Florian Engel · Billy Sperlich *Editors*

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General Considerations for Compression Garments in Sports: Applied Pressures and Body Coverage

Braid A. MacRae, Raechel M. Laing and Hugo Partsch

Abstract Compression garments are popular among competitive and recreational athletes alike. The debate about the efficacy of compression garments in sport is similarly popular, spanning the scientific literature, public press, social media, and the sports field itself. In this chapter we aim to assist both researchers and the general reader by discussing the core elements of the compression garment story. First, we consider *compression*—the applied pressures and factors influencing those pressures. Knowing the applied pressures in vivo and characteristics of the pressures during use are important for building a clearer idea about what aspects of sports performance and recovery are affected by compression garments and why. Second, we consider *garments*—that, like other clothing, compression garments cover and interact with the body, establish a microenvironment, and influence variables such as heat and moisture exchanges. Understanding characteristics of the garments themselves can be useful for aiding interpretation of certain physiological and psychological effects, including heat balance, comfort, and wearer acceptability. We hope that the detail here helps the reader to contextualise and critically evaluate research on compression garments in sport.

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Introduction

Scope

Compression garments have been widely adopted for use in sporting contexts. The types of garments available vary and include those that cover the torso and the arms in full or part, the lower-body from the waist in full or part, and those that cover specific limb-segments only (e.g. sleeves, socks, and stockings). While the type of garments used and the time of wearing them can vary by sport, personal preference, and intended purpose, a common feature is that all compression garments apply pressure to *and* cover body surfaces. These two components—applied pressures and body coverage—are the focus of this chapter.

Applied pressures. A fundamental assumption underpinning compression garment use is that the pressures applied to the body are important in some way. During use, these pressures can be influenced by garment properties (e.g. garment dimensions, garment construction, properties of the constituent fabrics and how these change over time) and characteristics of the underlying body segment (e.g. body dimensions, tissue type, and changes related to posture and movement). Irrespective of whether specific pressures, a general range of pressures, or simply some pressure is ultimately required for a particular outcome, actually knowing what those pressures are and the characteristics during use are essential for integrating and interpreting the literature and making useful recommendations for athletes.

Body coverage. Considerations about compression garments from the perspective of a layer of clothing that covers the body are introduced. Here, we include information that attempts to bridge the sport sciences with some of the wider clothing and textile sciences.

Pressure and coverage characteristics

Since early studies in sporting contexts (e.g. Berry and McMurray 1987; Carling et al. 1995; Kraemer et al. 1996, 1998a, b), a considerable body of research has accumulated investigating various applications (during sport, during recovery) and types of compression garments (different applied pressures and body sites covered). For the purpose of gauging the status of aspects relating to pressures and body coverage in the sport sciences, we characterised the literature from a ~5-year period (2011–Jan 2016; Table 1). (Note that this search period applies only for the data presented in Table 1, not for the chapter as a whole.) Over this period, 78 % of studies investigated effects during exercise, and 29 % during recovery from exercise. Lower limb compression has been the most common with 81 % of studies including the leg (calf) and 48 % including the thigh, while comparatively few have investigated upper-body effects (<16 % for each torso, upper arm, and forearm; Table 1). While the applied pressures were often reported, these pressures were measured only in approximately one of every three studies.

Table 1 Information from located studies (n = 58, 2011–Jan 2016) in which compression garments were used during or following exercise[a]

Variable	Yes (%)	No (%)	Not clear (%)
Body sites compressed			
Torso	12	88	–
Upper arm	16	83	2
Forearm	14	83	3
Thigh	48	48	3
Leg (calf)	81	17	2
Applied pressures			
Pressures reported	74	26	–
Pressures measured in vivo by authors	34	66	–
Other garment information reported			
Placebo garment used[b]	28	72	–
>1 compression condition (including placebo)[c]	43	55	2
>1 compression condition (excluding placebo)[c]	22	76	2
No garment/normal clothing as a control	78	22	–
Comment on how participants sized	78	22	–
Fibre type reported	53	47	–
Any fabric properties reported	5	95	–

[a]A 5-year period was used because, assuming that pressure measurement is becoming more common, the inclusion of older studies may inflate the percentage not measuring the applied pressures; see "Appendix 1: Search Details for Table 1" for a details about the search
[b] As reported as being a placebo garment in the article and may have been another type of garment or the same garment in a bigger size; in some instances the placebo was the control condition and in others it was simply a different condition of compression (i.e. one with less pressure)
[c]Placebo conditions have been reported both included and excluded as a separate condition of compression because it is plausible that placebo garments are, in effect, low-level compression garments

Compression Garments and the Applied Pressures

Establishing Applied Pressures

Sporting compression garments are smaller in dimensions than the corresponding body sites to be covered. During donning and use, the garment and its constituent fabric, yarns, and fibres/filaments are subjected to mechanical forces acting over an area (stress), which cause deformation, observable as extension (strain). Thus, compression is a product of the interaction between the body (e.g. tissue and surface curvature) and the forces involved with garment strain (Troynikov et al. 2013). Some indication of how interface pressures actually influence the underlying tissue pressures can be gained from Table 2 (Murthy et al. 1994; Giele et al. 1997; Uhl et al. 2014): note that modelling indicates heterogeneous pressure distributions are likely within a limb cross-section (Dubuis et al. 2012).

Table 2 Effects of external compression on subdermal and intramuscular pressures[a]

Site	Body position	Interface pressure, mmHg	Subdermal pressure (Δ from baseline), mmHg	Intramuscular pressure (Δ from baseline), mmHg
Medial mid-calf[b]	NR	No compression	6 (0)	
		36	22 (16)	
Posterior calf[b]	NR	No compression	−3 (0)	
		66	24 (27)	
Medial lower calf[b]	NR	No compression	1 (0)	
		59	31 (30)	
Medial calf (IMP in medial gastrocnemius)[c]	Supine	No compression		11 (0)
		10		13 (2)
		20		25 (14)
		30		36 (25)
		40		43 (32)
	Standing	No compression		32 (0)
		10		41 (9)
		20		50 (18)
		30		60 (28)
		40		68 (36)
Mid-calf (IMP in soleus)[d]	Supine	No compression		8 (0)
		16 ± 1 (L1)		21 (13)
		20 ± 1 (L2)		25 (17)
	Standing	No compression		37 (0)
		19 ± 1 (L1)		56 (19)
		23 ± 1 (L2)		55 (18)
	Walking			
	Contraction	No compression		152 (0)
		23 ± 1 (L1)		162 (10)
		26 ± 1 (L2)		174 (22)
	Oscillation[e]	No compression		161 (0)
		11 ± 1 (L1)		153 (−8)
		11 ± 1 (L2)		164 (3)
	Running			
	Contraction	No compression		226 (0)
		24 ± 1 (L1)		254 (28)
		29 ± 1 (L2)		245 (19)
	Oscillation[e]	No compression		242 (0)
		13 ± 1 (L1)		263 (21)
		14 ± 1 (L2)		245 (3)

[a]Subdermal and intramuscular pressures are reported as absolute values with the change from baseline (no compression) reported in parentheses; change scores are calculated from group means. Standard deviation is presented where possible but omitted from subdermal and intramuscular pressures for clarity of presentation
Δ, change; NR, not reported; IMP, intramuscular pressure; L1, ‘level 1’; L2, ‘level 2’
[b]n = 1 leg, compression applied using a “pressure garment” (Giele et al. 1997)
[c]n = 10 legs from 5 participants, compression applied using a blood pressure cuff and measured at the medial calf at widest girth (Uhl et al. 2014)
[d]n = 11 legs from 11 participants, compression applied using ‘level 1’ and ‘level 2’ ankle-to-knee elastic compression garments (Murthy et al. 1994); note that the original article reports data for both elastic and inelastic compression but only data from the elastic garments are reported here
[e]Oscillation represents the difference between peak and relaxation pressures

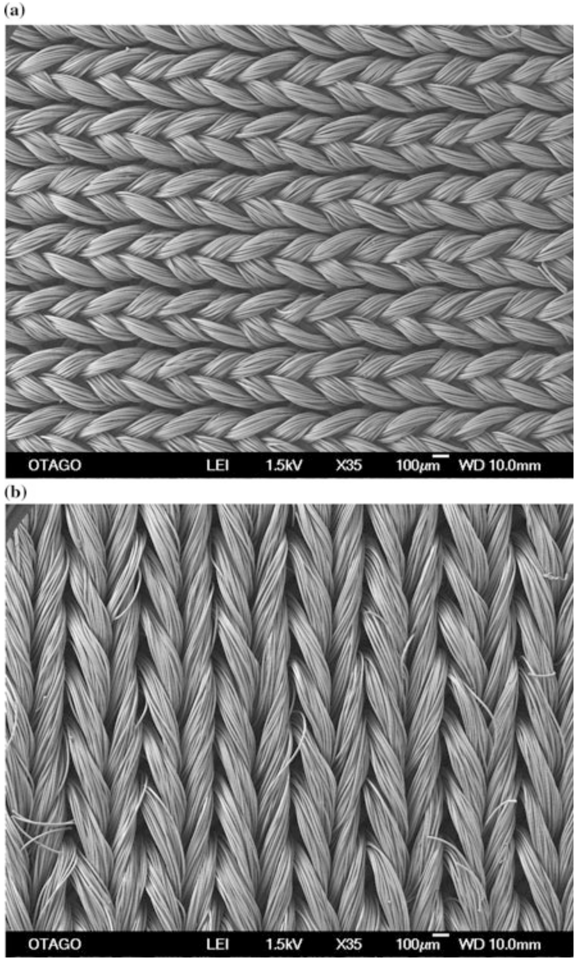

Fig. 1 Scanning electron microscope images of the fabric from a common sporting compression garment at X35 magnification; fabric outer (**a**) and inner (**b**) surfaces as used in the garment

An example of fabric from a commercially available sporting compression garment is shown in Fig. 1, imaged at 35 times magnification using a scanning electron microscope. In this case, it can be seen that filaments (fibres of indefinite length) are used to form yarns, which have then been knitted to form the fabric structure. Textile fibres are classified according to their origin and chemical composition (International Organization for Standardization 2012, 2013a). For sporting compression garments, the constituent fibres/filaments are often elastane (branded versions of this include Lycra® and spandex) and polyamide (nylon) or polyester. This particular example (Fig. 1) was reported by the manufacturer as being 76 % nylon and 24 % elastane.

A reasonable level of fabric extension and fabric elasticity (recovery following extension) will facilitate garment donning, wearer comfort, range of motion, and generic garment sizing. Extension characteristics will also influence the way the applied pressures respond when the volume or curvature of the underlying body segment changes. The related property of compression garment ‘stiffness’ is relevant here and is defined in the context of medical compression hosiery as the increase in compression pressure per 1 cm increase in leg circumference (Comité Européen de Normalisation 2001). While this definition is somewhat arbitrary and, at face value, applicable only to the lower body, understanding the relevance of garment stiffness can be of use for the sport sciences. [Note that stiffness is also used to describe fabrics in terms of resistance to bending and this is not the usage here; stiffness for compression garments or compression devices, as defined (Comité Européen de Normalisation 2001) and widely used (Partsch et al. 2006a), can be thought of as the outcome of a compression material’s resistance to extension.] As an example, stiffer garments versus those that are less stiff, exhibit greater changes in pressure following a change in position of the leg (Partsch 2005; Partsch and Mosti 2013) or arm (Hirai et al. 2010) and higher peak pressures during muscle contractions in the leg (Partsch and Mosti 2013) or arm (Hirai et al. 2010). For this reason, both the applied pressures in resting state *and* how the pressures change during use are each important to understand.

Measuring Applied Pressures

In Vitro

There are various in vitro approaches for classifying medical compression products (e.g. see Partsch et al. 2006b; Hegarty-Craver et al. 2015) and, in principle, these or similar approaches can also be used for sporting compression garments. Advantages of in vitro measurements include widespread characterisation of garments under comparable conditions (assuming the same test method is used) and the ability to systematically assess effects of fabric properties or garment characteristics (e.g. Kumar et al. 2013). These approaches help understand aspects of the applied pressures, however, the principal interest is ultimately the applied pressures when worn by people.

In Vivo

Measurement. We strongly encourage researchers to measure the applied pressures in vivo. Approximately three quarters of studies over a ~5-year period reported applied pressures but only one third reported actually measuring these (Table 1). While other characteristics are also relevant to report where possible (e.g. see Section “Some Measurable Fabric Properties and Why They Are Useful”), applied pressures should be viewed as a minimum requirement and equivalent to reporting other information such as participant height, mass, age, and trained status.

The pressures applied by compression garments are typically measured at the interface between the skin and the garment. Some pressure measuring systems have been evaluated (e.g. Flaud et al. 2010; McLaren et al. 2010; Partsch and Mosti 2010; Brophy-Williams et al. 2013). Shape, composition, and distribution of tissues comprising the underlying body segment can influence pressures measurements (Thomas 2003; Moffatt 2008; Dubuis et al. 2012), and if a sensor is placed over a bony protrusion or tendon, for example, greater localised loadings can be induced. The applied pressures have been shown to vary not only by position along a limb, but also around its circumference depending on the local curvature (Liu et al. 2005, 2007; Sperlich et al. 2013a, 2014; Miyamoto and Kawakami 2014).

Existing guides for stocking materials and the lower limb are available in the literature (Comité Européen de Normalisation 2001; Partsch et al. 2006a). Depending on garment coverage and research question, the sites of the area at which the Achilles tendon changes into the medial calf muscle (B1), the calf at its maximum girth (C), and the mid-thigh (F) seem appropriate to use as convention with sports compression as including one or a number of key sites consistent among studies ensures more direct comparisons. Other sites can be added according to research interest. Thus, specific measurement location (e.g. medial, lateral, anterior, posterior) and participant position should also be clearly described (Partsch et al. 2006a). Fewer, but still some studies in which the applied pressures of upper-body sites were measured exist (e.g. Williams and Williams 1999; Bochmann et al. 2005; Damstra and Partsch 2009; MacRae et al. 2012; Sperlich et al. 2014). The relative merit of particular sites on the upper body are less clear than that for the lower body, however, the same detail of noting location and participant position should be employed.

Reasoning. From the perspective of interpreting any outcome effects of compression in sport, understanding the applied pressures in the cohort studied is crucial. For example, if beneficial effects for a particular measure are not observed, is it because compression has no effect? Or could it be that the pressures applied by those garments were too low, or too high? Similarly, if there are discrepancies among studies investigating a certain variable, are differences in the applied pressures or areas compressed possible explanations? Irrespective of whether different levels of applied pressures are important or unimportant, knowing the pressures in the first place is a requirement to conclude either way.

The 'intended', in vitro, and/or manufacturer-reported pressures are, at present, insufficient for estimating the in vivo pressures for two reasons. First, they have been a mixed guide in the past for group means (e.g. Liu et al. 2005; Partsch et al. 2006b; Beliard et al. 2015), and second, there will be inherent inter-person variability with generic sizing (Hill et al. 2015). Even custom-made garments are subject to potentially relevant variation.

In a rare study from the sport sciences with both custom-made garments and investigator-measured pressures, compression shorts (covering the thigh from waist to above the knee) were made and fitted using the measured thigh girth (Sperlich et al. 2013a). Pressure at the thigh at maximum girth was aimed to be 35 mmHg. For the four measurement sites (rectus femoris, vastus lateralis, vastus medialis, biceps femoris) the group means (n = 6 participants) were 35, 36, 37, and 39 mmHg, respectively, with corresponding pressure ranges of 31–39, 33–41, 29–44, 36–42 mmHg, respectively (coefficient of variation, 5–17 %). Some variation in the applied pressures will always be expected, but the point is that an estimate, unmeasured by the authors (e.g. '20 mmHg at the calf'), while arguably better than no measurement, overlooks variation. If a range is reported (e.g. '16–22 mmHg at the calf') but not measured, the method used to attain that estimate should be reported otherwise the reader has little ability to judge the quality of that information. For example, source 'X' may have generated estimates by extensive in vivo testing using a range of athletic populations (in which case you would then also expect an indication of variation) while source 'Y' may have used rigid cylinders paired with one garment size, or worse, just guessed.

Sizing

Sizing systems can be created using a variety of methods ranging from trial and error to statistical analysis of anthropometric data (e.g. Laing et al. 1999), and are traditionally based on (or reduced to) one or a number of key dimensions (Chun-Yoon and Jasper 1993; Ashdown 1998).

As mentioned already with custom-made garments, generically sized sporting compression garments can vary appreciably in the pressures they apply, even when fitted according to the manufacturer's instructions (Hill et al. 2015). For pressures at the anterior thigh and medial calf at maximum girth, values ranged from 4 to 17 and 10 to 25 mmHg at the thigh and calf, respectively, for males (n > 26) and from 5 to 13 and 10 to 19 mmHg, respectively, for females (n = 24). This is unsurprising given that the proportional size and shape of individuals will also likely vary (Surhoff 2014). What is interesting, however, is that among a subgroup of 29 men all wearing a size medium lower-body compression garment, there were no significant correlations between anthropometric variables, including thigh and calf girths, and the measured applied pressures at the thigh and calf (Hill et al. 2015).

It may be that sizes (e.g. small, medium, large) are themselves arbitrary. Assuming it is some aspect of the applied pressures that is important for compression-related effects, the sizes are simply a vehicle to help fit an individual with particular applied pressures. Hill and colleagues (2015) demonstrated that particular 'intended' pressures, based on the work of Watanuki and Murata (1994), were often not met with correctly fitted garments. In extension of this work, it would be interesting to know whether an existing size range could be used to achieve particular pressures at particular sites by fitting garments by trial and error according to the resultant applied pressures instead (i.e. irrespective of given size). Measurement of the applied pressures would be required, which makes this more difficult outside a research setting. The other, and critical, difficulty with this approach is: what pressures are actually required for sport and in which circumstances do they apply?

What Applied Pressures?

Even with indication that compression garments can be useful in some sporting situations (Born et al. 2013; Hill et al. 2014a; Marqués-Jiménez et al. 2016), there appears to be a less cohesive story about what pressures are actually necessary (Beliard et al. 2015). There is appreciable diversity among potential compression-related effects and conditions of use (e.g. physiological or performance measures, body site, type of sport, use during sport or during recovery). It seems unlikely that one particular pressure profile will best suit all desired applications and outcomes (e.g. resting supine versus upright exercise; venous versus arterial haemodynamic effects). Thus, the influence of particular pressures across outcomes requires clarification. For these reasons, it would be surprising if manufacturers and distributors of sporting compression garments have a clear idea about what pressures are required and why.

