	5, M, 22 ± 3 2 F, 25 ± 4	Well-trained kayak athletes (VO_{2max} M: 63.0 ± 5.5; VO_{2max} F: 51.0 ± 4.8 mL kg^{-1} min^{-1})	Long sleeve shirt (G)	n.i.	P	Six-step incremental test followed by a 4 min TT on kayak ergometer	VO_2 ↔, HR ↔, performance ↔, La ↔, blood flow ↔, oxygenation profile ↔

Highly trained—national/international level and $VO_{2max} > 65$ mL • kg^{-1} • min^{-1}. *Well trained*—$VO_{2max} \geq 50$ mL kg^{-1} min^{-1}. *Moderately trained*—$VO_{2max} \geq 45$ mL kg^{-1} min^{-1} or running volume > 30 km/week. *Recreational*—running volume <30 km/week

↔ 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

Abbreviations: *CMJ* counter movement jump. *CK* creatine kinase. *F* female. *G* graduated. *HR* heart rate. *La* blood lactate concentration. *LDH* lactate dehydrogenase. *M* male. *MPO* mean power output. *n.i.* not indicated. *P* performance. *PB* personal best. *R* recovery. *RPE* rating of perceived exertion. *TT* time trial. *temp* body temperature. VO_2 oxygen uptake. VO_{2max} maximal oxygen uptake. VO_{2peak} peak oxygen uptake. *y* years

Ali et al. 2007; Barwood et al. 2013; Ali et al. 2011) (Table 1), as reflected in the times for a marathon, half marathon during a triathlon, 15-km trail running, 5- and 10-km runs and 400-m sprint. Of the 13 studies in which the time to exhaustion (TTE) in incremental or step tests or runs until exhaustion were analyzed, three reported small significant improvements of TTE as a result of compression garments (Armstrong et al. 2015; Sear et al. 2010; Kemmler et al. 2009). Eight studies found no alteration of TTE with the application of compression (Wahl et al. 2012; Ali et al. 2011; Dascombe et al. 2011; Goh et al. 2010; Menetrier et al. 2011; Varela-Sanz et al. 2011; Sperlich et al. 2010; Berry and McMurray 1987) and one study documented a negative effect on TTE (Rider et al. 2014).

The cycling performance in five studies improved with the application of compression clothing (Argus et al. 2013; Driller and Halson 2013; Ménétrier et al. 2013; de Glanville and Hamlin 2012; Chatard et al. 2004). Whereas, six different cycling trials in four studies detected no changes in variables related to performance (Burden and Glaister 2012; MacRae et al. 2012; de Pauw et al. 2011; Scalan et al. 2008) (Table 2).

The studies which applied protocols in ice speed skating (Born et al. 2014), triathlon (Del Coso et al. 2014), double poling on a cross country skiing ergometer (Sperlich et al. 2014), and on an kayak ergometer (Dascombe et al. 2013) revealed no influence of compression clothing on the respective endurance performance (Table 3).

Physiological Parameters During Running

Maximal or peak oxygen uptake was not affected in any of the considered studies during running (Priego et al. 2015; Dascombe et al. 2011; Rider et al. 2014; Wahl et al. 2012; Varela-Sanz et al. 2011; Sperlich et al. 2010; Kemmler et al. 2009; Berry and McMurray 1987), cycling (Scalan et al. 2008), ice speed skating (Born et al. 2014), cross country skiing (Sperlich et al. 2014) and kayaking (Dascombe et al. 2013). Whereas, two studies identified increased oxygen uptake during submaximal running (Lovell et al. 2011; Bringard et al. 2006) and four studies found no changes in submaximal oxygen uptake (Priego et al. 2015; Varela-Sanz et al. 2011; Ali et al. 2010; Sperlich et al. 2010) and three studies showed both increased and decreased amounts of oxygen uptake during submaximal running (Dascombe et al. 2011; Sperlich et al. 2011; Sear et al. 2010). During cycling, none of the studies revealed alterations in submaximal oxygen uptake (Leoz-Abaurrea et al. 2015; Burden and Glaister 2012; de Glanville and Hamlin 2012; Scalan et al. 2008).

No significant differences for blood lactate concentration were detected during running (Areces et al. 2015; Rider et al. 2014; Vercruyssen et al. 2014; Wahl et al.