What Pressures—An Example Using Compression Effects on Leg Haemodynamics

Sport presents a challenging set of conditions for understanding the effects of compression garments on haemodynamics. With respect to particular applied pressures, a pervasive example includes the concept of graduated compression and effects on haemodynamics. The dogma is that we need higher values distally and lower pressures proximally. Such pressure gradients are still an important quality criterion for the so-called graduated elastic compression stockings (e.g. Comité Européen de Normalisation 2001; Deutsches Institut für Gütesicherung und Kennzeichnung 2008), the basic concept being that higher pressures over the calf than over the ankle could impede rather than augment venous flow. However, while this may have some importance in the horizontal position in which compression pressure may actually lead to some venous narrowing, such effects are less likely in the upright position let alone during exercise. Indeed, compression stockings of 20–30 mmHg, for example, were found to reduce the internal diameter of posterior tibial and peroneal veins (vs. without stockings) in healthy people in a supine position, however these effects were not present when standing upright (Lord and Hamilton 2004).

Perhaps pressures remain too low to have demonstrable venous haemodynamic effects when upright (Partsch and Partsch 2005; Partsch et al. 2010) and during activity like moderate or high-intensity orthostatically stressful exercise. Central cardiovascular effects were investigated using conventional ‘elastic’ compression garments and athletic cohorts during submaximal running (Sperlich et al. 2011) and cycling (MacRae et al. 2012) and neither group found evidence for benefits from the compression garments used. Sperlich and colleagues (2011) used five separate conditions, four with knee-high socks applying different levels of compression (~14, 23, 32, and 39 mmHg at the calf at maximum girth) and one condition without compression. Cardiac output, stroke volume, and heart rate were similar during exercise irrespective of condition and may implicate the dominating influence of mechanisms like the calf muscle pump. There is some indication, however, that compression may influence cardiovascular strain during lower-intensity exercise. Lovell et al. (2011) investigated the effects of lower-body compression (waist to ankle; ~20 mmHg at the ankle and 15 mmHg at the calf) on various cardiorespiratory variables during multi-stage running at different intensities. During the two active recovery stages (6 km/h), heart rate was significantly lower by ~4–5 beats/min in the compression condition versus regular running shorts. However, no differences in heart rate were observed at the other running intensities (10 km/h and 85 % peak oxygen uptake).

Especially during sporting activities, rhythmic muscle contractions will lead to fluctuations in the applied pressures (see next section). The pressure amplitudes depend on the consistency of the moving tissue, on changes of the local body configuration, and on the stiffness of the compression device. Simply increasing the pressure applied by 'elastic' compression garments would lead to unpleasant and even painful feelings of constriction, thereby decreasing comfort and wearer acceptance (Liu et al. 2008), especially during rest. On the other hand, relatively inelastic compression which does not need to increase the resting pressure, but which is able to increase the pressure in the standing position and during walking, is an approach that has already shown promise in both patient (e.g. Mosti et al. 2008) and healthy (Partsch and Mosti 2013) cohorts (Fig. 2).

Stiff, low-yielding wraps superimposed over a sport stocking may increase the pressure peaks considerably, even without major changes in the supine resting pressures. External pressures of more than 50–60 mmHg may occur on the lower

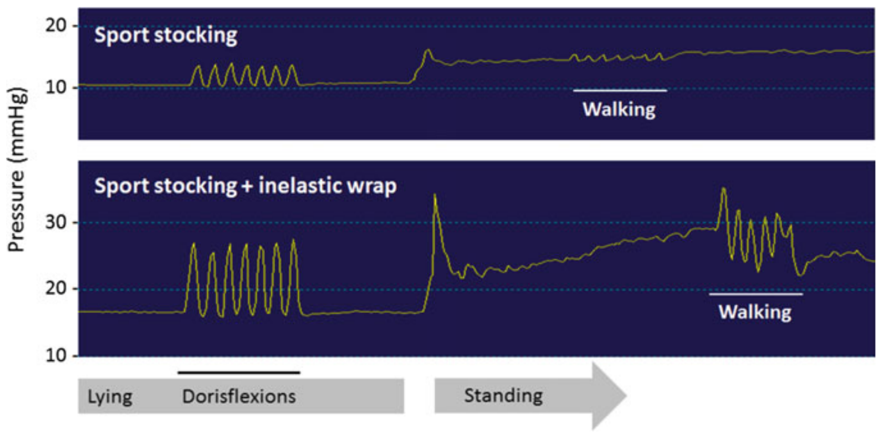

Fig. 2 Interface pressures at the medial calf at maximum girth during rest in the lying position, repeated dorsiflexion while lying, standing, and walking. Below-knee sport compression stockings (*top panel*) and compression stockings with the addition of an inelastic (i.e. 'stiff') strap applied lightly over the midcalf (*bottom panel*). Data are from Partsch and Mosti (2013)

leg during walking or running which are high enough to intermittently overcome the local intravenous pressure, thereby exerting hemodynamic effects. By magnetic resonance imaging (MRI) in the standing position, it could be shown that wrapping the calf with inelastic material (over a conventional sport stocking) increased the pressure to 42 mmHg which led to a narrowing of all lower leg veins, while the sport stocking alone exerting 23 mmHg had practically no influence on venous diameters (Partsch and Mosti 2013). Such venous narrowing is a prerequisite for a haemodynamic effect. By measuring the calf pump function during a standardised walking test in healthy sports people, a significant increase of the ejection fraction could be demonstrated with addition of the inelastic wrap and contrasts that of the conventional stocking alone, which did not show improvement (Partsch and Mosti 2013).

Such compression systems may capitalise on the calf region being where veins are forming a kind of dense sponge. Indeed, the idea that 'progressive' below-knee pressure is more effective than conventional ('degressive') graduated pressure was demonstrated in venous patients by showing a higher increase of ejection fraction compared to graduated pressure (Mosti and Partsch 2011). Miyamoto and Kawakami (2015) also challenged the convention of graduated compression by showing that pressure at the calf seemed to be more important (than the graduation of ankle-calf pressure) for reducing surrogates of muscle fatigue when compression garments were worn by healthy subjects during 30 min treadmill running. Unfortunately, the pressures were not measured by the authors and were instead as reported by the manufacturer.

Briefly, augmentations of arterial inflow have been demonstrated with compression of the forearm during rest and low-intensity handgrip exercise (13–23 mmHg; Bochmann et al. 2005) and leg during rest (30–40 mmHg; Mayrovitz and Larsen 1997; Mayrovitz 1998). However, reductions of blood flow in the thigh muscles have also been demonstrated with compression following high-intensity exercise ($\sim$37 mmHg; Sperlich et al. 2013a). While there is more to learn about the effects of compression on arterial haemodynamics, indications are that effective pressures are not necessarily equivalent to those that benefit venous haemodynamics when upright.

Although not exhaustive, these examples help demonstrate that the concept of broadly applicable applied pressures and pressure profiles is unlikely, particularly for encompassing all forms of sport and recovery, and that further insight may be gained by challenging the status quo.

Posture and Movement

Posture and movement influence the pressures applied as shown with compression stockings (e.g. Wildin et al. 1998; Wertheim et al. 1999; Liu et al. 2007) and sports compression garments (McLaren et al. 2010; MacRae et al. 2012; Brophy-Williams et al. 2014). An example of the real-time influence of movement can be seen in

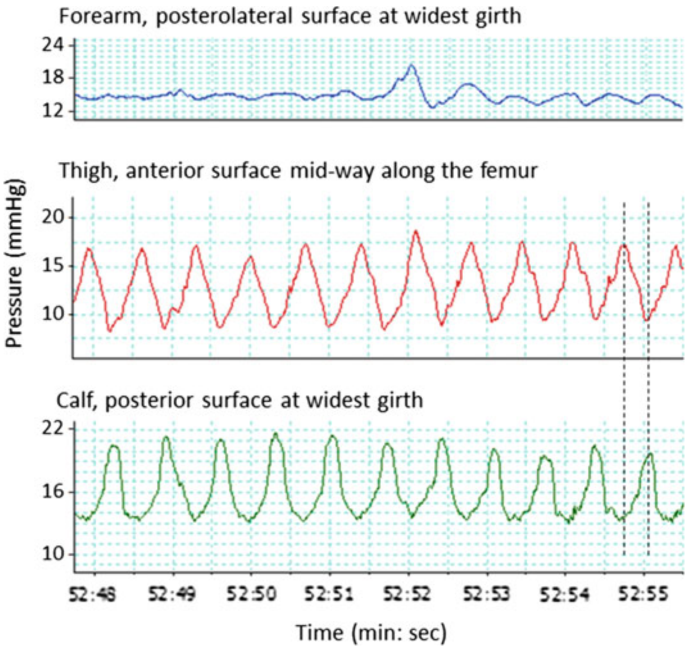

Fig. 3 Example of applied pressures in vivo during cycling exercise for sports compression garments fitted according to the manufacturer's recommendations. *Dashed vertical lines* superimposed on the thigh and calf traces are to indicate that they are out of phase. Data are from MacRae et al. (2012)

Fig. 3, showing interface pressures during cycling exercise while wearing full-body sports compression garments.

As mentioned, the extent to which the applied pressures change with posture and movement will also be related to garment stiffness (Partsch 2005; Hirai et al. 2010; Partsch and Mosti 2013). The implications here are that the fabric/garment stiffness may be altered according to desired end-characteristics: an increase in stiffness will, for example, exhibit greater peak pressures during contraction of the underlying muscle while 'elastic' garments will show lesser changes (Fig. 2). Different body sites may have different requirements relating to pressure dynamics.

Different Applied Pressures

Blinding and placebo garments. Blinding participants is difficult with compression garment research, and this is especially so with participants who regularly use compression garments (Driller and Halson 2013a). No compression or normal garments (e.g. regular running shorts and ankle-length socks) are commonly used as a comparison condition (∼78 % of studies; Table 1) with attempted placebo garments used less commonly (~28 %). Even if placebo garments are noticeably less tight, there can still be merit in controlling for body coverage.

Note that placebo garments, even 'non-compressive' tights, typically do still apply some pressure. For example, de Glanville and Hamlin (2012) reported a mid-calf pressure of 14.7 ± 2.5 mmHg with full-length lower body compression garments and 5.7 ± 0.9 mmHg at that same site with the placebo garment. These pressures, while low, could still be enough to confound a 'no compression' condition. For example, it could be shown that so-called placebo stockings were able to reduce occupational leg swelling in the evening (Partsch et al. 2004). Thus, terms like 'no compression' should be used cautiously. Approaches investigating 'different levels of compression' are also worth considering versus placebo garments per se (e.g. Ali et al. 2010; Miyamoto et al. 2011; Sperlich et al. 2013b). A view on blinding (or the lack thereof) from a practical or non-mechanistic standpoint could be that placebo effects, if found, are effects nonetheless.

Different levels of pressure. The applied pressures can vary by garment size, although the significance of this can depend on the type of garment (Brophy-Williams et al. 2014). Further, the extent to which different sizes differ in applied pressures can be of less practical significance than the difference between garment types. In a hypothetical example, for garment type 'A' there may be 5 mmHg difference between the group means of correctly sized and over-sized garments (e.g. 15 and 10 mmHg, respectively), but a difference of 15 mmHg between garment types 'A' and 'B', each correctly sized (15 and 30 mmHg, respectively). This is another reason why knowing the applied pressures is important beyond simply knowing the size itself. There are examples where changing the level of compression does have demonstrable physiological effects (e.g. Mayrovitz 1998; Bochmann et al. 2005), although such pressure-intensity effects in sport are often overshadowed by a lack of effect in the first place (e.g. Ali et al. 2010).

Changes in Pressure with Wear and Repetitive Use

Seemingly little is known about the maintenance of applied pressures in vivo with use for sport. Considerations here include issues of short-term deformation, due to mechanical forces associated with one wear period (Manshahia and Das 2014), and longer-term deformation and degradation, due to mechanical forces associated with repetitive wear and laundering and via prolonged exposure to agents such as ultraviolet light, sweat, and detergent.

Sporting compression garments are extended ('stretched') when they are worn, both during the donning process and once in place. Thus, these garments will be exposed to a combination of sustained and variable stress and strain over the duration of a period of wear. When materials such as fibres and fabrics are subjected to constant strain (i.e. when extended and held at a particular length and width, and multi-axially, as in the case of compression clothing), the stress can gradually decay with time (Morton and Hearle 2008). This phenomenon is known as stress relaxation (Walker 1993). In a variable strain environment below the breaking extension, such as cycles of extension and recovery during movement, a fibre or fabric will typically increase in length until it reaches a stable limiting value (Morton and Hearle 2008).

The observed strain in fabrics is usually comprised of a combination of elastic, viscoelastic, and permanent components of deformation (Nikolic and Mihailovic 1996). True elastic deformation is 'instantaneously' reversible when the applied force is removed, viscoelastic deformation is where the strain is time-dependent, and the permanent component is both time-dependent and irreversible (Walker 1993). The strain in compression garments associated with the stress of wear will depend on a multitude of factors, including properties and characteristics of the fibres (e.g. inter-atomic and intermolecular bonds), yarns (e.g. bending rigidity) and the fabric (e.g. stitch length and density, inter-yarn friction, and residual tensions from the knitting process) (Morton and Hearle 2008; Karimi et al. 2009).

In one study, Faulkner and colleagues (2013) reported in vivo pressures before and following a 400 m running performance test. There were two conditions for compression garments: full-length lower-body garments (hip to ankle) or a combination of compression shorts (hip to knee) with calf compression sleeves (ankle to knee). Six of the eight sites where the applied pressures were measured indicated a significant main effect of time ($P < 0.05$): for the full-length garment and the garment combination, the changes at these sites were decreases of 0.8–2.3 and 0–1.7 mmHg, respectively, from pre- to post-exercise (calculated from reported group means). A seventh site, the gluteal, showed a significant decrease with the full-length garment only (by 1.2 mmHg). In this study there were no effects of either compression condition versus regular running shorts for 400 m performance or 100 m split times, heart rate, or blood lactate profiles (Faulkner et al. 2013). Thus, the practical significance of any changes in pressure is hard to judge given the lack of pressure effect in the first place. Moreover, although statistically significant, the changes in pressures were (on average) typically small. Further investigation of changes in applied pressures with use over longer wear sessions (e.g. endurance exercise or during recovery) or with multiple wear sessions is warranted. In any such studies there is also justification for including pressure measurements at multiple time points to assess when (or if) pressures stabilise.

In previously unpublished work, fabric samples were cut from commercially available sporting compression garments in areas with no seams (see "Appendix 2: Multi-axial Extension and Recovery Testing of a Compression Garment Fabric" for more detail). In brief, fabrics were then subjected to extension and recovery cycling (repeated multi-axial 'stretching') using a laboratory tensile tester fitted with a hemispheric head and pre-loaded to 0.5 N. The number of extension and recovery cycles was chosen to approximate an exercise session of $\sim$80 min. Prior to the beginning of fabric cycling, the period of fixed strain (pre-load extension depth) resulted in stress-relaxation of the fabric: the mean minimum loads at the start of

Table 3 Multi-axial extension and recovery cycling of compression garment fabrics using a laboratory tensile tester

Cycle stage	Mean ± SD (N)
Pre-load (0.5 N)[a]	0.00
Minimum load[b]	
Start	0.25 ± 0.01
Middle	0.32 ± 0.03
End	0.35 ± 0.05
Maximum load[c]	
Start	−1.35 ± 0.05
Middle	−1.26 ± 0.06
End	−1.24 ± 0.08

SD, standard deviation
[a]Fabrics were pre-loaded with an extension that gave 0.5 N, then zeroed as the start point of extension and recovery cycling (i.e. became 0 mm and 0 N)
[b]Minimum load is the extension load at a cycle depth of 0 mm (0 N indicates complete recovery, 0.5 N indicates no recovery)
[c]Maximum load is the extension load at a cycle depth of 10 mm (negative indicates load direction)

cycling had reduced by 50 % from pre-load (Table 3). Results indicated that both the minimum and maximum loads reduced from beginning to midway through cycling (each $P \leq 0.01$), but not thereafter ($P = 0.503$ and 0.173, respectively). These results suggest that fabrics stabilise with acute use, although how this translates to pressure stabilisation is not known.

An example of why it may be useful to know how applied pressures change with wear comes from the work of Mayrovitz (1998), also reiterating potential arterial haemodynamic consequences of compression. With ankle-to-knee compression bandaging of ~30 mmHg, below-knee pulsatile blood flow was acutely higher by ~45 % relative to the contralateral leg (with “noncompressive” control bandaging) in resting healthy women in the supine position. Increased pulsatile blood flow (evaluated using nuclear magnetic resonance flowmetry) was attributed to an overall increase in below-knee blood flow. However, these increases were not present when re-evaluated after 7 h of normal activity. The bandage-applied pressures had reduced by ~40–50 % to 16–19 mmHg by the second measurement period, so this may represent a causal relationship between the flow and applied pressures (Mayrovitz 1998). While compression bandages are considerably different to sports compression garments (such dramatic changes in the applied pressures over this duration could only be expected using inelastic bandaging), the point remains, if a particular beneficial outcome is present, this outcome may not remain if the applied pressures change beyond certain thresholds.

Compression Garments and Body Coverage

Body Coverage

Compression garments must cover particular body sites to be able to apply compression. The result is either a higher proportion of body surface covered (the addition of coverage for sites that would otherwise be uncovered), or an additional layer of clothing (for sites already covered). Like other clothing, compression garments will influence heat and moisture exchanges between the body and its environment. The effects of coverage may be inconsequential or even useful in some situations, such as during warm up or when the ambient temperature is cool, however, in other situations this coverage must be balanced against comfort and thermoregulatory considerations. While a review of the thermophysiological effects of compression garments is beyond the scope of this chapter, here we briefly introduce some pertinent information about compression garments as a clothing layer per se.

Garment-Body Interactions

Comfort

Given the direct proximity of compression garments with the body covered, comfort is likely to influence an athlete’s tolerance to wearing these garments. Conceptually, wear comfort can be considered to comprise four aspects: thermophysiological, skin sensorial, ergonomic, and psychological wear comfort (Bartels 2005; Yoo and Barker 2005). Thermophysiological wear comfort relates to the way clothing buffers, dissipates or transports metabolic or environmental heat and moisture through the clothing. Skin sensorial wear comfort embodies the mechanical sensations caused by a textile in direct contact with the skin. These sensations (and subsequent perceptions) include smoothness, softness, roughness, stiffness, and the clinging feeling of wet clothing. Ergonomic wear comfort relates to the fit of the clothing and the freedom of movement it allows, and is affected by factors such as the garment design, fabric structure, and extension properties of the materials. Psychological wear comfort is how the individual feels in that clothing, and is influenced factors such as fashion, personal preferences and ideology (Bartels 2005; Yoo and Barker 2005). In speculation, perceived advantages of wearing compression garments will contribute to psychological wear comfort, and under any given conditions, will be balanced against potential disadvantages of thermophysiological, skin sensorial, and ergonomic wear comfort, where such disadvantages exist.

Heat and Moisture

When clothing is worn it establishes a microclimate next to the body. This microclimate is comprised not only of the materials used to form the clothing (fibres, yarns and fabrics), but the air and (if present) moisture within the fabric, between clothing layers (if other layers are worn), and adhered to the surfaces as boundary layers. The exchange of heat between the body and environment occurs via conduction, convection, and radiation. Evaporation also contributes to heat exchange via mass transport (i.e. water vapour transfer). These processes of heat and mass transport depend on gradients (e.g. thermal or vapour pressure), and thus the ambient conditions are also important.

Air is a poor conductor of heat, and because fabrics act to stabilise air within its structure, fabrics are generally good insulators (Wilson et al. 2002). With body movement or ambient air movement, convection displaces warmed air within the fabric microclimate, leading to increased heat loss. Easily displaced air may be advantageous when heat loss is required and disadvantageous when insulation is required.

Sweating is crucial for heat balance during exercise. The interaction of sweat with clothing occurs in both liquid and vapour forms. Clothing typically resists the transfer of water vapour away from the body, thereby increasing the local vapour pressure and reducing the gradient for evaporation at the skin surface. Water vapour transfer, like heat transfer, is augmented by forced convection. Further, the water vapour permeability of a stretched fabric will likely be greater than that of that same fabric in a relaxed state.

Compression garments are often claimed to 'wick' sweat to the garment surface where it can be evaporated easily, but the role of this liquid transportation in increasing *heat loss* from the body appears to lack empirical support. Wicking, also known as capillary transport, is the spontaneous transport of a liquid driven into a porous system by capillary forces (Kissa 1996; Patnaik et al. 2006). It is plausible that capillary transport along the yarns in the spaces between fibres may act to disperse liquid moisture from a wetted area (Saricam 2015), thus contributing to speedier evaporation. Further, with higher levels of liquid, the inter-yarn capillary spaces can saturate, making transverse capillary transport possible (i.e. liquid movement from the skin surface to the outer fabric surface, perpendicular to the plane of the fabric) (Rossi et al. 2011). However, if sweat is transported from the skin surface before it evaporates, the contribution of the skin to the heat of vaporisation will decline. Indeed, the evaporation of sweat from the fabric surface of a garment is less efficient (in terms of heat loss from the body) than evaporation directly from the skin surface itself (Craig and Moffitt 1974; Nagata 1978). The site of evaporation notwithstanding, liquid sweat displaces air and increases fabric thermal conductivity (Chen et al. 2003) and so, in practice, an interaction of increases and decreases in heat and moisture transfer likely occurs with wetted fabrics.

While heat loss is typically desirable during exercise, residual sweat in the garments following exercise can lead to thermal discomfort via unwanted heat loss ('post-exercise chill'). Garments that have a short drying time mitigate such effects (Bartels 2005).

Some Measurable Fabric Properties and Why They Are Useful

Characterising the garments. Much like characterising participants and the applied pressures is useful, so too is characterising a garment system and fabrics from which these are made. Garment properties are not static, but also respond to the conditions in which they are used: moisture from the ambient environment and from the body may be absorbed, adsorbed, or moved through a fabric by a wicking process; an extended textile may exhibit non-elastic behaviour. What properties are relevant to compression and compression products? How might products which superficially appear similar actually differ?

Table 4 lists two groups of fabric properties: those related to structure of the fabric and those related to performance, and for each a list of test methods relevant to compression garments. Note that international test methods dominate, as compliance with these is more likely to yield agreement among interested parties. Note

Table 4 Selected fabric test methods relevant to compression clothing

Property	Test method	Test determines	Title (reference)
Structure			
Thickness	ISO 5084: 1996 (reviewed 2013)	Thickness of textiles and textile products under specified pressure	Textiles—Determination of thickness of textiles and textile products (International Organization for Standardization 1996)
Mass	ISO 3801: 1977 (reviewed 2011)	Mass per unit length and mass per unit area of piece or sample length of fabric and mass per area of small samples	Textiles—Woven fabrics—Determination of mass per unit length and mass per unit area (International Organization for Standardization 1977)
Mass	BS EN 12127: 1998 (current)	Mass per unit area based on measurement of small samples of fabrics	Determination of mass per unit area using small samples (British Standards Institution 1998)
Mass	ASTM D3776 M—09a (reapproved 2013)	Mass per unit area of full piece, bolt, cut, full width specimens, small swatch and narrow fabrics	Standard test methods for mass per unit area (weight) of fabric (ASTM International 2013)

(continued)

Table 4 (continued)

Property	Test method	Test determines	Title (reference)
Elongation with force	ISO 13934-1: 2013	Maximum force, force of rupture, elongation at maximum force and at rupture	Textiles—Tensile properties of fabrics—Part 1: Determination of maximum force and elongation at maximum force using the strip method (International Organization for Standardization 2013b)
Elongation with force	ISO 13934-2: 2014	Maximum force, force of rupture, elongation at maximum force and at rupture of fabrics containing elastomeric fibre	Textiles—Tensile properties of fabrics—Part 2: Determination of maximum force using the grab method (International Organization for Standardization 2014a)
Elasticity	BS EN 14704-1: 2005 (current)	Recovery from extension of fabrics	Determination of the elasticity of fabrics. Strip tests (British Standards Institution 2005)
Performance			
Absorption	ISO 18696: 2006 (reviewed 2015)	Resistance of fabrics to wetting (the absorption of water into, but not through, the fabric). Suitable for measuring the water-repellent efficacy of applied finishes	Textiles—Determination of resistance to water absorption—Tumble-jar absorption test (International Organization for Standardization 2006)
Water penetration (rain resistance)	ISO 18695: 2007 (reviewed 2011)	Resistance of fabrics to the penetration of water by low impact—can predict the probable rain penetration resistance	Textiles—Determination of resistance to water penetration—Impact penetration test (International Organization for Standardization 2007)
Water penetration (water under pressure)	ISO 811: 1981 (revision in progress as ISO/WD811)	Resistance to the passage of water through the fabric	Textiles—Determination of resistance to water penetration—Hydrostatic pressure test (International Organization for Standardization 1981)
Air permeability	ISO 9237: 1995 (reviewed 2011)	Permeability of fabrics to air	Textiles—Determination of the permeability of fabrics to air (International Organization for Standardization 1995)
Thermal resistance	ISO 5085-1: 1989 (reviewed 2015)	Thermal insulation provided by textiles/transmission of heat through a textile	Textiles—Determination of thermal resistance—Part 1: Low thermal resistance (International Organization for Standardization 1989)

(continued)

Table 4 (continued)

Property	Test method	Test determines	Title (reference)
Thermal and water-vapour resistance	ISO 11092: 2014	Thermal and water-vapour resistance using a variety of environmental conditions, involving combinations of temperature, relative humidity, air speed, and in the liquid or gaseous phase, to simulate different wear and environmental situations	Textiles—Physiological effects—Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test) (International Organization for Standardization 2014b)
Exothermic and endothermic properties	ISO 16533: 2014	Exothermic and endothermic properties by moisture absorption and desorption	Textiles—Measurement of exothermic and endothermic properties of textiles under humidity change (International Organization for Standardization 2014c)
Force of seam rupture	ISO 13935-1: 2014	Maximum force of sewn seams when the force is applied perpendicular to the seam	Textiles—Seam tensile properties of fabrics and made-up textile articles—Part 1: Determination of maximum force to seam rupture using the strip method (International Organization for Standardization 2014d)
Force of seam rupture	ISO 13935-2: 2014	Maximum force of sewn seams when the force is applied perpendicular to the seam for fabrics containing elastomeric fibre	Textiles—Seam tensile properties of fabrics and made-up textile articles—Part 2: Determination of maximum force to seam rupture using the grab method (International Organization for Standardization 2014e)
UV	AATCC TM183-2014	Ultraviolet radiation blocked or transmitted by textile fabrics	Transmittance or blocking of erythemally weighted ultraviolet radiation through fabrics (American Association of Textile Chemists and Colorists 2014)
UV	AS/NZS 4399: 1996 (current)	Requirements for determining the rated UV protection factor of sun protective textiles	Sun Protective Clothing—Evaluation and Classification (Standards Australia and Standards New Zealand 1996)

too, that because many properties of textiles differ with ambient conditions, the testing of fibres, yarns, fabrics, and garments is conducted under standard environmental conditions following a period of conditioning in that same environment [typically 24 h at 20 ± 2 °C, 65 ± 4 % relative humidity according to ISO 139 (International Organization for Standardization 2005) or 21 ± 2 °C, 65 ± 5 % relative humidity according to ASTM D1776 (ASTM International 2016)]. However, there may be good reason to test under different conditions, perhaps simulating conditions of use.

Structural properties. Most fabrics are constructed of fibre and in compression products these are typically synthetic fibres (e.g. polyester, polyamide) which may be blended (e.g. with some form of elastane). Most are continuous filaments with various cross-sectional structures, typically with a smooth surface, and may be single or plied. These yarns then are knitted either using weft or warp technologies, yielding different fabric properties, particularly elasticity. Warp knits are typically more resistance to extension than weft knits.

Consider the structural properties listed in Table 4 (and take the following remarks as 'if all other factors are equal'). Thickness of a fabric has a major effect on thermal resistance: the thicker the fabric, the more thermally resistant. Because most fabrics are themselves compressible, the test method for fabric thickness specifies the pressure under which the thickness is measured. Mass of fabrics is expressed in grams per square metre (g/m^2). The relevance here to compression garments is the effect that fabric mass per unit area has on mass of the total garment. The trend in garments generally is for apparel fabrics to be manufactured so the end products are lighter. Elongation is one of several tensile-related properties. Note that while the test requires the strip of fabric to be extended to rupture, investigators are often more interested in extending a fabric/garment an estimated percentage and typically allowing recovery, and repeated extension/recovery cycles (elasticity). Changes evident with this type of test (decay) are a better reflection of a compression garment or bandage, yet, surprisingly few examples of fabric cycling experiments exist (see Section "Changes in Pressure with Wear and Repetitive Use" and "Appendix 2: Multi-axial Extension and Recovery Testing of a Compression Garment Fabric"). Elastic recovery is more likely when the fabric contains an elastane filament (e.g. Lycra® or spandex, or a non-branded elastane). So from the perspective of an end-user interested in compression, knowing that the elasticity changes over time is highly relevant.

Performance properties. The second part of the table focuses on some examples of performance properties. Together these deal with water, air, thermal, and UV properties. In relation to water, interest may be in the extent to which the fabric absorbs moisture (from sweat or from an external source). If a fabric absorbs and holds moisture, either in the fibre itself or in the fabric, this may have a measureable effect on thermal resistance and on perceptions of discomfort of the wearer. Air permeability is self-explanatory: to what extent does air pass through the fabric? The instrument settings for this test depend on the fabric structure, so comparison of test results obtained on different fabrics where the settings have differed is not appropriate. Thermal resistance too, is self-explanatory: to what extent does a fabric resist transmission of heat? The physical set-up for the test attempts to simulate the skin-fabric interface. Fabrics differ in thickness and mass, as noted in the preceding section, and both of these properties affect thermal transmission: a thicker fabric will typically exhibit greater resistance. So for comparisons among fabrics, derived values can also be used (e.g. warmth: weight, warmth: thickness). Resistance to water vapour transmission is measured using a similar set-up, with a thin layer of water on the plate, and ratios are also derived for appropriate comparisons among fabrics. Compression garments are often worn outdoors, and in Australasia, protection against UV penetration is a health-related consideration. Fabrics will be extended during wear so testing when extended will provide a more useful indicator of fabric performance in this regard.

To summarise, fabrics for compression items, while appearing similar, will differ in properties when new and when worn. They are not static, but change during use, absorbing moisture (or not), changing in thickness when extended, which in turn reduces thermal resistance. Thus, simply reporting fibre content and perhaps country of origin (manufacture) on a label or promotional information for a compression item is unlikely to provide sufficient information for use in scientific investigations of effects of compression garments, or indeed, for the consumer's personal information. Further, while test results on some fabrics may be provided by manufacturers/suppliers, these need to be scrutinised to ensure an appropriate method has been used. Reporting fabric and garment properties also helps identification of/changes in manufacturing trends over time and, in particular, assists in establishing whether comparability of findings from different studies are warranted. For example, the compression shorts used in one highly cited study were 4.76 mm thick and made from 75 % closed-cell neoprene and 25 % butyl rubber (Doan et al. 2003); conventional sporting compression garment fabrics have been reported as less than 0.7 mm thick (MacRae et al. 2012; Del Coso et al. 2014).

Comments and Conclusions

Compression garments apply pressure to *and* cover body surfaces. In this chapter we have deliberately highlighted aspects of pressure and coverage that can be of importance yet often have been overlooked. In particular, we argue that measuring, reporting, and understanding characteristics of the applied pressures in vivo are essential for integrating the literature irrespective of whether or not compression influences a particular outcome. That is, to support or rule out the influence of compression, the compression itself must be known. Further, it is not yet clear what applied pressures are required, particularly across different outcomes. We have also introduced aspects relevant for compression garments from the perspective of a layer of clothing that covers the body. Body coverage can have consequences for heat and moisture interactions with the environment, and for wearer comfort. We hope that the detail here helps the reader to contextualise and critically evaluate research on compression garments in sport.

For further detail specifically about the physiological or performance effects of compression garments in sport we refer the reader to the other chapters in this book and previously published reviews or commentaries (e.g. Kraemer et al. 2004; Perrey 2008; MacRae et al. 2011; Born et al. 2013; Hill et al. 2014a; Surhoff 2014; Beliard et al. 2015; Marqués-Jiménez et al. 2016).

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Appendix 1: Search Details for Table 1

For the purpose of summarising key characteristics (Table 1), a systematic search was performed to identify relevant journal articles published over a ~5-year period (2011 to 15 Jan 2016). Inclusion criteria were: (1) original research studies involving human participants and published in English, (2) studies in which compression garments were worn for sport and exercise or recovery from sport and exercise, and (3) that compression garments were worn for a period or periods during and/or after sport and exercise. There was no restriction on type of compression garment in terms of body area covered, although the garment was to be similar to commercially available sporting garments (e.g. bandaging was excluded). Exclusion criteria were: (1) studies in which compression garments were used for recovery from injury, (2) use for disease prophylaxis, even if in association with exercise (e.g. exercise in patients with lymphedema), and (3) abstracts and unpublished studies. The search was performed in Ovid® MEDLINE using the search strategy (Table 5), identifying 166 articles. One author (BM) screened the results first by title and abstract (101 excluded: 9 reviews or commentaries, 1 repetition, 91 topic medical, not compression garments, and/or not sport) then by full text (12 excluded: 3 injury related, 5 not sport or exercise, 4 due to garment); 5 further articles were located from reference lists giving a total of 58 included (Ali et al. 2011; Dascombe et al. 2011a; Goh et al. 2011; Lovell et al. 2011; Ménétrier et al. 2011; Miyamoto et al. 2011; Sperlich et al. 2011; Varela-Sanz et al. 2011; Dascombe et al. 2011b; Burden and Glaister 2012; Coza et al. 2012; de Glanville and Hamlin 2012; Hamlin et al. 2012; MacRae et al. 2012; Rimaud et al. 2012; Wahl et al. 2012; Argus et al. 2013; Bahnert et al. 2013; Barwood et al. 2013; Bovenschen et al. 2013; Driller and Halson 2013a; Faulkner et al. 2013; Pruscino et al. 2013; Rugg and Sternlicht 2013; Sperlich et al. 2013a; Tsuruike and Ellenbecker 2013; Valle et al. 2013; Driller and Halson 2013b; Bieuzen et al. 2014; Born et al. 2014a; Del Coso et al. 2014; Duffield et al. 2014; Ferguson et al. 2014; Goto and Morishima 2014; Lien et al. 2014; Michael et al. 2014; Miyamoto and Kawakami 2014; Pereira et al. 2014a; Rider et al. 2014; Sperlich et al. 2014; Venckunas et al. 2014; Vercruyssen et al. 2014; Born et al. 2014b; Hill et al. 2014b;

Table 5 Search terms

Item #	Search term/search restriction	Number of results
1	compression.ti,ab.	82,145
2	compressive.ti,ab.	15,945
3	1 or 2	94,566
4	clothing.mp.	16,689
5	(garment or garments).mp.	1929
6	(stocking or stockings).mp.	4479
7	(sock or socks).mp.	811
8	(sleeve or sleeves).mp.	6599
9	tights.mp.	48
10	leggings.mp.	23
11	shorts.mp.	277
12	top.mp.	67,366
13	upper-body.mp.	3442
14	lower-body.mp.	9254
15	4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14	108,307
16	3 and 15	2951
17	exercise*.mp.	278,507
18	sport*.mp.	71,794
19	physical activity.mp.	66,804
20	(run or running or ran).mp.	118,260
21	(cycle or cycling or cycled).mp.	432,976
22	endurance.mp.	28,954
23	sprint*.mp.	4923
24	resistance.mp.	654,350
25	17 or 18 or 19 or 20 or 21 or 22 or 23 or 24	1,500,610
26	16 and 25	429
27	limit 26 to yr = "2011—Current"	175
28	limit 27 to english language	166

Pereira et al. 2014b; Areces et al. 2015; Armstrong et al. 2015; Gupta et al. 2015; Hooper et al. 2015; Lucas-Cuevas et al. 2015; Martorelli et al. 2015; Ménétrier et al. 2015; Mills et al. 2015; Miyamoto and Kawakami 2015; Priego et al. 2015; Priego Quesada et al. 2015; Stickford et al. 2015; Zaleski et al. 2015).

Appendix 2: Multi-axial Extension and Recovery Testing of a Compression Garment Fabric

Garment pre-treatment and cutting of fabric samples. Unworn upper-body compression garments to be used for fabric testing (for garment descriptions see MacRae et al. 2012) were subjected to six consecutive gentle wash cycles as outlined in procedure 8A in ISO 6330 (International Organization for Standardization 2000) and air dried in ambient laboratory conditions. This pre-treatment protocol has been shown to achieve reasonable stability in properties of a range of fabrics (Gore et al. 2006). An Electrolux Wascator FOM71MP-Lab (James Heal and Co Ltd., Halifax, England) automatic washing machine was used with Heal's ECE formulation non-phosphate reference detergent (B). Standard ballast (knitted 100 % polyester fabric) was used to make up the total dry mass of 2 kg per load of test garments. Fabric specimens were cut from garments according to BS EN 12751 (British Standards Institution 1999). Fabrics were conditioned (for 24 h) and tested in a standardised environment 20.0 ± 2.0 °C and 65.0 ± 4.0 % relative humidity (International Organization for Standardization 2005).