2012; Ali et al. 2011; Dascombe et al. 2011; Varela-Sanz et al. 2011; Sperlich et al. 2011; Ali et al. 2010; Cabri et al. 2010; Sear et al. 2010; Sperlich et al. 2010; Kemmler et al. 2009), cycling (Driller and Halson 2013; Ménétrier et al. 2013; Burden and Glaister 2012; de Glanville and Hamlin 2012; de Pauw et al. 2011; Scalan et al. 2008), ice speed skating (Born et al. 2014) and kayaking (Dascombe et al. 2013) between the conditions with or without compression clothing. Three studies documented reductions in blood lactate concentration while wearing compression garments during submaximal running (Lovell et al. 2011), 10 km cycling time trial (Burden and Glaister 2012) and cross country skiing (Sperlich et al. 2014).

Four studies revealed improved post exercise lactate removal due to wearing compression clothing (Rider et al. 2014; Rimaud et al. 2010; Chatard et al. 2004; Berry and McMurray 1987). One study showed no effect on blood lactate elimination following submaximal running (Cabri et al. 2010).

In most of the studies the heart rate was not influenced during running by the compression garments (Armstrong et al. 2015; Priego et al. 2015; Priego Quesada et al. 2015; Bieuzen et al. 2014; Ferguson et al. 2014; Rider et al. 2014; Venckūnas et al. 2014; Vercruyssen et al. 2014; Wahl et al. 2012; Ali et al. 2011; Dascombe et al. 2011; Ménétrier et al. 2011; Varela-Sanz et al. 2011; Ali et al. 2010; Kemmler et al. 2009; Ali et al. 2007), although two studies observed positive effects on heart rate during submaximal treadmill running (Sperlich et al. 2011), respectively during a 5 km submaximal run (Cabri et al. 2010). One study reported contradictory, partially decreased and partially increased heart rates, during 30-min submaximal treadmill running (Lovell et al. 2011).

In most of the studies heart rate during cycling was not altered by wearing compression clothing (Leoz-Abaurrea et al. 2015; Ménétrier et al. 2013; Burden and Glaister 2012; de Pauw et al. 2011; Rimaud et al. 2010; Scalan et al. 2008). Although, two studies reported a decreased heart rate during recovery from cycling (Leoz-Abaurrea et al. 2015; de Glanville and Hamlin 2012) and one an improved cardiac output during cycling (MacRae et al. 2012). Only one study reported a reduced heart rate during cycling (Driller and Halson 2013).

During ice speed skating (Born et al. 2014), cross country skiing (Sperlich et al. 2014) and kayaking (Dascombe et al. 2013) heart rate was not influenced by compression clothing.

Neither blood saturation nor partial pressure of oxygen were influenced to any great extent by the compression garments during running (Venckūnas et al. 2014; Wahl et al. 2012; Sperlich et al. 2011; Sperlich et al. 2010), ice speed skating (Born et al. 2014), double poling (Sperlich et al. 2014) and kayaking (Dascombe et al. 2013). However, three studies observed positive effects on tissue oxygen saturation during rest and recovery following running (Ménétrier et al. 2011), muscle oxygenation during cycling (Scalan et al. 2008) and tissue oxygen saturation during and following submaximal cycling (Boucourt et al. 2014).

Body and Perceived Temperature

Body core temperature during running (Bringard et al. 2006; Venckūnas et al. 2014), cycling (Leoz-Abaurrea et al. 2015; MacRae et al. 2012) and triathlon (Del Coso et al. 2014) was not affected by compression clothing, whereas skin temperature was elevated by compression during running (Priego Quesada et al. 2015; Venckūnas et al. 2014) and cycling (MacRae et al. 2012). In one study skin temperature was not affected by compression (Leoz-Abaurrea et al. 2015). The perceived temperature during running with compression was not altered in two studies (Venckūnas et al. 2014; Barwood et al. 2013).

Psychological Variables While Exercise

There was no significant effect of compression clothing on perceived exertion in most studies during running (Bieuzen et al. 2014; Rider et al. 2014; Rugg and Sternlicht 2013; Venckūnas et al. 2014; Vercruyssen et al. 2014; Barwood et al. 2013; Ménétrier et al. 2011; Varela-Sanz et al. 2011; Ali et al. 2007, 2010, 2011; Sperlich et al. 2010; Bringard et al. 2006; Areces et al. 2015; Miyamoto and Kawakami 2014; Armstrong et al. 2015; Priego et al. 2015; Priego Quesada et al. 2015). Only in three studies compression clothing influenced perceived exertion during running (Rugg and Sternlicht 2013; Sperlich et al. 2010; Miyamoto and Kawakami 2014) and one study revealed positive and negative effects of compression (Ali et al. 2011).

Positive effects of compression on perceived exertion were neither shown during cycling (Leoz-Abaurrea et al. 2015; Ménétrier et al. 2013; de Glanville and Hamlin 2012; de Pauw et al. 2011; Rimaud et al. 2010) nor during triathlon (Del Coso et al. 2014), cross country skiing (Sperlich et al. 2014) or ice speed skating (Born et al. 2014).