Multi-axial extension and recovery. The behaviour of a compression garment fabric (n = 3) during extension and recovery cycling was examined in accordance with a modified version of ISO 3379 (International Organization for Standardization 1976). An Instron Tensile Tester (Model 4464, Instron Limited, England) with a 100 N load cell was fitted with a ball burst attachment (half sphere, diameter = 50 mm) that cycled between fixed extension limits. Fabric specimens (diameter = 100 mm within clamping ring) were pre-loaded with the ball burst attachment to 0.5 N (i.e. moderate extension), and cycled to a depth of 10 mm from the pre-load zero point for 7000 cycles, with a head speed of ~1000 mm/min (~50 cycles/min). The number of cycles was selected to approximately represent one exercise session (e.g. bicycling with a cadence of 90 RPM, 7000 extension and recovery cycles is ~78 min of exercise). Load data were transferred to PC computer (PowerLab 16 SP; ADInstruments, Dunedin, New Zealand) and collected at 1000 Hz using Chart software (Chart 4.2 for Windows; ADInstruments). Means for cyclic minima and maxima were calculated at the beginning, middle, and end of cycling, each over 15-min periods (minutes 0–15, 62–77, and 127–142). Note that the tensile tester required 142 min to complete the 7000 cycles (cf. the estimate of 78 min for exercise with a pedalling cadence of 90) because it was not practicable to have a head speed equivalent to 90 cycles/min. Linear mixed models with a compound symmetry covariance matrix was used for statistical analysis (SPSS 16.0, SPSS Inc). Bonferroni correction for multiple comparisons was used when required.

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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

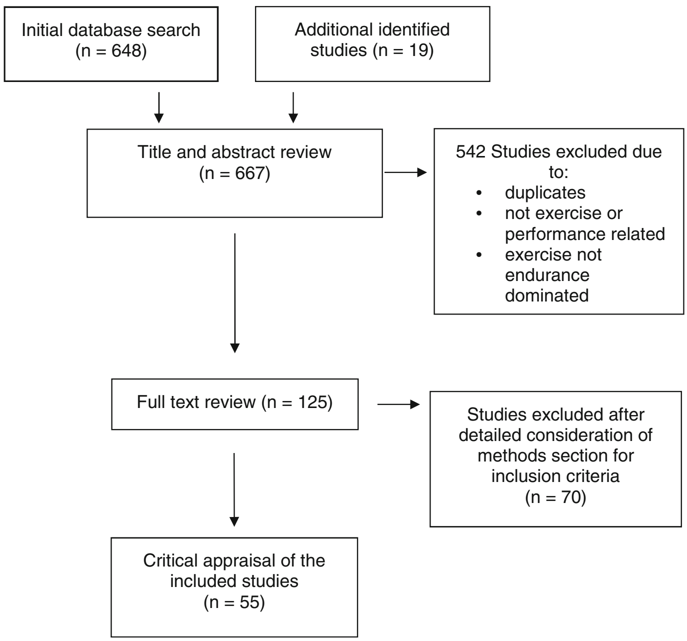

Fig. 1 Pathway of identified and subsequent excluded or reviewed articles

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)

		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
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 ↑

(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
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 ↔

(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
Goh et al. (2010)	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 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}

(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
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 $\leftrightarrow$, HR $\leftrightarrow$, RPE $\leftrightarrow$ R: SO_2 calf during rest and recovery $\uparrow$
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 $\uparrow\downarrow$, La $\leftrightarrow$, CP $\uparrow\downarrow$, SO_2 $\leftrightarrow$, HR $\uparrow$
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 $\leftrightarrow$, TTE $\leftrightarrow$, La $\leftrightarrow$, RPE $\leftrightarrow$, VO_2 $\leftrightarrow$, HR_{peak} $\leftrightarrow$, % HR_{max} $\uparrow$, Kinematics $\leftrightarrow$ Running economy test: TTE $\leftrightarrow$, HR $\leftrightarrow$, La $\leftrightarrow$, RPE $\leftrightarrow$, VO_2 $\leftrightarrow$
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 $\leftrightarrow$, La $\leftrightarrow$, HR $\leftrightarrow$, CMJ $\leftrightarrow$, RPE $\leftrightarrow$
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 $\leftrightarrow$, La removal post test $\leftrightarrow$, HR $\uparrow\downarrow$

(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
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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Effects of Compression Garments in Strength, Power and Speed Based Exercise

Rob Duffield and Judd Kalkhoven

Abstract Compression apparel is a popular method to aid sports performance and recovery. The ubiquitous nature of compression garments in sport attests to their popularity with athletes. In particular, use of compression clothing is evident in a range of strength and power focused sports. Regardless of their popularity, a growing theme of research in this area highlights the mixed, if not neutral, effects of compression garments on athletic performance and recovery. In part such conclusions stem from the diverse nature of research projects and exercise modes utilised. Thus a more detailed focus of the effects of compression apparel on specific physical capacities is warranted. This chapter will respectively discuss the effects of compression garments on strength, power and repeated-effort exercise. Further, hypothesised mechanisms for the improvement, or lack thereof, in performance indices will be provided. The findings of this discussion will suggest that the use of compression garments show mixed, if not minimal, benefits for exercise performance for prolonged repeat-sprint athletes. However, some small benefits for maximal strength or peak power movements may be evident. Furthermore, whilst compression garments show minimal recovery benefits, some evidence for small improvements in muscle damage marker clearance may exist. Despite the limited evidence for improved performance, compression garments seem beneficial for the reduction of muscle oscillation and perception of reduced exercise-induced muscle soreness (possibly resulting from a placebo effect). Accordingly, the addition of compression garments may be warranted to assist in the perceived readiness of an athlete to train or compete.

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Introduction

Training and competition demands increase the physical and perceptual stress on the athletic body. A popular method to aid performance and recovery includes the use of compression therapy (Kraemer et al. 2001a, b; Gill et al. 2006). Compression therapy incorporates external, skin-tight synthetic garments with engineered stitching aimed at increasing the compressive forces exerted against the skin. Specifically, the compressive forces are suggested to replicate the natural shape of skeletal musculature and provide distal to proximal graduated compression to aid muscle pump regulated venous return (Agu et al. 1999; Ali et al. 2011). The principle of compressive support is to artificially increase extra-vascular pressure, and thus to assist return the difference between extra- and intra-vascular pressures to values closer to resting. As evidenced in Fig. 1, compression garments are reported to provide compressive forces of 8–20 mmHg at the ankle, although medical grade compression may be as high as 30 mmHg (Ali et al. 2007; Dascombe et al. 2011). Regardless of the actual or perceived compressive force of the garments, their ubiquitous nature in sport attests to their popularity with athletes. In particular, use of compression clothing is evident in a range of strength and power focused sports, especially sprint, jump and resistance-based sports (Kraemer et al. 1998a, b; Doan et al. 2003; Born et al. 2013).

External compressive support is suggested to have a range of physiological effects, including the minimisation of oedema accumulation, improved microcirculation, maintenance of venous return, improved metabolite removal and improved muscle efficiency (Berry and McMurray 1987; Bringard et al. 2006). Accordingly, the use of compression garments as a performance intervention has gained popularity based on initial clinical evidence of improved venous return in patients with peripheral vessel disease complications (Agu et al. 1999; Kahn et al.

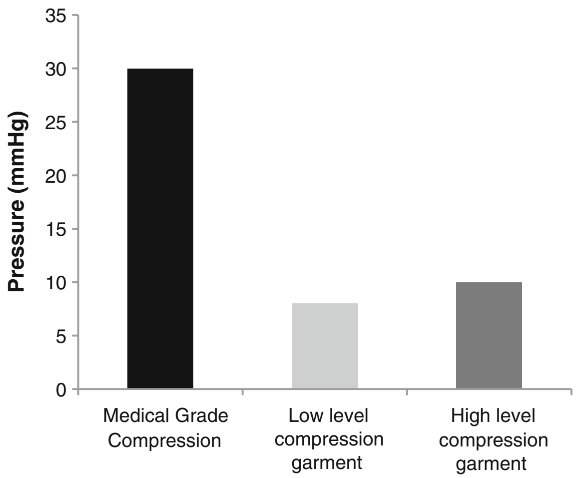

Fig. 1 Examples of the pressure (mmHg) exerted against the skin at the ankle by respective types of compression apparel

2003). More relevant to strength and power athletes, it has been hypothesised that compression garments can improve athletic performance through improved power production and assistance with a more efficient muscle unit (Doan et al. 2003). In part, the improvement in movement efficiency is suggested to result from greater support and amplified proprioceptive feedback (Iles 1996; Doan et al. 2003; Bernhardt and Anderson 2005). However, despite these assertions the evidence from studies on athletic populations as to the performance benefits of compression garments in strength, power and speed-based activities remains equivocal (Barnett 2006).

Use of compression garments in athletic populations owe their origins to medical evidence suggesting that external compression can improve venous return and lymphatic swelling via the maintenance of peripheral pressure in post-operative and venous disease patients (Lawrence and Kakkar 1980; Kahn et al. 2003). Clinical evidence in fact, supports the use of medical grade compression stockings to improve the external peripheral gradient by assisting the distal to proximal regulation of venous return and reduction of lymphatic swelling (Mayberry et al. 1991; Ibegbuna et al. 2003; Agu et al. 2004). Venous return requires a series of muscular pumps and valves to overcome the constraints of hydrostatic pressure and gravity to funnel venous blood back to the heart (Lawrence and Kakkar 1980). It is presumed that the superficially applied compressive force of the garments assists to increase extra-vascular pressure and provide additional distal to proximal support of pressure gradients to prevent peripheral venous pooling (Agu et al. 1999; Kahn et al. 2003; Dascombe et al. 2011). From a clinical perspective, such additional pressure for circulatory or musculoskeletal systems degenerated by age or disease, additional compressive support can prevent ensuing secondary issues arising from disease or post-operative care (Kahn et al. 2003). Consequently, compression therapy has evolved into an important part of the training and recovery procedures of many athletes (Kraemer et al. 1996; Gill et al. 2006). Although the musculoskeletal and circulatory systems of highly-trained athletes are in opposition to that of a post-operative patient, it is thought the stress and demands of regular high-intensity training may create an environment whereby compressive therapy may assist musculoskeletal performance during these exercise-induced stresses.

However, to date evidence-based support of the role of compression therapy for healthy, highly-trained strength and power-based athletic populations remains mixed (Scanlan et al. 2008; Duffield et al. 2010). While it is suggested compression garments can be worn both during training or competition (depending on uniform and sponsorship requirements), the evidence supporting the use of compression therapy for performance outcomes is of lower abundance than the positive perceptual assistance they provide. To date, several studies suggest some benefit for the performance of maximal counter movement jumps (Kraemer et al. 1996; Doan et al. 2003). Further, several studies suggest compression therapy may improve the recovery of some physiological and perceptual markers of post-exercise muscle damage (Trenell and Thompson 2006; Duffield and Portus 2007). However, few studies report any performance improvement alongside these altered perceptual and physiological responses (Duffield et al. 2008; French et al. 2008; Davies et al. 2009).

Regardless, compression therapy is often used as a method to aid sports performance; with athletes commonly wearing compression garments in both training and competition environments. Given the high prevalence of compression garment use by elite and sub-elite athletes, a greater awareness of the efficacy of such ergogenic aids is important. In particular, the popularity and use of part- or full-body compression in elite speed, power and team-sport athletes are of note. Accordingly, the aim of this chapter is to discuss the evidence of using compression therapy, particularly via the use of whole-body or full lower-body garments, on performance of speed, strength and power based activities.

Effects of Compression Garments on Strength Performance

Research on the effects of compression garments on strength performance remains minimal, with the majority of research in this area focussed on recovery, blood flow and fatigue minimisation (Born et al. 2013). Regardless, it appears that compression garments may result in small improvements in force production and strength performance; in part, via changes in intramuscular pressure (IMP), mechanomyography (MMG) and electromyography activity (EMG) (Born et al. 2013). Additionally, compression may improve repeated strength performance by delaying the onset of peripheral fatigue (Miyamoto et al. 2011). However, the absence of clear research outcomes in this area means the influence of compression on strength performance is largely theoretical.

Doan et al. (2003) suggest that compression garments may contribute to improved maximal force production through enhanced proprioception. Though not directly measured, it was hypothesised that compression garments enhance the activation of mechanoreceptors in the superficial tissues of the human body. If so, activated mechanoreceptors located in the skin, muscles, ligaments, joint capsules, and connective tissue reduce presynaptic inhibition (Iles 1996) and serve as a major contributor to sensory feedback (Bernhardt and Anderson 2005). As such, greater activation of these mechanoreceptors will likely result in boosted sensory feedback and subsequently improved proprioceptive capabilities which may be beneficial to strength performance. However, such mechanisms remain more speculative than supported by empirical evidence.

Compression garments have also been theorised to dampen the natural muscular oscillations that occur during muscle contraction (Doan et al. 2003). In turn, these reduced oscillations were suggested to result in improved strength performance. Several studies thus far suggest compression clothing can decrease the oscillatory displacement of the leg muscles during high-load contractions (Kraemer et al. 1998a, b; Doan et al. 2003). As justification, reductions in muscle oscillations appear to reduce the number of recruited muscle fibres required to perform a given work output (Nigg and Wakeling 2001). Considering strength performance largely relies on neural factors such as muscle activation and recruitment strategies, beneficial effects would ensue from a combination of delayed fatigue and reduced structural damage resulting from reduced oscillation (Doan et al. 2003). However, it appears that relatively high amounts of pressure are necessary to reduce the oscillatory displacement (Nigg and Wakeling 2001), and therefore careful consideration of the impact of such pressure on blood flow is crucial. Greater research is still required to clarify the optimal amount of pressure exerted by compression clothing and whether reduced oscillatory displacement without altered hemodynamics is possible (Born et al. 2013).

Preliminary studies have investigated the role of commercially available compression on strength based activities, including maximal voluntary contraction (MVC) and EMG (Fu et al. 2012; Born et al. 2013). For example, Miyamoto et al. (2011) examined the effects of wearing a graduated elastic compression stocking, with different pressure profiles, during a fatiguing calf-raise exercise session on triceps surae torque. The protocol used consisted of 15 sets of 10 repetition MVC's interspersed by 30 s rest periods on a dynamometer. The authors reported triceps surae EMG amplitude was not altered by varying pressure levels induced by the compression socks. Furthermore, no significant differences in MVC torque was observed among three different stocking conditions, including low (7–8 mmHg), medium (7–19 mmHg) and high (10–30 mmHg) graded compression (knee to ankle). Miyamoto et al. (2011) suggests that these findings may have occurred due to MVC and EMG amplitude being dependent on central fatigue, on which compression wear is unlikely to impart any influence. Although some research has been conducted in this area, Fu et al. (2012) maintains that a lack of clarity still surrounds the effect of external devices that increase IMP on EMG and MMG and resultant maximal force outcomes. Regardless, the effect of compression apparel to improve force or torque from central mechanisms seems unlikely; there may still be a role for performance improvement via peripheral factors.

Although largely unexplored, recent research suggests that compression wear may enhance repeated strength performance by delaying the onset of peripheral fatigue; although not directly enhancing intrinsic muscular strength per se. In the same aforementioned study, Miyamoto et al. (2011) reported that compression stockings exerting the highest graded pressures minimised the reduction of evoked torque in the triceps surae during repeated calf raise MVC. Additionally, these same compression stockings elicited superior mean power during the extensive calf raise protocol. These findings led to suggestions that certain (higher) graded pressure induced by external compression wear may enhance repeated strength performance. Such performance enhancement was attributed to the delay in peripheral fatigue, with the authors hypothesising increased venous flow velocity as the main contributor to these outcomes.

Given the above findings, research relating to the effects of compression garments on maximal strength performance remains somewhat limited. That said, compression apparel may have some benefit for strength performance via increased proprioception and reduced muscular oscillations during muscle contraction.

Additionally, the influence of intramuscular pressure on muscle activation and maximal force outputs remains an intriguing area of research that is yet return definitive conclusions. Despite the lack of clarity surrounding the effect of compression wear on maximal force production it appears that external compression devices may have some benefit for strength athletes.

Effects of Compression Garments on Speed and Power Performance

The abundant use of compression garments in athletic populations is perhaps best exemplified in the speed and power-based sports, i.e. sprinting, football, basketball etc. In part, this popularity likely stems from the belief that compression can provide a mechanical advantage in muscle force production that can transferred into a sporting performance improvement. For example, Doan et al. (2003) reported a 5 % increase in maximal jump height when wearing compressive shorts relative to a non-compression condition. The authors postulated that the elasticity and compression from the shorts provided an ergonomic mechanism to enhance power production. It should be noted that the compression shorts used in this study were designed to provide a greater level of compression than the conventional spandex or Lycra compression garment, as based on the materials of the shorts and customised fitting to limbs (Doan et al. 2003). Kraemer et al. (1996) investigated the effect of compression shorts in performing a series of countermovement jumps for collegiate level volleyball players. In contrast to the above finding, this study found that wearing compression had no effect on maximum height achieved for a single jump; however, there was increased force production over a series of repeated vertical jump efforts (Kraemer et al. 1996). The findings from this study suggest that compression could offer an athletic advantage in the maintenance of repeated peak power, which could be of benefit for athletic events requiring repeated explosive efforts.

Conversely several studies have found that wearing compression garments do not elicit any improvement in maximal power. For example, a number of studies have reported compression to have no effect on vertical jump performance (Jakeman et al. 2010; Kraemer et al. 2010). Likewise, no difference was reported for sprint performances over 20 m (Duffield et al. 2010, 2008; Duffield and Portus 2007) 60 m (Doan et al. 2003) or 400 m distances (Faulkner et al. 2013). In addition to no change in running speed, Duffield et al. (2010, 2008) assessed the influence of wearing lower-body or full-body compression on repeated sprint ability for representative level team sport athletes (cricket and rugby). Unlike Kraemer et al. (1996) who found compression assisted in the maintenance of lower leg power as measured by vertical jump performance, compression did not result in any benefit on the maintenance of sprint times. It can be theorised that the purported mechanistic assistance of decreased oscillation offered by compression garments may elicit improvement in maximal jump performance, but in sprinting, the magnitude of mechanistic assistance from compression garments becomes of less significance. There is also argument that the cardiovascular or heamodynamic benefits derived from compression garments have no effect on anaerobic and power based performance tasks (Higgins et al. 2009). In summary, the nature of the garment i.e. short versus long leg and the respective task i.e. multi- or single-limb, seemingly cloud the clarity of findings in relation to the effects of compression garments on speed and power activities.

Effects of Compression Garments on Repeated-Effort Performance

Team sports involve intermittent demands of near maximal effort, separated by varying lengths and durations of sub-maximal intensities over prolonged durations of 60–120 min (Carling et al. 2008). Again, few studies highlight any improved performance during repeated-sprint exercise (Higgins et al. 2009; Houghton et al. 2009) or sub-maximal bouts separating maximal efforts (Duffield and Portus 2007). Although Sear et al. (2010) suggest that compression garments may improve prolonged intermittent-sprint performance due to improved muscle oxygenation, particularly with improved metabolic adjustments between high-intensity efforts. Moreover, the ability to maintain repeated counter movement jump has been reported to be improved with compression shorts (Kraemer et al. 1996), despite evidence to the contrary in peak vertical jump (Bernhardt and Anderson 2005; Davies et al. 2009). Regardless, the improvement in repeated effort power performance remains equivocal.