Perceived Muscle Soreness

Compression exerted positive effects on post-running leg soreness and delay in the onset of muscle fatigue in most studies (Bieuzen et al. 2014; Areces et al. 2015; Valle et al. 2013; Hill et al. 2014a, b; Ali et al. 2007; Ferguson et al. 2014). In three studies compression clothing had no effect on post running leg soreness (Bovenschen et al. 2013; Sperlich et al. 2010; Trenell et al. 2006). Leg compression clothes reduced muscle soreness following cycling in two studies (Ménétrier et al. 2013; Chatard et al. 2004) with no effect in another study (Driller and Halson 2013). Following a half ironman triathlon compression socks had no influence on perceived muscle soreness (Del Coso et al. 2014).

Discussion

Due to the methodological diversity of analyzed studies regarding sample sizes [n = 6–36], age [19–63 years], gender [male n = 41 studies, female n = 1 study, mixed gender n = 13 studies], type of compression clothing [knee-high socks n = 22, tights n = 17, knee-high calf sleeves n = 5, shorts n = 4, shirt n = 2, long sleeve shirt n = 2, whole-body compression n = 3], variations in timing and duration of application, as well as amount of compression [6–45 mm Hg], and training level of participants [well-trained vs. recreational athletes and untrained individuals], we have refrained from meta-analysis. However, the fairly large number of studies [n = 55] and participants [n = 788] involved provides an adequate overview (Tables 1, 2 and 3) of the impact of compression clothing on parameters related to performance and physiological processes during endurance dominated exercise.

The findings of the present investigation were that compression clothing had no significant impact on: (*i*) performance parameters during running, ice speed skating, triathlon, cross country skiing and kayaking; (*ii*) physiological parameters VO_{2max}, VO_{2peak}, blood lactate concentration, heart rate and blood saturation or partial pressure of oxygen during exercise in almost all analyzed studies; (*iii*) body core temperature; (*iv*) perceived exertion in most studies. Compression clothing revealed significant effects on: (*i*) improvement of performance in five out of eleven cycling trials; (*ii*) decline in post-exercise leg soreness and delayed onset of muscle fatigue in eight out of 13 studies; (*iii*) increase in skin temperature in two out of three studies; (*iv*) improvement of post exercise lactate elimination in four studies.

As reflected in running times (400 m–42.195 km) compression clothing does not assist to improve running performance (Areces et al. 2015; Zaleski et al. 2015; Bieuzen et al. 2014; Del Coso et al. 2014; Venckūnas et al. 2014; Vercruyssen et al. 2014; Ali et al. 2007; Barwood et al. 2013; Ali et al. 2011). The time to exhaustion in incremental or step tests or runs until exhaustion was improved by compression in three (Armstrong et al. 2015; Sear et al. 2010; Kemmler et al. 2009) out of 13 studies, therefore runners do not seem to benefit from any kind of compression clothing in respect to performance improvements during running competitions. Furthermore, this seems to be in line with other findings reported by Beliard et al. (2015) and Born et al. (2014).

However, cycling performance seems to be more positively affected by compression clothing, as five studies showed significant improvements of cycling performance, e.g. in repeated Wingate Anaerobic Tests (Argus et al. 2013), time trail performance of different lengths [5 min (Driller and Halson 2013); 15 min (Ménétrier et al. 2013); 40 km (de Glanville and Hamlin 2012); 2 × 5 min (Chatard et al. 2004)]. Therefore, wearing compression clothing during cycling competitions could be an effective strategy for performance improvements.

Since the performance during ice speed skating (Born et al. 2014), triathlon (Del Coso et al. 2014), cross country skiing (Sperlich et al. 2014) and kayaking (Dascombe et al. 2013) was not increased significantly, the application of compression clothing in these kind of endurance exercise may not be promising.

However, the number of participants in three studies (Born et al. 2014 [n = 10]; Sperlich et al. 2014 [n = 10]; Dascombe et al. [n = 7]) was considerable low. Only Del Coso et al. (2014) displayed a sufficient high number of participants (n = 36). Therefore, general recommendations to the application of compression clothing in these kinds of exercise cannot be made and during half ironman triathlon, compression socks seem to have no influence on performance.

The results clearly reflect that physiological parameters such as VO_{2max}, VO_{2peak}, submaximal oxygen uptake, blood lactate concentration, heart rate, blood saturation and partial pressure of oxygen are mostly not altered by wearing compression clothing during endurance exercise. Since endurance performance is partly determined by physiological parameters such as the athlete's VO_{2peak}, velocity or power output at the lactate threshold (Støren et al. 2013) and economy of locomotion (Coyle et al. 1988; Williams and Cavanagh 1987) endurance athletes will most probably not benefit from compression garments.

A potential benefit of compression clothing is displayed during the immediate recovery from intense cycling (Rimaud et al. 2010; Chatard et al. 2004; Berry and McMurray 1987) and running (Rider et al. 2014) since blood lactate concentrations were reduced during this period.

Since compression clothing covers a large portion of the body surface the clothing may contribute to increased body temperature since it represents a barrier to heat transfer and sweat evaporation. Since elevated skin and body temperature or hyperthermia may cause impaired endurance performance (Nybo et al. 2014) there is a potential risk of decreased performance while wearing compression clothing in hot conditions during endurance exercise. Whereas, all analyzed studies showed no significant effect of compression clothing on body core temperature (Bringard et al. 2006; Venckūnas et al. 2014; Leoz-Abaurrea et al. 2015; MacRae et al. 2012; Del Coso et al. 2014), three studies revealed increased skin temperature with compression clothing (Priego Quesada et al. 2015; Venckūnas et al. 2014; MacRae et al. 2012) with no influences on performance.

Compression appears to exert positive effects on perceived leg or muscle soreness and delayed onset of muscle fatigue following running and cycling. The positive impact appears mostly within the following 24 h after exercise if compression clothing is worn during running (Areces et al. 2015; Bieuzen et al. 2014; Valle et al. 2013; Ali et al. 2007). When compression clothing is applied merely for recovery purposes following exhaustive running for twelve (Ferguson et al. 2014) or 72 h (Hill et al. 2014a, b), or after high-intensity cycling (Ménétrier et al. 2013; Chatard et al. 2004) athletes experience less leg soreness. Presumably, the leg compression clothing exerts a protective effect on muscle fibers during running due to reducing muscle oscillation (Doan et al. 2003; Kraemer et al. 2004) and impact forces (Doan et al. 2003; Valle et al. 2013). The placebo effect could account for the positive effect of compression clothing on improved post exercise leg muscle soreness, too. Since it is difficult to create a placebo condition for compression garments, it cannot be excluded that improved psychological parameters are influenced by improved perceptions and a result of the participants' intuitions of expected findings.

Nevertheless, the protective characteristics of leg compression clothing on muscle fibers has been demonstrated by Valle et al. (2013). The application of compression shorts during downhill running reduced the amount of histological muscle injury, as shown by biopsies (measuring intracellular albumin, lymphocytes CD3+, neutrophils intra/interfibrillar infiltrates) of vastus lateralis by 25 %. This indicates a possible benefit of compression garments for running competitions taking place for multiple days and containing amounts of eccentric muscle contractions during downhill sections like in trail run events. Furthermore, the positive impact of compression clothing on perceived post exercise muscle pain may be caused by the external pressure gradient which reduces the space for swelling (Davies et al. 2009; Kraemer et al. 2004), diminishes structural damage to the muscles (Valle et al. 2013) and facilitates clearance of metabolites through improved blood flow (Davies et al. 2009) and lymphatic outflow (Kraemer et al. 2001). Additionally, the analytical review by Hill et al. (2014a) found moderate effect size values for reductions in post-exercise levels of creatine kinase and delayed onset muscle soreness, but their investigation involved vertical jumping, repeated sprinting and resistance training, rather than running.

The application of compression clothes had no significant influence on perceived exertion during running in 18 studies and in all included studies which applied cycling and other endurance exercise. Only three studies reported improved perceived exertion during running (Rugg and Sternlicht 2013; Sperlich et al. 2010; Miyamoto and Kawakami 2014). These results clearly reflect the limited impact of compression clothing on this parameter.

Conclusions

On the basis of 55 studies, it seems that the use of compression has no effect on performance in running (400 m–42.195 km), ice speed skating, triathlon, cross country skiing and kayaking. Apparently, by wearing compression garments cyclists might slightly improve variables related to time trial performance.

A risk of impaired performance due to hyperthermia could not be confirmed when wearing compression, however compression clothing increased skin temperature.

Furthermore, the present results show that physiological parameters like VO_{2max}, VO_{2peak}, submaximal oxygen uptake, blood lactate concentration, heart rate, blood saturation and partial pressure of oxygen are mostly not altered by wearing compression clothing during endurance exercise.

If compression clothing is worn during and following intense or prolonged endurance exercise athletes should benefit from improved lactate elimination, reduced muscle pain, damage and inflammation during recovery. These processes are likely due to reductions of muscle oscillation during exercise, improvements in clearance of metabolites through improved blood flow, lymphatic outflow and reduced space for swelling. Potentially, this might improve recovery and enhance subsequent performance.

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