Gill et al. (2006) reported that the use of compression garments following competitive rugby was physiologically beneficial, in that post-match markers of muscle damage were reduced with compression; although, the applied field-based nature of the study precluded any measure of performance. Montgomery et al. (2008) reported the use of compression garments following competitive basketball matches in a consecutive day tournament scenario. However, of the post-match recovery interventions used (cold water immersion, carbohydrate consumption and stretching and compression therapy), compression was the least effective at maintaining sprint and agility performance across the 3-day tournament. Similarly, Duffield et al. (2008) reported that on consecutive days of intermittent-sprint exercise simulating the demands of a rugby match, peak and repeated speed and peak power in a single-man scrum machine were not different to a control condition. In agreement, Davies et al. (2009) reported no change in repeated sprint or agility for 48 h following repeated plyometric drop jumps in lower-body compression garments. Furthermore, as highlighted earlier, Duffield et al. (2010) suggested that compression garments did not alter skeletal muscle function during or following high-intensity, intermittent sprint and plyometric activity. Despite inducing significant decrements in skeletal contractile function, compression garments did not improve the acute (2 h) or prolonged (24 h) recovery of muscle function and force production. Accordingly, a majority of studies on repeated effort performance following simulated or actual team-sport suggest few ergogenic effects with the use of compression therapy.

In summary, a mixture of positive and negligible evidence exists for the use of compression garments as a repeat-sprint performance aid. However, compression garments do not seem to be deleterious for maximal repeated effort bouts or power production. Such findings may suggest that the use of compression therapy for the physical demands of training or competition may not directly be performance enhancing. It is also evident that no negative side effects are reported with the modalities of use suggested in the literature.

Effects of Compression Garments on Recovery of Strength and Power

Speed and power athletes require the production of high skeletal neuromuscular force in a co-ordinated and controlled fashion (Kraemer et al. 2001a, b; Doan et al. 2003). Post-training or competition recovery often relates to the regeneration of peak contractile force production following the cessation of exercise. Compression garments are proposed to improve force production via the reduction in muscle vibration (Doan et al. 2003), and increased clearance of metabolites (Berry and McMurray 1987; Trenell and Thompson 2006) resulting in improved contractile function. However, research evidence for the faster regeneration of post-exercise muscle force following the use of compression garments is mixed (e.g. Kraemer et al. 2001a, b; Duffield et al. 2010).

Several studies have reported increased force production in repeated vertical jump efforts (Kraemer et al. 1996) and faster recovery of force production in single arm bicep curls (Kraemer et al. 2001a, b) between 24 and 72 h post-exercise. Specifically, Kraemer et al. (1996) suggest that in high-performance volleyball players, lower-body compression garments can maintain peak jump height during the performance of repetitive maximal counter movement jumps. Conversely, several studies have shown no improvement in the 24 h recovery of skeletal muscle force production (Duffield et al. 2010) or maximal sprint times (Doan et al. 2003; Duffield et al. 2008). These studies report that following repeated sprint and maximal plyometric bounding activities, maximal quadriceps force did not differ 2- or 24 h following exercise with compression garments. French et al. (2008) reported no change in 10–30-m sprint time, 5RM squat or counter movement jump distance when compression garments were worn for 12 h following heavy squat and eccentric load lifting. Despite mixed findings, there does seem to be some evidence that compression garments may assist the maintenance of maximal vertical jumping ability (as measured by the height reached with a counter movement jump), which has been often used to monitor recovery patterns of mechanical power production in the lower limbs for athletes requiring short-duration, maximal efforts.

Potential Mechanisms of Compression on Strength, Speed and Power Markers

Mechanical Contraction

It has been hypothesised that compression garments can improve athletic performance through improved power production and muscle unit efficiency (Doan et al. 2003). This is propsed to occur by a dampening of the oscillating forces experienced by the muscle, resulting in reduced muscle fatigue. The mechanical advantage of compression can also transfer into an improvement in power performance. It has been suggested that constriction of the muscle unit allows it to transfer muscular force more efficiently. Doan et al. (2003) used video and motion analysis to evaluate the effect of wearing mid-length neoprene and rubber compressive shorts on a vertical jump movement. The authors reported a reduction in muscle oscillation during the landing phase of the vertical jump. In a different application, Sperlich et al. (2013) exposed downhill skiers to 3 min of vibration via an oscillating vibration platform whilst wearing a compression shorts and socks. There was a decreased level of muscle activity, as measured via EMG of upper and lower leg muscles and lower perceived exertion (RPE) reported by participants in the compression condition. Such findings suggest that compression can offer a mechanical advantage in dampening muscle oscillation, countering fatigue and lowering perceived exertion in power-based activities such as sprinting and jumping (Doan et al. 2003; Sperlich et al. 2013).

Maximal force production is a result of both voluntary and involuntary skeletal muscle recruitment, alongside the efficiency of force transmission from muscle to tendon (Hill 1938). Duffield et al. (2010) reported no change in either voluntary peak contractile force, superimposed stimulated force or the rate of force production in fatigued muscles when wearing compression garments. These findings suggest that when stimulated, the muscle could produce no more force than without compression garments. Such lack of difference between conditions with superimposed contractile force suggests no neuromuscular differences exist due to the compression garments. Accordingly, it may be the improved mechanical efficiency of whole muscle movements that explains the observed improvements in muscle function with compression garments.

Metabolite Removal

An important tenant of the role of compression is often suggested to be the reduction of metabolite accumulation; particularly the reduction of blood lactate, which may have influence (via pH mediated changes) on muscle contractile function and production of peak power (Barnett 2006). Contrasting findings are evident for the effect of compression therapy on post-exercise lactate accumulation (Berry and McMurray 1987; Chatard et al. 2004). Specifically, Berry and McMurray (1987) reported that a faster reduction in lactate was evident with compression socks following a maximal cycling protocol. Lactate accumulation was reduced during exercise and recovery with compression, but not when compression was only used during exercise. These authors suggested some compressive effect resulted in slower lactate diffusion into the blood, resulting in intracellular accumulation. Conversely, Duffield et al. (2010) reported no difference between lower-body compression and a control group for the post-exercise change in lactate, pH or HCO_3 following high-intensity plyometric exercise. While some benefit of compression therapy to aid removal of metabolites has been reported, a majority of studies report no blunting of post-exercise metabolite accumulation (Duffield et al. 2010). Furthermore, increased metabolite accumulation, that is not otherwise explained by increased exercise intensity, has not been reported following recovery in compression garments, suggesting few negative effects are present. Accordingly, an altered removal rate may indirectly indicate altered blood flow or physiological functioning due to the use of compression garments. Regardless, to date limited evidence exists to indicate either during or following exercise that compression garments alter the appearance or removal of exercise-induced markers of metabolism.

Muscle Damage Markers

The strenuous demands of regular strength and power training or competition may result in skeletal muscle damage, and hence the appearance of indirect markers of that damage into the blood (Halson et al. 2002; Peake et al. 2005). Accordingly, a popular use of compression garments includes the attempt to remove or reduce blood-based markers of muscle damage during highly strenuous exercise (Gill et al. 2006; Davies et al. 2009). Evidence of the effects of compression to improve clearance of post-exercise markers of muscle damage is mixed, although several studies suggest that the benefits of using compression garments may relate to the reduction of exercise-induced damage (Trenell and Thompson 2006; Kraemer et al. 2001a, b). Gill et al. (2006) reported a reduction in Creatine Kinase (CK) following competitive rugby matches compared to passive recovery. They concluded that compression therapy was effective at enhancing the rate of recovery of CK following matches, for which markers were often elevated for up to 72 h post-match.

Furthermore, Duffield and Portus (2007) reported a trend for lowered CK values 24 h post-exercise when wearing compression garments as an overnight recovery tool. The exercise involved repeated sprint and throwing exercise to induce significant muscle damage, and the use of different full-body compression garments suggested improved clearance rates. Additionally, Trenell and Thompson (2006) reported reduced appearance of phosphodiester as an indicator of skeletal muscle damage following prolonged downhill and eccentric walking. Further, Kraemer et al. (2001a, b) reported reduced CK values 2–5 days following eccentric exercise with compression sleeves. Alongside these reductions, Kraemer et al. (2001a, b) have also reported the reduction in muscle girth as an indirect measure of post-exercise oedema and swelling. These results highlight the use of compression garments during and following strenuous exercise may provide some amelioration of the appearance of muscle damage markers, possibly through altered inflammatory responses as opposed to compression-induced vasoconstriction. In contrast, several studies report no benefits of compression to reduce muscle damage markers (Davies et al. 2009). Specifically, several studies have reported no difference in CK or c-reactive protein (CRP) values in the short (2 h) or prolonged (24 h) periods post-exercise (Duffield et al. 2008, 2010). In particular, these protocols elicited repeated and maximal efforts of lower body musculature. Regardless, neither inflammation nor damage markers were altered as a result of full-length lower-body compression garments. Accordingly, equivocal evidence exists for the use of compression garments as a tool to promote improved clearance of muscle damage markers following high-intensity strength and power exercise.

Perceptual Soreness

Despite the equivocal results relating to improved strength and power performance, compression garments seem a powerful tool to aid the perceptual state of an athlete (Jakeman et al. 2010). Although such findings suggest the notion of a placebo effect, an athlete's perceived readiness to perform is of high importance for the daily rigours of high volume or intensity demands (Barnett 2006; Gill et al. 2006). For example, numerous studies report that following high-intensity speed and power-based exercise, compression garments result in decreased sensations of muscle soreness and improved perception of recovery (Duffield et al. 2010; Kraemer et al. 2010). In particular, it seems the greater the induced soreness as a result of exercise load, the more tangible the perceptual benefits of compression (Chan et al. 2016). Accordingly, multiple studies report that when worn during eccentric or high-intensity exercise, compression garments result in the suppression of perceived muscle soreness for up to 48 h (Doan et al. 2003; Duffield et al. 2008, 2010).

However, it must be recognised that few studies use a “sham” control, and when non-compressive elastic stockings are used as a control condition, perceptual effects of compression are ameliorated (Ali et al. 2007). Specifically, Ali et al. (2007) reported that the use of elastic tights had no physiological effects but resulted in reduced perception of soreness. Accordingly, reductions in post-exercise perceptual muscle soreness following training and competition may not relate to any physiological effect of the compression itself. Regardless, post-training or competition perceptual benefits of reduced muscle soreness may still be of importance for ensuing sessions. Further, no studies report any negative effects of compression to increase muscle soreness or perceived fatigue. Accordingly, for athletes these benefits may be of from continued stressors imposed by training or competition or possibly during prolonged travel (Hagan and Lambert 2008).

Conclusions

A growing theme of this chapter highlights the generally mixed, if not neutral, effects compression therapy has on athletic performance and recovery. In order to assist tease out this theme, we have created a visual representation of some of the current collection of research data. Figure 2 outlines the volume for research suggesting positive (green bars), neutral (orange bars) or negative (red bars) effects of compression garments on a range of performance, physiological and perceptual responses. As per the information provided above, a distinct lack of beneficial effects are present for the use of compression therapy as a recovery tool; although this is matched by the few studies reporting any negative side effects of compression therapy.

In conclusion, compression garments show mixed, if not minimal, benefits for exercise performance for prolonged repeat-sprint athletes; although some benefits for maximal strength and peak power movements may be present. Furthermore, compression garments show minimal recovery benefits for most physiological systems; however, some evidence for small improvements in muscle damage marker clearance may exist. Despite the limited evidence for improved performance or physiological responses, compression garments seem beneficial for the reduction of muscle oscillation and improved perception of exercise-induced muscle soreness (possibly resulting from a placebo effect). Accordingly, the addition of compression garments may be warranted to assist in the perceived readiness of an athlete to train or compete. Further, the use of medical grade or undersized compression therapy does not seem to improve physiological or performance responses, and as such, athletes should be guided by manufacturers recommendations and personal comfort for sizing and fit, particularly during extended use.

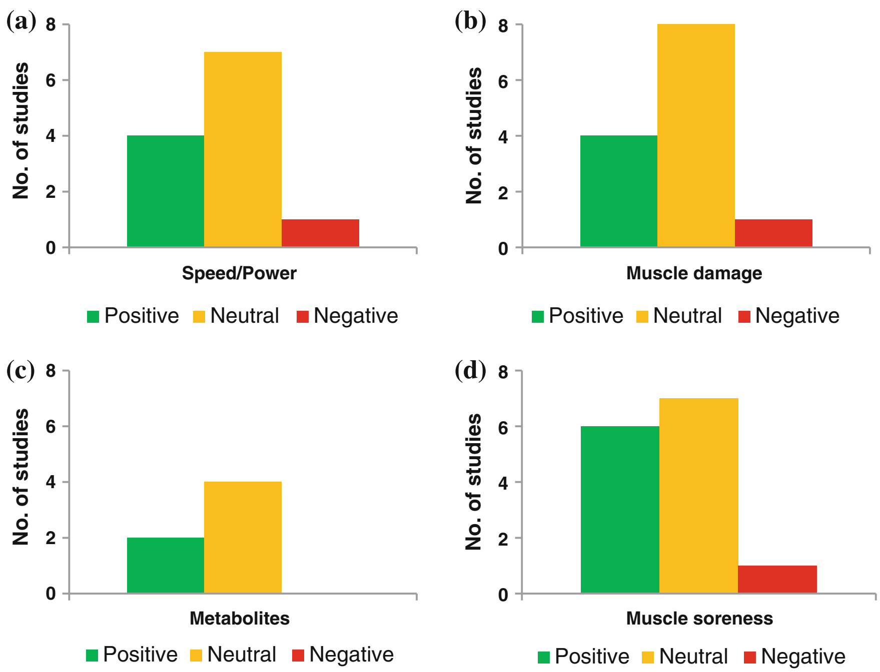

Fig. 2 A summary of the number of studies suggesting positive (*green*), none or neutral (*orange*) or a negative (*red*) effect of compression garments on post-exercise recovery of **a** speed/power performance **b** muscle damage markers **c** metabolite accumulation and **d** muscle soreness responses

Practical Applications

Most studies report equivocal or no effects of compression garments on recovery, although some aspects of the recovery of speed and power may be benefited.
The recovery of perceived muscle soreness seems to be most benefited by the use of compression therapy.
Few studies report negative effects of recovery in compression garments.
Given equivocal reports of the effects of undersized garments, athlete comfort and manufacturers recommendations should be adhered to regarding the fit and compression level of the garments.
Minimal ergogenic benefits for endurance or prolonged repeat sprint exercise but some small improvements in repeated power activities.
Minimal recovery benefits for most physiological systems; although some evidence for small improvements in clearance of muscle damage markers and improved muscle oxygenation.

Compression therapy seems to improve the perceived recovery following exercise; particularly reduced muscle soreness and despite a placebo effect, may benefit athlete recovery.
Recovery interventions should ensure adequate rest, sleep, nutritional intake and hydration, and compression garments may be included as additional to these practices to help optimise the overall recovery process.

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Compression Garments and Performance Enhancement in Balance and Precision Tasks

Lars Donath and Oliver Faude

Abstract Compression garments (stockings, sleeves, shirts and shorts) are increasingly used in various sports. The effects of compression garments (CG) on performance (e.g., maximal strength, aerobic performance, sprint performance, jump height) and recovery (e.g., body temperature, creatinkinase, muscle swelling, blood lactate clearance) are heavily debated. Current evidence is heterogeneous due to a variety of different study designs, types of compression clothes and applied pressures. Few studies also suggest that compression may improve balance performance and motor skill precision. Neuromuscular benefits from CG use include reduced muscle oscillation, improved joint awareness, augmented perfusion, higher skin temperature and improved oxygen utilization. It is assumed that mechanical pressure of CG to the skin stimulates cutaneous tactile receptors that improve proprioception. These additional "proprioceptive cues" together with a decreased reliance on the visual system might enhance balance performance. Studies of CG use on dynamic balance performance have not yet been conducted. Research on the association between skill precision and compression shirts indicated that driving accuracy of high-level Golf players improved during upper body movements. Another study on movement discrimination revealed better joint replacement when wearing tight Neoprene shorts. However, these beneficial effects were only present in low ability performers, whereas high-skilled participants showed a reverse effect. Compelling evidence derived from high-quality research is scarce and underlying mechanisms are still poorly understood. Available studies comprise notable heterogeneity (e.g., study design, target population, type of exercises, type of CG, fabric properties, CG pressure? unclear, variations in CG fit). Future research may focus on effects of CG on neuromuscular performance in various populations (athletes, clinical populations, seniors) and settings.

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Introduction

Wearing compression garments (CG) gained increasing popularity within the last two decades, particularly in sportive settings. Various types of CG exist: stockings, sleeves, shorts, upper- and lower-body garments. The majority of available studies investigated effects of CG on performance enhancement (e.g., maximal strength, submaximal and maximal oxygen uptake, sprint performance, jump height, time to exhaustion, subjective exertion level) and recovery indices (e.g., body temperature, creatinkinase, muscle swelling, blood lactate removal, heart rate response) in numerous populations and sport disciplines (strength, endurance, speed). The results are contradictory due to methodological limitations and heterogeneity (e.g., study design and quality, target population, type of exercises, fabric properties, pressure and fit variations). Underlying physical, physiological and psychological mechanisms are not well elucidated. Studies on effects of CG on balance performance and task precision are scarce. Few available studies in this regard assumed improved proprioceptive feedback via cutaneous stimulation that may enable enhanced neuromuscular performance. Also task precision seems to benefit from CG use. Based on previous and recent evidence, this chapter aimed at introducing potential mechanisms behind CG use and balance as well as skill accuracy improvements. Additionally, some methodological limitations and practical implications will be discussed.

Physical and Physiological Assumptions

Employing compression garments provide a gradual mechanical pressure (ideally highest distally and lowest proximally) to the body surface (skin) that seems to beneficially affect hemodynamics and circulation (Ali et al. 2007; Mayberry et al. 1991). The optimal pressure gradient is, however, poorly investigated and rarely given by the manufacturers. Main physical and physiological effects of CG use during exercise that are considered to potentially improve neuromuscular performance such as postural control includes (1) less muscle oscillation, (2) improved "joint awareness" via improved tactile feedback, (3) augmented perfusion, (4) higher skin temperature and (5) improved oxygen utilization (MacRae et al. 2011). Data from studies that specifically investigated those effects in studies on balance performance and skill accuracy and precision are, however, limited.

Improvements of Postural Control During CG Use

Adequate balance performance in sport-related settings varies from maintaining upright posture following external perturbations to complex motor skills. A proper projection of the center of mass over the base of support suited to the demands of the context is required (Donath et al. 2012) and can positively affect postural control (Era and Heikkinen 1985), athletic performance and injury risk (Myer et al. 2006; Granacher and Gollhofer 2011). A coordinated interplay between the somatosensory, visual and vestibular as well as the musculoskeletal system is needed and might benefit from CG use.

Enhanced Proprioceptive Cues

Only limited studies on the association between motor control and CG use exist. It is assumed that CG elicits increased cutaneous stimulation of tactile mechanoreceptors. These additional "cues" are considered to improve proprioceptive function. However, elite athletes seem to benefit less from additional proprioceptive stimulation (Cameron et al. 2008) compared to less-skilled athletes (Pearce et al. 2009) in terms of skill precision (movement discrimination testing) (Cameron et al. 2008). Less skilled athletes might be insufficiently attuned to their intrinsic feedback systems and, as a consequence, "extra" external feedback presentations via CGs might turn out to be helpful in those groups. On the other hand, elite athletes may suffer from conflicting cutaneous sensory information that is difficult to ignore compared to their highly attuned internal sensorimotor representation (Michael et al. 2014). These assumptions still remain speculative and high-quality research including differently skilled athletes is scarce. Most of the available studies used joint repositioning approaches and showed that CG lead to less error scores at mid-range angles of 45° and 60° (Kraemer et al. 1998). Joint repositioning at 30° and 90° did not reveal any differences between CG-use versus non CG-use. This mechanism of external "proprioceptive cues" arising from CG seems to be less effective when the limb is positioned around the endpoints of the range of motion. However, these findings are limited to the lower extremity. Upper extremity studies are lacking. More research should focus on the relevance of proprioceptive enhancement via CG on clear endpoints (falls in seniors, injuries, performance and recovery in athletes of various sports). Thereby, standardized pressure and garment manufacturing as well as wearing time should be considered in order to minimize heterogeneity of the findings.

Decreased Dependency on Visual Input

Sensory input obtained from the visual system is a meaningful resource to adjust for balance constraints and perturbations, respectively. Compared to the vestibular and somatosensory systems, visual information are considered to be crucial sensory cues for adequate postural control that becomes increasingly important during the process of aging: It has been repeatedly reported that seniors' postural regulation predominantly rely on the visual system (Manchester et al. 1989; Colledge et al. 1994). Occluded vision has been shown to adversely affect postural control during perturbed and unperturbed stance in seniors but also in young adults. As a consequence, sway of the center of pressure (COP, vertical projection of the center of mass) and the time to stabilize the sway of the COP following external perturbation is compromised (Donath et al. 2013).

The application of long tights with compression during single limb standing with *eyes open* in active females did not yield meaningful differences in postural sway compared to non-CG use (Michael et al. 2014). In contrast, CG use during single limb stance with closed eyes (occluded vision) improved standing balance performance (postural sway) compared to non-CG use (Fig. 1). It has been further observed that the sway of the center of mass/pressure was quiet similar during single limb stance with closed eyes using well-fit CGs compared with the "open-eye-condition" (Fig. 1, left panel). Thus, enhancement of proprioceptive function via CGs might increase the sense of joint positioning in order to compensate for visual occlusion. A study conducted by Pearce and colleagues revealed better visuomotor tracking performance after fatiguing exercise (Pearce et al. 2009). This finding indicates that CG may support active muscle function by a decrease of visual dependency during motor tasks (Pearce et al. 2009) accompanied by improved proprioceptive function (Feuerbach et al. 1994). Corroboratively, early findings of Jeka and Lackner (1994) indicated that minimal somatosensory (tactile)

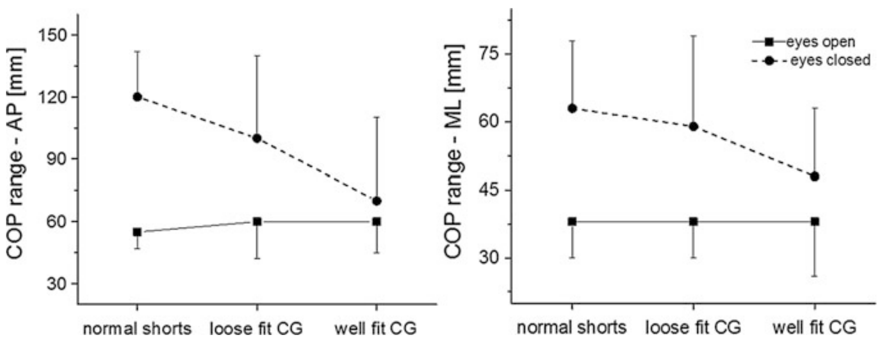

Fig. 1 Postural sway (range of the center of pressure, COP) in anterior-posterior (*left penal*) and medio-lateral (*right panel*) with *opened eyes* (*squares* with *solid line*) and closed eyes (*circles* with *dashed line*) for normal shorts (*without compression*), loose fit compression garments (CG) and well fit CGs. Adapted from Michael et al. (2014)

stimulation (e.g., from light finger touch with a stationary bar during standing balancing) might trigger postural muscles with reductions of postural sway (Jeka and Lackner 1994). However, it is also reasonable to assume that CG also contributes to passive stability during upright standing balance. Passive stability via CGs could decrease active muscle activity for the postural control of upright standing. This mechanism might lead to a withdrawal of cortical resources of postural control during upright standing. These free resources could be used for dual task requirements during daily life. However, these mechanisms are speculative. Future studies should address this issue adequately.

Task Precision of Athletic Performance

Compression garments might also be beneficial in order to improve precision or accuracy of athletic performance tasks. The application of CG seems to facilitate proprioception that could enhance kinesthetic sense during movement execution (Kraemer et al. 1998). However, very few studies examined the effects of CG on athletic skill accuracy. For example, Duffield and colleagues investigated the impact of wearing CG on throwing accuracy of cricketers including a control condition and failed to proof benefits of wearing CGs (Duffield and Portus 2007). In contrast, a recent study by Hooper and coworkers (2015) found significant improvements of driving-, approach-, shot-, and chipping accuracy in high-level collegiate golfers (Division 1) as well as fastball accuracy of Division 1 collegiate baseball pitchers when using upper body CG following familiarization (Hooper et al. 2015). Power-related performance parameters (throwing distance) remained unaffected. The study of Hooper and colleagues (2015) followed a counterbalanced within-group study design. The applied upper body T-shirt had an X-shape compression band with 80 % nylon and 20 % elastane. The remaining parts comprised 85 % Nylon and 15 % elastane. The study by Hooper et al. (2015) also assessed comfort of wearing CG. They did not find differences in comfort between CG and control clothes. Interestingly, golfers showed improved comfort of wearing CG. This finding highlights potential associations between comfort of wearing and skill performance. Another study applied Neoprene shorts and investigated leg swing movement discrimination based on joint repositioning (Cameron et al. 2008). These authors found that participants with low leg swing discrimination scores benefited notably from wearing tight fitting Neoprene shorts. It is assumed that large leg swing phases, similar to the findings of the Neoprene study, might lead to large movements between the leg and shorts, which stimulates rapidly adaptive tactile receptors and further enhance afferent input (Perlau et al. 1995). In contrast, participants with good discrimination scores showed an inverse effect (Fig. 2). Better discrimination scores in low ability groups (e.g., deconditioned or *injured*) have been also observed in other studies when using elastic support over the respective body region. Thus, CG potentially supports injury rehab. However, this assumption need to be further investigated. Moreover, it has been presumed that tight elastic

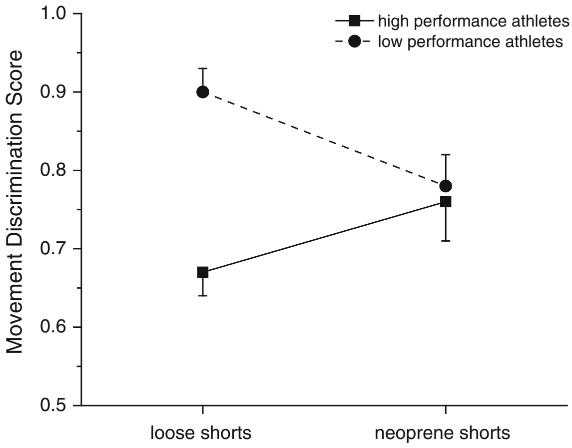

Fig. 2 Effects of short condition on mean leg movement discrimination scoring (*left* and *right* combined) of participants with high and low ability. Adapted from Cameron et al. (2008)

garments increase cutaneous stimulation and afferent signals to proprioceptive centers that can improve joint repositioning (Chu et al. 2002). A lack of accuracy improvement in subjects with higher ability has been attributed to the presence of "physiological normal values" for proprioception that has an upper limit (Newcomer et al. 2001). Another explanation implied that sleeves around a joint of athletes with higher neuromuscular performance might cause afferent stimulation that are confusing to the control system (Perlau et al. 1995). Thus, excessive external afferent information to the lower limb control centers induced by tight shorts may lead to conflicting processing that diminish already sufficient internal supply of sensory information. However, this has been considered to be transient (up to 5 min) as accommodation to the compression shorts might lead to "resetting of proprioception" (Cameron et al. 2008). Overall, the application of close-fitting neoprene shorts in athletes with worse neuromuscular control (e.g., leg swing accuracy) might serve as a low-cost and minimally invasive intervention to improve proprioception. However, further techniques to enhance proprioceptive function in the long term should be examined in rehabilitation and injury prevention.

Perceived Perception of Benefits

Another beneficial factor of performance improvements from compression garments is the concept of "perception of benefits" by the athlete himself. Studies on effects of CG on performance include a lack of blinded control conditions as control garments (placebo/sham) need to be produced and compression might then be perceived differently between real compression and placebo/sham interventions, respectively. This conception of "garment feel" has been examined early by Kramer and colleagues (Kraemer et al. 1998). Thereby, athletes have been asked how they felt the garment was affecting their jumping performance without having a feedback during repetitive jumps. Participants reported a significant "perception of improvement" in favor of the compression garments compared to the control condition. Also vitality scores, arm function during daily life and muscle soreness (with range of motion and palpation) were rated more favorable (at 72–120 h post exercise) when wearing a compression sleeve than without (MacRae et al. 2011). Overall, effects of CG on various perceptual responses tend to be better or at least not worse than without compression. No such data have been obtained in studies on balance performance or task precision. Besides proprioceptive improvements, "compression garment feel" might also psychologically improve physical performance when wearing CG. However, few studies on comfort and wearer acceptability are available to date and should be considered in future studies. This is particularly important as athletes that feel uncomfortable when wearing CG will likely not improve their performance or will simply not wear them.

Limitations

Most of the available studies on the relationship between CG use and performance or recovery improvements did not meet high quality criteria for randomized controlled trials (e.g., determined by the PEDro score). For example, adequate control conditions such as blinded control arms have not been considered. As a consequence, psychological effects cannot clearly be isolated from underlying physiological mechanisms. Thus, "garment feel" might account for a notable amount of occurring positive effects of CG on performance and/or recovery. Future studies should therefore (1) include manufactured placebo garments and (2) focus on the differences between "responders" and "non-responders". Despite the fact that seemingly obvious pressure differences between "real" and "sham" compression garment might be detected by the athletes, the personal judgment whether athletes do wear CG or not might comprise a notable percentage of uncertainty. In comparison, strong studies that applied placebo hypoxic conditions successfully followed a similar protocol (Roach et al. 2005) asking athletes if they think that hypoxia is present or not and how certain they are. Mostly, athletes were not sure about the baric condition they were in. A transfer of such a protocol to research on CG might be conceivable and reasonable, respectively. Although one review article did not report meaningful differences of "compression garment effects" depending on the applied pressure (Beliard et al. 2015), notable transversal load on the muscle has been shown to reduce strength output (Siebert et al. 2014a, b). Available studies on the effects of CG on performance and recovery outcomes include notable heterogeneity such as (a) manufactural diversity (e.g., percentage of elastane and nylon), (b) compression pressure differences (e.g., sometimes not indicated), (c) garment shape differences, (d) outcome measures (recovery, performance), (e) time course (short term vs. long term effects).

Summary and Practical Implications

The effects of compression garments on performance (e.g., maximal strength, aerobic performance, sprint performance, jump height) and recovery (e.g., body temperature, creatinkinase, muscle swelling, blood lactate clearance) are debatable. Only little research has been done on CGs with regard to balance and skill precision improvements. It is assumed that CG may cause less muscle oscillation, improved joint awareness, augmented perfusion, higher skin temperature and improved oxygen utilization. Also mechanical pressure of CG to the skin could stimulate cutaneous tactile receptors that enhance proprioception. These "proprioceptive cues" accompanied with decreased reliance on visual information beneficially contribute to balance performance improvements. Research on skill precision and compression shirts revealed improved driving accuracy during upper body movements in elite Golf players. Another study on movement discrimination revealed better joint replacement when wearing tight Neoprene shorts. These effects were, however, only present in low performers, whereas highly skilled participants showed a reverse effect. Comprehensive evidence derived from high-quality research is scarce and underlying mechanisms are still poorly understood. Available studies comprise notable heterogeneity (e.g., study design, target population, type of exercises, type of CG, fabric properties, compression unclear, fit variations) and future research may focus on effects of CG on neuromuscular performance in various populations (athletes, clinical populations, seniors) and settings.

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Compression Garments and Recovery

Jessica Hill

Abstract Achieving the highest levels of performance in competition is only possible through an ordered well thought-out training process designed to stimulate structural and metabolic adaptations in the systems of the body, these adaptations enable the athlete to reach a higher performance level (Smith in Sports Medicine 33:1103–1126, 2003; Stone et al. in Principles and practice of resistance training, Human Kinetics, Champaign 2007).

Introduction

Achieving the highest levels of performance in competition is only possible through an ordered well thought-out training process designed to stimulate structural and metabolic adaptations in the systems of the body, these adaptations enable the athlete to reach a higher performance level (Smith 2003; Stone et al. 2007). Optimal adaptation to training occurs when the training load is appropriately sequenced, alternating increasing loads with recovery (Smith 2003). Recovery is a necessary part of the training process, important in reducing the experience of fatigue and inducing adaptation (Smith 2003). Recovery and growth of the systems exposed to training stress occurs in the rest phases that follow exhaustive training, for this reason rest periods and temporary decreases in training are vital (Siff 2003). Achieving appropriate recovery between training sessions may enable athletes to tolerate higher training loads in the form of volume, frequency or intensity (Barnett 2006). Due to this, manipulation of the recovery time frame is becoming increasingly more important, with the optimisation of recovery becoming a priority for many athletes.

The physiological stress associated with training and competition can result in an athletes performance being temporarily impaired (Barnett 2006; Davies et al. 2009).

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Impairment that lasts for several days may be due to exercise induced muscle damage (EIMD) and associated delayed onset muscle soreness (DOMS). Due to the deleterious effects of EIMD and DOMS on performance athletes and their coaches are exploring a wide range of recovery modalities that may alleviate the negative symptoms associated with muscle damage and enhance recovery. In addition, insufficient recovery from EIMD may result in the athlete being unable to compete or train at the desired intensity (Barnett 2006). Knowledge of the mechanisms of muscle damage is important in enabling the understanding how recovery strategies such as compression garments can help to prevent or reduce the severity of EIMD following strenuous exercise.

Exercise-Induced Muscle Damage

It is well documented that strenuous exercise, eccentric exercise, or unaccustomed exercise can result in damage to the muscle fibres and is the cause of soreness and a reduction in muscle function, both of which affect performance (Armstrong 1990; Fridén and Lieber 2001). This phenomenon is often referred to as exercise-induced muscle damage (EIMD) and is characterised by a number of signs and symptoms including pain, strength loss, stiffness, swelling and an increase in blood circulation of intra-muscular enzymes such as creatine kinase (CK). These symptoms follow individual time responses, with some symptoms, such as CK, presenting slowly and becoming more prominent 24–48 h following the damaging exercise bout and others such as decreases in muscle function, peaking immediately after the exercise bout and persisting for several days after (Allen 2001).

The severity of EIMD depends on a number of factors including exercise familiarity, intensity and duration (Connolly et al. 2003). Unaccustomed exercise or exercise that is prolonged in nature can cause damage to the muscle fibres resulting in ultra-structural changes and delayed onset muscle soreness (DOMS) (Armstrong 1986, 1990). Whilst EIMD can occur from concentric, isometric or eccentric exercise, activities that include an eccentric component, such as downhill running or lowering a weight, have been found to result in a greater manifestation of symptoms (Clarkson and Sayers 1999; Enoka 1996).

An eccentric contraction is a muscle action whereby the muscle lengthens under tension, during which the load placed upon the muscle is greater than the force developed by the muscle (Faulkner et al. 1993; Fridén and Lieber 2001). Eccentric muscle contractions occur during every day activities; one example can be found in the normal gait cycle where the lower limb extensor muscles eccentrically contract when the foot strikes the ground (Fridén and Lieber 2001; Lieber et al. 1996). Eccentric actions are often incorporated into training programmes in order to induce structural adaptations and to enhance neural commands (Enoka 1996). These adaptations also occur following concentric exercise, however not to the same extent (Enoka 1996).

Mechanisms of Muscle Damage

The muscle damage experienced following exercise is thought to occur though several contributing processes, including the initial mechanical stress resulting from repetitive loading on the muscle fibres, a disruption in calcium homeostasis, the inflammatory response and oxidative stress (Clarkson and Sayers 1999). The inflammatory response occurs following the initial mechanical damage and is characterised by fluid accumulation and an infiltration of phagocytes to the damaged area (Clarkson and Sayers 1999). The activation of phagocytes results in the increased production of reactive oxygen and nitrogen species (RONS) known to cause oxidative stress (Aoi et al. 2004). Oxidative stress has been implicated in the exacerbation of skeletal muscle damage following the initial mechanical damage (Aoi et al. 2004; Halliwell and Chirico 1993; Mastaloudis et al. 2006). Thus, reducing the inflammatory response or quenching the activity of RONS may attenuate symptoms of EIMD, prevent any performance decrements and accelerate the rate of repair.

Due to the deleterious effects of EIMD and DOMS on performance athletes and their coaches are exploring a wide range of recovery modalities that may alleviate the negative symptoms associated with muscle damage and enhance recovery. More recently there has been an increase in interest surrounding the use of compression garments as a recovery modality.

Manufacturers promote the use of compression garments in the sporting arena with claims that the garment can improve the circulation of blood and attenuate swelling and oedema (Watanuki and Murata 1994). In addition these claims have been supported by literature indicating that compression garments can enhance performance (Bringard et al. 2006b; Doan et al. 2003; Kraemer et al. 1996) and improve the recovery time frame (Bottaro et al. 2011; Kraemer et al. 2010; Trenell et al. 2006). This support has increased the popularity of compression garments within an athletic setting and athletes are now using compression garments as training aids (Ali et al. 2010; Bernhardt and Anderson 2005; Doan et al. 2003). Ali et al. (2011) emphasized the level of confidence athletes place in the performance benefits of compression garments by highlighting that several world records have been set whist athletes have been wearing the garments. It has recently been postulated that the use of compression garments can alleviate the symptoms associated with exercise induced muscle damage (Kraemer et al. 2004; Noonan and Garrett 1999). However the research supporting these claims is inconsistent.

Compression Garments for Recovery

Compression garments have historically been used in clinical settings for the treatment of a number of pathologies including deep vein thrombosis (Byrne 2001), post thrombotic syndrome (Brandjes et al. 1997), and lymphedema (Brennan and

Miller 1998). These conditions are characterised by swelling and oedema of the limbs (Brandjes et al. 1997; Brennan and Miller 1998; Byrne 2001). The application of compression is a widely used treatment strategy in the management these pathologies. It is postulated that compression may improve venous hemodynamics (Ibegbuna et al. 2003) and assist in the maintenance of interstitial fluid homeostasis, thus attenuating oedema formation and reducing the degree of swelling and inflammation, however the exact mechanism remains unclear (Brennan and Miller 1998).

The inflammatory characteristics of these conditions, which include pain, swelling and reduced function, are largely similar to the inflammatory characteristics of acute muscle injury (Kraemer et al. 2004), therefore it stands to reason if compression is beneficial in the treatment of these conditions it might be beneficial in the treatment of EIMD. The healing process appears to be promoted with the application of compression, perhaps due to enhanced local tissue environment (Kraemer et al. 2001a, b). The application of external compression may create a pressure gradient that reduces the space available for swelling (Davies et al. 2009; Noonan and Garrett 1999). A reduction in swelling and inflammation may accelerate the recovery time frame enabling athletes to return to training sooner or tolerate higher training volumes (Duffield and Portus 2007; Trenell et al. 2006).

Research has also indicated that the use of compression garments can maintain muscle function and attenuate concentrations of serum creatine kinase (CK) (Duffield and Portus 2007; Kraemer et al. 2001a, b). The reduced concentrations of CK and retention of muscle function observed with the use of compression garments have been attributed to a reduction in the inflammatory response (Kraemer et al. 2001a, b). In addition to this, compression garments have been indicated to improve venous return during and after exercise (Ali et al. 2007), reduce venous pooling (Kraemer et al. 2001a, b) and reduce muscle soreness (Ali et al. 2007; Duffield and Portus 2007; Kraemer et al. 2001a, b).

Venous Return

It has been postulated that the application of external pressure achieved with the use of a compression garment may reduce venous stasis (Bringard et al. 2006a), perhaps by enhancing the skeletal muscle pump (Ali et al. 2010; Miyamoto et al. 2011), improving valve function (Ali et al. 2007), and facilitating venous return (Chatard et al. 2004; Ibegbuna et al. 2003; Watanuki and Murata 1994). This may lead to an accelerated clearance of metabolites, improved oxygenation and a reduced vascular load, all of which could benefit performance and recovery (Ali et al. 2007; Chatard et al. 2004).

Several studies have used heart rate to indicate changes in blood flow, where it is assumed that a reduced heart rate at a given intensity indicates improved venous return (Ali et al. 2007; Dascombe et al. 2011). No significant differences were identified between treatment groups in either study. Contrasting this work Bringard et al. (2006a) used near-infrared spectroscopy (NIRS) to assess venous function and oxygen saturation of the muscle. Changes in blood volume were ascertained from changes in total haemoglobin concentration (Hbtot), and changes in muscle oxygenation were ascertained from changes in deoxyhemoglobin (HHb) and from the tissue oxygenation index (TOI). The authors identified that venous pooling was significantly reduced, and muscle oxygenation was improved with the use of a compression garment. Suggested mechanisms for the improved muscle oxygenation include; improved capillary blood flow; improved perfusion and utilization of oxygen; and enhanced venous return (Bringard et al. 2006a). These observed changes in tissue oxygenation and venous function may benefit recovery and maintenance of performance (Bringard et al. 2006a, b; Kraemer et al. 2010).

Chatard et al. (2004), observed a 2.1 % improvement in cycling performance and a reduction in blood lactate and hematocrit when compression garments were worn for 80 min following a prior bout of maximal cycling. The authors hypothesised that these findings were due to improved blood flow which aided the clearance of lactate from the muscle and increased muscle oxygenation (Chatard et al. 2004). It is important to note that these variables were not directly measured and that the authors made their hypothesis based upon the relationship between blood lactate clearance and $\dot{V}O_{2max}$ during the recovery period (Chatard et al. 2004). The authors of this study also indicate that a placebo effect may have influenced results. Current literature is limited as venous return has not been stringently measured. It appears that the benefits of compression on venous return are largely speculative and there is a need for more rigorous techniques in measuring venous return and blood flow to ascertain true effectiveness (Ali et al. 2007).

Swelling and Inflammation

Swelling associated with the inflammatory response facilitates the removal of broken down cell fragments via the lymphatic system and has been used as a marker of inflammation (Clarkson and Sayers 1999). Swelling occurs as a result of increased vascular permeability (Clarkson and Sayers 1999; Smith 1991; Stauber et al. 1988). The affected area experiences an infiltration of chemical mediators such as leukocytes, which cause an increase in osmotic pressure within the tissue, and a decrease in the osmotic pressure within the capillaries (Kraemer et al. 2001a, 2004). The change in pressure causes fluid to move from the muscle compartment and surrounding capillaries into the interstitial space between cells.

The use of compression garments have been found to reduce the degree of swelling within the lower limb (Kraemer et al. 2010; Partsch et al. 2004). It is thought that the application of compression may lessen the change in osmotic pressure gradient, and reduce the space available for swelling to occur (Chleboun et al. 1995; Kraemer et al. 2004). In addition to this, improved circulation arising from enhanced venous return may also help attenuate the inflammatory response (Pruscino et al. 2013).

Limb Circumference

Limb circumference or volume is often used as an indicator of the degree inflammation (Eston and Peters 1999; Goodall and Howatson 2008; Paddon-Jones and Quigley 1997). Studies investigating the use of compression have observed reductions in limb circumference following EIMD (Chleboun et al. 1995; French et al. 2008; Kraemer et al. 2001a). Kraemer et al. (2001a) observed a reduction in upper arm circumference with the use of a compression sleeve worn immediately after an eccentric exercise protocol. In this study 15 non-strength trained males were randomly allocated to either a compression or a control group. Following an eccentric exercise protocol consisting of 2 sets of 50 arm curls, participants wore a compression garment for 72 h. The authors propose that pressure-induced chemical and mechanical responses associated with the application of compression attenuated damage to the tissue arising from EIMD (Kraemer et al. 2001a, b). Furthermore it is thought that the pressure applied by the compression garment can facilitate lymphatic drainage and reduce fluid movement from the capillaries (Kraemer et al. 2001a, b). These responses have been linked to a reduced inflammatory response and accelerated repair time frame (Kraemer et al. 2004; Trenell et al. 2006).

On the basis of these claims the use of compression may be effective in managing the secondary muscle damage phase, which arises as a result of the inflammatory response (Jakeman et al. 2010). However it should be noted that the reliability of limb circumference as a measure has been questioned as it cannot differentiate between muscular swelling and swelling in other compartments (Chleboun et al. 1998). A large variation between individuals has also been reported for this measure (Cleak and Eston 1992).

It is also worthwhile considering that swelling demonstrates a delayed onset following the initial damaging exercise often not showing symptoms until 24 h post exercise (Bowers et al. 2004; Chleboun et al. 1998). Peak swelling may not occur until 4–5 days post exercise, beginning initially inside the muscle and eventually moving into the subcutaneous area (Clarkson et al. 1992; Clarkson and Sayers 1999; Nosaka and Clarkson 1996). Many studies only measure up to 48–72 h post exercise, thus it is possible that changes may have occurred after this time and were not identified.

Cytokines and Inflammatory Proteins

Assessing changes in the serum concentration of cytokines and inflammatory proteins is often used to provide information on the extent of the inflammatory response. Cytokines are small polypeptides that act as immune-modulators and have a role in directing the regeneration of injured tissue, thus high levels of cytokines are expected following strenuous exercise (MacIntyre et al. 1995; Peake et al. 2005; Suzuki et al. 2003). The most commonly assessed cytokines include interleukin-1 beta (IL-1β), Interleukin-6 (IL-6) and tumor necrosis factor alpha (TNFα) (Bruunsgaard et al. 1997; Nieman et al. 2001; Ostrowski et al. 1999; Suzuki et al. 2003). IL-1 and TNFα are pro-inflammatory cytokines that have an important role in priming leukocyte function and stimulating the activation of macrophages (MacIntyre et al. 1995). IL-1 and TNFα both have a role in inducing the release of IL-6, an anti-inflammatory cytokine (MacIntyre et al. 1995; Nieman et al. 2001). The assessment of cytokines provides an indication of the magnitude of the inflammatory response, however, the literature examining the efficacy of compression garments has rarely measured concentrations of cytokines as indicators of inflammation. Investigation of the cytokine response with the application of compression may provide further insight into the anti-inflammatory benefits of compression.

Trenell et al. (2006) identified increased levels of phosphodiesters, the breakdown products of phospholipids, hour post exercise with the use of compression. This observation was attributed to accelerated inflammatory and repair processes providing further efficacy for the use of compression garments in the recovery process (Trenell et al. 2006). However contrasting these findings the effects of compression on the inflammatory protein C reactive protein (CRP) was measured following a marathon run (Hill et al. 2014). This study did not observe any significant group differences in serum concentrations of CRP. The biomarker CRP provides information on the inflammatory response, and the fact that no group effects were observed for CRP suggests that the inflammatory response might not be modulated by a compression garment.

Compression is thought to positively affect the inflammatory response by reducing the level of oedema, however the low levels of compression pressure exerted by many of the garments worn for recovery purposes may not exert sufficient pressure to significantly affect swelling, oedema and inflammation (French et al. 2008). These investigations measured very few markers of inflammation; further research should include a more comprehensive assessment of inflammatory markers in order to understand the interaction between the inflammatory response and use of compression.

Range of Motion

The experience of swelling following damaging exercise is associated with a decreased range of motion (ROM) and increased muscle stiffness (Clarkson and Sayers 1999). During the inflammatory response swelling in the muscular compartment causes a rise in intra-compartmental pressure. As the affected muscle becomes more swollen, motion is affected resulting in a decreased ROM. Kraemer et al. (2001a, b) observed a significantly reduced loss of motion 48 h post exercise concluding that compression may be a mediator for reducing the magnitude of EIMD.

Adaptation

A reduction in the inflammatory response following injury is often considered a positive effect in lessening the damage response (Maughan et al. 2004). However the inflammatory response is reported to be involved in the muscle repair, regeneration and growth response, assisting with the removal of broken down cell fragments via the lymphatic system (Clarkson and Sayers 1999; Tidball 2005). Inflammation has also been outlined as an important process in the adaptive response to the repeated bout effect (Lapointe et al. 2002). Recently it has been suggested that as inflammatory response is involved the adaptation process of muscle tissue, the suppression of inflammatory pathways may be detrimental to the adaptation and repair process, thus recovery modalities that blunt the inflammatory response may be detrimental to the athlete (Barnett 2006). For these reasons further investigation is required into the long-term effects of using compression garments in order to identify any effect on muscle adaptation.

Creatine Kinase

The efflux of intracellular proteins from the muscle fibre into the plasma can provide information on the state of the muscle tissue and have been used to indicate muscle damage severity (Brancaccio et al. 2007; Faulkner et al. 1993). Elevations in the concentration of intracellular proteins including CK, lactate dehydrogenase (LDH), and myoglobin (Mb) have been observed following a range of different exercise modalities including distance running (Howatson et al. 2010; Janssen et al. 1989; Kratz et al. 2002; Lippi et al. 2008), and eccentric exercise protocols (Child et al. 1998; Clarkson et al. 1992; Lee et al. 2002). Whilst a number of serum markers are frequently used to assess the degree of EIMD CK is the most commonly assessed blood marker. Creatine kinase is an enzyme that is usually found within the muscle and has a role in maintaining ATP availability during muscular contraction (Fridén and Lieber 2001). The presence of CK in serum represents increased permeability of the sarcolemma resulting from structural damage and increased vascular permeability (Eston et al. 1995; Fridén and Lieber 2001; Lee et al. 2002; Newham et al. 1987; Stauber et al. 1990).

Creatine kinase is often used as a marker of muscle membrane disruption (French et al. 2008; Gill et al. 2006; Jakeman et al. 2010). An attenuation of the CK response is likely to be a consequence of either a reduction in the release of the marker from the muscle cell or improved clearance of the marker with the use of compression (French et al. 2008; Kraemer et al. 2004). Reduced concentrations of CK with the use of compression garments have been attributed to enhanced tissue repair (Kraemer et al. 2010). However, evidence that compression can reduce the concentration of serum CK is equivocal, with research indicating that compression is effective in reducing concentrations of CK (Duffield and Portus 2007; Gill et al. 2006;

Kraemer et al. 2001b, 2010) and research showing no effect of compression on concentration of CK (Ali et al. 2007; Davies et al. 2009; French et al. 2008).

Duffield and Portus (2007) investigated the efficacy of compression garments on throwing and sprint performance in cricket players. Subjects took part in four randomised sessions (3 different brands of compression garments and a control) each session involved a 30 min sprint protocol and throwing tests. Compression garments were worn during the exercise and for 24 h post exercise. Results indicated no significant differences between brands and no performance benefits of wearing compression garments. However CK concentration, muscle soreness was significantly attenuated post 24 h in those who wore the compression garments, indicating there may be a role of compression garments in the recovery process (Duffield and Portus 2007).

In contrast to this research Pruscino et al. (2013) observed a significant change in CK over time, however failed to observe a significant difference between a compression garment group and a control group. The authors suggest that the significant time effect indicated membrane permeability had occurred as a result of EIMD following a LIST test however the use of compression garments did not affect recovery. Consistent with these findings Davies et al. (2009) observed no benefit of compression on concentrations of CK following an eccentric drop jump protocol in a population of netball and basketball players. The concentration of CK in this study changed very little from baseline to post exercise indicating the participants experienced little muscle damage. Davies et al. (2009) suggest that the 'trained' status of their subjects may explain the small change in CK.

Differences in findings are likely to be a result of the wide variation in exercise modalities used in each study. For example Gill et al. (2006) investigated the efficacy of compression in a group of elite male rugby players, following a competitive rugby match, whereas Ali et al. (2007) investigated the efficacy of compression following a 10 k run. The demands of these exercise modalities are considerably different and it is also likely that the mechanism of muscle injury is also slightly different. However it is important to note that Gill et al. (2006) analysed CK from transdermal exudate, a method that has not been validated (French et al. 2008). It is also important to consider that the high impact collisions involved in rugby may have influenced the CK response and may make these findings less applicable to other sporting situations (French et al. 2008), therefore these findings need to be interpreted with caution.

Concentrations of CK depend on several factors including age, gender, ethnicity, muscle mass, and training status (Brancaccio et al. 2007). Resting concentrations of CK in athletes are higher than an untrained population, likely due to the cumulative effect of training sessions and increased muscle mass, however following exercise the rise in CK concentration is attenuated in an athletic population (Vincent and Vincent 1997; Mougios 2007).

Hill et al. (2014) also found no effect of compression on CK following a marathon run in experienced runners. Following a marathon run this study observed average CK concentrations of 1022 U/L in the placebo group, compared to considerably higher concentrations of 2814 U/L (Howatson et al. 2010) and 3424 U/L

(Siegel et al. 1980). It appears that the participants in Hill et al. (2014) study experienced considerably less damage to the ultra-structure of the muscle (Fridén and Lieber 2001). It is acknowledged that well trained individuals experience an attenuation in serum CK concentrations following strenuous exercise this response is a result of the protective effect afforded by the repeated bout effect (Brancaccio et al. 2007; Vincent and Vincent 1997). Furthermore, concentrations of CK in women appear to be lower than men, these differences may arise from variations in muscle mass as well as the protective effect of oestrogen (Janssen et al. 1989; Mougios 2007; Tee et al. 2007). These differences need to be considered when comparing research findings in different populations.

In addition to gender and training experience, the duration, type and intensity of exercise all have an effect on the CK response (Brancaccio et al. 2007; Lippi et al. 2008). Elevations in CK occur following a number of different exercise modalities and the magnitude of the CK response as well as the time course following these modalities can vary (Clarkson et al. 1992). Concentrations of CK as high as 2814 ± 2235 IU/L have been observed following a marathon run, with peak values occurring 24 h post marathon (Howatson et al. 2010). In comparison to eccentric exercise protocols which have observed CK concentrations over 6000 IU/L which peak 3–5 days post exercise (Clarkson et al. 1992; Lee et al. 2002). Furthermore, large inter-individual variability has also been observed in the CK response to exercise (Clarkson et al. 1992). Due to the variance in the CK response observed between individuals and in response to different types of exercise caution when interpreting mechanisms to explain EIMD and recovery should be exercised (Clarkson et al. 1992).

Delayed-Onset Muscle Soreness

Delayed onset muscle soreness is the experience of pain and discomfort that manifests in the days following strenuous exercise and often presents alongside other symptoms such as reduced force production and elevated enzyme concentrations (Allen 2001; Cheung et al. 2003; Fridén and Lieber 2001; Vincent and Vincent 1997). Soreness is experienced by many individuals including both elite and novice athletes, with symptoms ranging from minor tenderness to debilitating pain and can have a negative impact on sporting performance (Cheung et al. 2003). Additionally, the experience of soreness that arises as a consequence of engaging in novel exercise may deter individuals from adhering to an exercise programme (Lanier 2003). Any intervention than can reduce or minimise the severity of these symptoms can be of benefit to athletes, and individuals wishing to embark on exercise programs.

Soreness generally presents 24 h post exercise increasing to reach a peak 48–72 h post exercise, returning to baseline approximately 7–10 days after the initial event, (Chleboun et al. 1998; Clarkson et al. 1992; Eston et al. 1995; MacIntyre et al. 1995; Smith 1992). Several theories have been proposed to explain the onset of muscle soreness, these include; (1) damage to the connective tissue associated with the muscle, (2) the mechanical muscle damage that has occurred to structures within the muscle fibres, (3) disruptions in Ca^{2+} homeostasis, and (4) the inflammatory response (Cheung et al. 2003). It is generally accepted that DOMS occurs as a result of the integration of all of the above theories as opposed to one singular event (Cheung et al. 2003; Rodenburg et al. 1993; Vincent and Vincent 1997).

Frequently individuals continue to exercise whilst they are experiencing DOMS (Cheung et al. 2003). Muscle soreness is thought to provide a protective effect, deterring the individual from harmful stimuli, this may have a role in acceleration of tissue repair (Smith 1991, 1992). If soreness dissipates before the muscle has fully recovered, the athlete may return to training before full recovery increasing their risk of injury (Cheung et al. 2003; Cleak and Eston 1992). Exercising at this time may place strain on weakened tissue structures (Cheung et al. 2003), thus recovery is important before returning to training.

When compression garments are worn following strenuous or high intensity exercise, there appears to be a reduction in DOMS (Hill et al. 2014; Pruscino et al. 2013). This is perhaps a result of reduced structural damage or a reduction in swelling (Ali et al. 2007; Duffield and Portus 2007; Duffield et al. 2008; Jakeman et al. 2010). Pruscino et al. (2013) observed a reduction in the severity of DOMS experienced following a simulated hockey protocol (LIST). The authors speculate that attenuation in DOMS may be due to mechanical stability provided by the compression garment which reduced displacement in the active muscle. In addition to this the application of compression may increase the pressure of the interstitial fluid surrounding the capillaries, this increase in pressure may help to facilitate the return of fluid back into the circulatory system (Watanuki and Murata 1994). The resultant reduction in swelling and oedema may reduce the stimulation of pain afferents thus resulting in a reduced experience of DOMS (Kraemer et al. 2004).

Whilst the majority of the current research indicates there is a positive effect of compression on the severity of DOMS there is a small body of evidence indicating no effect. Trenell et al. (2006) and Sperlich et al. (2010) both observed no difference in the severity of DOMS between a control group and a compression group. However it could be argued that the type of exercise modality used was not sufficient to cause any major discomfort, this is particularly true of (Sperlich et al. 2010) who used maximal and submaximal running as an exercise modality.

A meta-analysis including 12 studies, involving a total of 205 participants, indicated that that compression garments were able to attenuate the severity of DOMS following EIMD (Hill et al. 2013). This study indicated that 66 % of the population is likely to experience reduced DOMS with the use of compression. It is important to note that the majority of the studies investigating compression have not used a placebo group. This is perhaps due to the difficulty in blinding subjects in studies investigating the use of compression garments, of the 12 studies included in the meta-analysis none controlled for a placebo effect, thus it is possible the placebo effect may have influenced DOMS scores in the studies included in this meta-analysis, this may have influenced the overall outcome for DOMS as a variable, due to this, there is a need for future research to address this limitation.

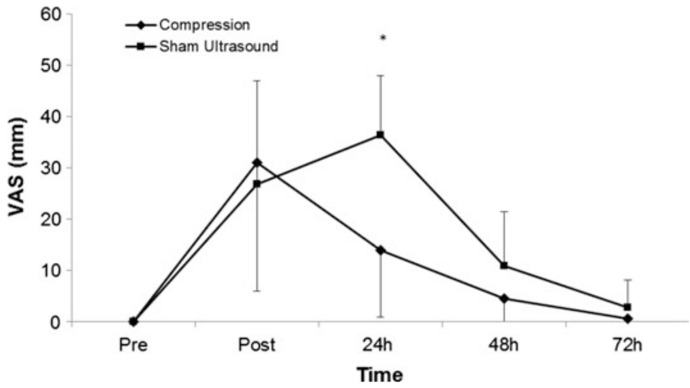

Fig. 1 Perceived rating of muscle soreness for the compression and sham groups before and after the marathon. * Denotes significantly higher experience of soreness in the sham group compared to the compression group

Studies have attempted to address the issue of the placebo effect in compression research by using a sham treatment group, where participants received 10 min of sham ultrasound. Hill et al. (2014) demonstrated that the experience of DOMS was significantly reduced 24 h post exercise with the use of compression garments compared to the sham group (Fig. 1). In the compression group soreness peaked immediately after the marathon, whilst soreness in the sham treatment group continued to increase peaking 24 h post Marathon. This provides some evidence supporting the use of compression in facilitating recovery, when the placebo effect was controlled for. It is possible that the application of compression reduced the accumulation of interstitial fluid at the damaged site thus reducing the stimulation of pain afferents (Kraemer et al. 2004).

In addition to this the experience of pain and soreness is subjective making it difficult to quantify levels of DOMS (Cleak and Eston 1992; Nosaka et al. 2002). Visual analogue scales (VAS) are often used as an index of soreness (Warren et al. 1999), these scales require participants to rate their perceived level of pain often on a scale. There are limitations to the use of this scale, a particular concern is the individual subjectivity, participants who place their mark at the same point may be experiencing different levels of soreness (Nosaka et al. 2002). Furthermore other factors such as mood can also influence where participants place their mark (Nosaka et al. 2002). However the trend is generally the same between studies, muscle groups and activities.

Muscle Function

Measurements of muscle function are generally considered the best indicators for assessing the magnitude of EIMD (Byrne et al. 2004; Warren et al. 1999). A decline in the ability of the muscle to produce force following damaging exercise has been repeatedly demonstrated (Byrne and Eston 2002a; Cleak and Eston 1992; Prasartwuth et al. 2005; Warren et al. 2001). Decreased muscular strength is observed immediately after exercise and usually reaches a nadir 24–48 h post exercise, gradually returning to normal over the following days (Chleboun et al. 1998; (Prasartwuth et al. 2005; Connolly et al. 2003). However, some studies have observed a decline in muscular strength that does not return to baseline for over a week (Chleboun et al. 1998; Howell et al. 1993; Lauritzen et al. 2009). This loss of muscle function is of particular concern to athletes and their coaches as it results in underperformance during training and competition (Byrne et al. 2004).

The maintenance of muscle function appears to be positively affected when compression garments are worn following strenuous exercise (Chatard et al. 2004; Jakeman et al. 2010; Kraemer et al. 2001a). A meta-analysis indicated that compression garments worn for recovery purposes are able to facilitate the return of strength and power (Hill et al. 2013). The mechanism for the maintenance of muscle function has been linked to stabilisation of muscle fibre alignment (Jakeman et al. 2010; Kraemer et al. 2001a). It is proposed that disruption to the muscle sarcolemma may result in a reduced ability of the muscle to contract, a compression garment may be able to stabilise the alignment of muscle fibres thereby helping to prevent large decrements in strength loss (Jakeman et al. 2010; Kraemer et al. 2001a).

Kraemer et al. (2010) observed improved bench throw performance with the use of a compression garment when compared to a control group, following whole body heavy resistance exercise in males and females. These observations were attributed to improved recovery from the neuromuscular deficit arising as a result of the stress induced by the upper body resistance exercise (Kraemer et al. 2010). Similarly in two other studies squat jump performance was improved with use of compression (Jakeman et al. 2010) and counter-movement jump height was maintained with the use of a compression garment (Ali et al. 2011).

Research has also indicated that wearing a compression garment during performance improved jump height in both single (Doan et al. 2003) and repeated (Kraemer et al. 1996) jump tests. Kraemer et al. (1996) observed that compression garments helped to maintain power output during a repeated jumping exercise. It was speculated that the garment facilitated the maintenance of performance as fatigue began to develop, perhaps as a result of reduced muscle oscillation, improved proprioception and reduced energy expenditure (Bringard et al. 2006a, b; Doan et al. 2003; Kraemer et al. 1996), however the exact mechanism is yet to be identified (Ali et al. 2011).

In contrast to these positive findings some studies have failed to observe improved recovery of strength following EIMD (Carling et al. 1995; Hill et al. 2014). No improvement of muscular strength was observed when a compression garment was worn for 72 h following a marathon run (Hill et al. 2014). In this study the recovery of muscle function was assessed using a maximal voluntary isometric contraction (MVIC). Whilst this test is considered one of the most valid measured for assessing the severity of EIMD and is widely used in the research (Child et al. 1998; Goodall and Howatson 2008; Howatson et al. 2010), the isolated muscle actions similar to those produced during the MVIC assessment do not often occur in everyday life. Normal movement includes the cyclic eccentric contraction of a muscle followed immediately by a concentric contraction, this is known as the stretch shortening cycle (SSC) (Byrne and Eston 2002b; Komi 2000). Jumping tests, specifically the counter movement jump (CMJ) and drop jump utilise this typical movement pattern and thus provide a means of assessing the impact of EIMD on the SSC (Byrne and Eston 2002b).

Functional Recovery

Armstrong et al. (2015) suggest that assessing functional recovery via a sport specific exercise or movement may be a better indicator of recovery of muscle function compared to the assessment of changes in static or dynamic strength. Armstrong et al. (2015) used a graded exercise test (GXT) to exhaustion on a treadmill to assess functional recovery after a marathon run. Participants in this study were randomly allocated to either a compression group or a placebo group, before completing a marathon run. Participants assigned to the compression group wore below the knee compression socks for 48 h post marathon. Exact compression pressures were not measured, however compression pressures reported by the manufacturers were 30–40 mmHg at the ankle and 21–28 mmHg at the calf.

A GXT was completed 2 weeks before the marathon and again 2 weeks after the marathon run, with the change in treadmill time used as in indicator of performance. Performance in the compression group was significantly improved compared to performance in the placebo group ($P > 0.05$). With those in the compression group achieving an improved performance time of 2.6 % (52 ± 103 s) and those in the placebo group experiencing a decrease in performance time of 3.4 % (−62 ± 130 s). These observations indicate that the use of compression can significantly improve functional recovery when assessed using a sport specific treadmill test. The authors suggest that these findings indicate those in the compression group were able to recover from the marathon and adapted to improve their performance, whilst those in the placebo group failed to fully recover in the two weeks after the marathon run (Armstrong et al. 2015). This was attributed to decreased ultrastructural muscle damage.

Training Status

A large part of the literature to date has been carried out using untrained or recreational populations (Carling et al. 1995; French et al. 2008; Jakeman et al. 2010; Kraemer et al. 2001a; Kraemer et al., 2001b), therefore whether compression is beneficial for elite populations is still unclear (Pruscino et al. 2013). It has been identified that training history might be responsible for the variation in findings within the literature as prior training is known to reduce the severity of symptoms of EIMD due to the repeated bout phenomena (Ali et al. 2010; French et al. 2008). It is also possible that the recovery characteristics of trained participants may be more developed compared to untrained or recreational participants (French et al. 2008). More research is needed to ascertain the relationship between training status and the efficacy of compression garments in recovery from high intensity or strenuous exercise.

Pruscino et al. (2013) examined the effects of lower limb compression garments on recovery following a sport specific muscle damaging protocol (LIST) in national and international level hockey players. No significant differences were observed between groups for blood markers of muscle damage and inflammation (CK, IL-1β, IL-6, TNFα and CRP), in addition to this, no improvements in muscle function were observed. It is possible that in the highly trained population used within this study a LIST test did not induce enough muscle damage for a physical benefit of compression to be observed (Pruscino et al. 2013). Furthermore, compression pressures applied in this study were 19.1, 7.2 and 4.9 mmHg at the ankle, calf and thigh respectively. It is also possible that the level of compression exerted in this study may not have been sufficient to achieve a benefit.

Optimum Pressure

The fit of the garment and the level of pressure applied appears to be a factor that influences the effectiveness of compression garments, therefore selecting an appropriate garment is important (Ali et al. 2011). A large number of studies do not report the level of compression (Duffield and Portus 2007; Higgins et al. 2009) and some report the level of compression suggested by manufacturers or by previous research (Davies et al. 2009; French et al. 2008; Jakeman et al. 2010) The degree of pressure exerted by a compression garment should be measured for each individual because the level of compression exerted by a garment is dependent on the size and form of the body (Jakeman et al. 2010).

Varying levels of compression pressures have been reported in the literature with values ranging from 10 to 12 mmHg (French et al. 2008) up to 32 mmHg (Ali et al. 2010), however the optimal level of compression necessary to enhance recovery is yet to be identified. Many of the observed benefits of compression and subsequent recommendations on compression pressures have been derived from clinical studies (Brandjes et al. 1997; Ibegbuna et al. 2003). There is limited evidence to suggest that these levels of compression are suitable for athletes (Dascombe et al. 2011). Partsch and Mosti (2008) suggest that in order for compression to be effective, the level of pressure exerted by the garments must be greater than intravenous pressure in order to influence haemodynamic factors. Venous pressure in the lower limb is approximately 10–15 mmHg in a supine position, increasing to 30–90 mmHg when standing, suggesting the degree of pressure required for compression garments to be effective is dependent upon body position (Partsch and Mosti 2008).

Cardiac output and venous return were improved when compression garments exerting 20 mmHg at the thigh and 25 mmHg at the calf were applied to the limb (Watanuki and Murata 1994). Watanuki and Murata (1994) estimated that minimum compression pressures of 17.3 mmHg at the calf, decreasing to 15.1 mmHg at the quadriceps were required to improve venous return. In contrast to this Partsch and Mosti (2008) found compression pressures of 10–15 mmHg effective in reducing the diameter of superficial veins when participants adopted a supine position. However, when standing, much higher levels of compression were required to achieve the same results.

Ali et al. (2010) investigated the physiological and perceptual effects of wearing compression garments of different grades. Ten subjects took part in the study, completing a 40 min treadmill run under three different conditions, wearing a control garment that did not exert any pressure, wearing a low grade compression garment (12–15 mmHg) and wearing a high grade compression garment (23–31 mmHg). No differences in muscle function were observed between trials, however during the trial with the high grade garment subjects reported pain that began as a dull ache, progressing to pins and needles around the ankle. Higher grade compression garments may not be comfortable for long periods of time and this is likely to affect compliance, however a comfortable grade of compression may not exert sufficient pressure to be effective in improving recovery (Kraemer et al. 1996; Ali et al. 2011).

Whilst the optimum level of compression is yet to be elucidated positive effects of compression have been observed with pressures of 15–30 mmHg at the ankle dissipating at the thigh. (Agu et al. 2004; Ali et al. 2010; Ibegbuna et al. 2003). In addition to this higher levels of compression (approximately 30 mmHg at the calf) have been indicated to impair venous return (Lawrence and Kakkar 1980). Therefore there is a need for more information on the most effective level of compression required to facilitate a physiological response. Future research needs to define exact levels of compression pressures applied as this will enable further understanding of the pressures required to affect parameters of recovery.

Evidence for the benefits of compression as a recovery aid is equivocal, one explanation for this is that popular commercially available compression garments do not exert sufficient enough pressure to be of benefit. Commercially available compression garments are often fitted based upon an individual's height and weight which then dictates which compression garment size an individual should wear. Given that there are large variations in anthropometric characteristics within a given population, concerns have been raised over whether standardised size categories are an effective means of fitting a garment (Davies et al. 2009).

Research has identified differences in compression garment fit with large variations in compression pressures between individuals (Hill et al. 2015). In this study 50 participants were fitted with commercially available lower limb compression garments according to manufacturer's guidelines. Pressure applied at the calf ranged from 10.3 to 15 mmHg and pressure at the quadriceps ranged from 4 to 16.7 mmHg (Fig. 2). It is likely that this is because the standardised sizing systems used by manufacturers are insufficient in meeting the considerable range of body

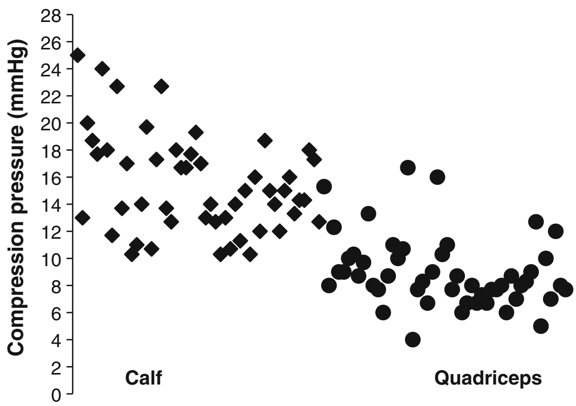

Fig. 2 Compression pressures received by each individual. *Diamonds* represent pressure received at the *calf* and *circles* represent pressure received at the quadriceps

shapes within the population (Ashdown 1998). Hill et al. (2015) observed that individuals categorised into one garment size categorisation vary in body shape and size. For example the thigh and calf circumference of the individuals who fitted a medium sized garment ranged from 46.1–56.3 to 33.0–39.5 cm at the thigh and calf respectively. This is likely to affect the fit of the garment.

Another notable observation made by these authors was that there were no correlations between anthropometric variables (hip, waist, ankle and thigh circumference, and body composition expressed as both a percentage and as a total sum of skinfolds) and compression pressure at the thigh and calf; this indicates that the interaction between the garment and various anthropometric characteristics is complex and warrants further investigation (Hill et al. 2015). It is of particular interest that there was no significant relationship between thigh and calf circumference and compression pressure received at these locations. Rather than fitting compression garments based upon height and weight, some compression companies are using limb circumferences as an alternative method of fitting their compression garments. The lack of a relationship between circumference measures and compression pressures observed in this study indicate that fitting compression garments based on circumference measures is not effective.

Some manufacturers are now offering bespoke garments, these garments are fitted with greater precision using multiple surface measurements or by using a body scanning device. These approaches are likely to improve garment fit, increasing the consistency and level of the compression pressures exerted by the garment.

Conclusions

To conclude, EIMD and its associated symptoms are an unavoidable part of the training process (Kraemer et al. 2004). Reducing the severity of these symptoms and reducing the recovery time frame between training sessions and competitions, would be very beneficial to a range of athletes (Bringard et al. 2006b). Compression garments are being advocated in the attempt to enhance recovery with coaches and athletes being advised to take advantage of their potential benefits particularly during competition periods where recovery time frame between performances is minimal (Bottaro et al. 2011). However, whilst the use of compression garments in sport has a rational basis, the physiological and biochemical responses of wearing compression garments have yet to be established in relation to reducing muscle damage and enhancing recovery. The application of compression immediately after strenuous exercise appears to offer some benefit in alleviating muscle soreness and facilitates the return of muscle function. Therefore further investigation into the effects of wearing compression garments and identification of the underlying mechanisms is necessary in order to quantify their use as a recovery modality.

The wide variation of findings within the literature is perhaps due to heterogeneity in methodological design to include the population investigated, duration of wear, the degree of compression exerted on the limb, exercise modality and absence of a control group (Sperlich et al. 2010). It is possible that in some studies the garment may not have been worn long enough to have a meaningful impact on recovery mechanisms, it is also possible that the degree of pressure exerted was not sufficient to have any benefit (French et al. 2008).

Research investigating the optimal compression pressures is also lacking. A large number of studies on compression garments fail to measure the actual level of compression applied by the garment either failing to report compression levels altogether or simply reporting the levels of compression indicated by the manufacturers (Ali et al. 2007; Bringard et al. 2006a, b; Davies et al. 2009; Kraemer et al. 2010). This is unhelpful when attempting to discern optimal levels of compression. The level of compression is likely to be an important factor in determining whether compression garments are effective. Thus an improved knowledge on the effects of different compression pressures is paramount.

In addition to this it is likely that 'off the shelf' compression garments do not exert the same compression pressures in every individual. Compression garments are often fitted according to the height and mass of an individual, given the variation in body sizes within a population it is unlikely that all individuals will receive appropriate levels of compression (Ashdown 1998; Brophy-Williams et al. 2014). It is likely that a number of individuals using compression garments are not receiving adequate levels of pressure to be of benefit. If the level of compression exerted by the garment is insufficient then the garment will not be able to contain the oedema associated with the inflammatory response (French et al. 2008) nor will it modulate venous return (Partsch and Mosti 2008; Watanuki and Murata 1994), both of which are mechanisms by which compression is proposed to be of benefit. This has implications for athletes wishing to use these garments as a recovery strategy and indicates the importance of measuring the exact levels of compression exerted by garments on each individual. The assessment of compression levels in future research is fundamental to the advancement of our knowledge and understanding of compression as a recovery strategy. Thus an understanding of how compression garments fit different individuals is also key to improving knowledge surrounding the use of compression garments.

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