Florian Engel · Billy Sperlich *Editors*

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

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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

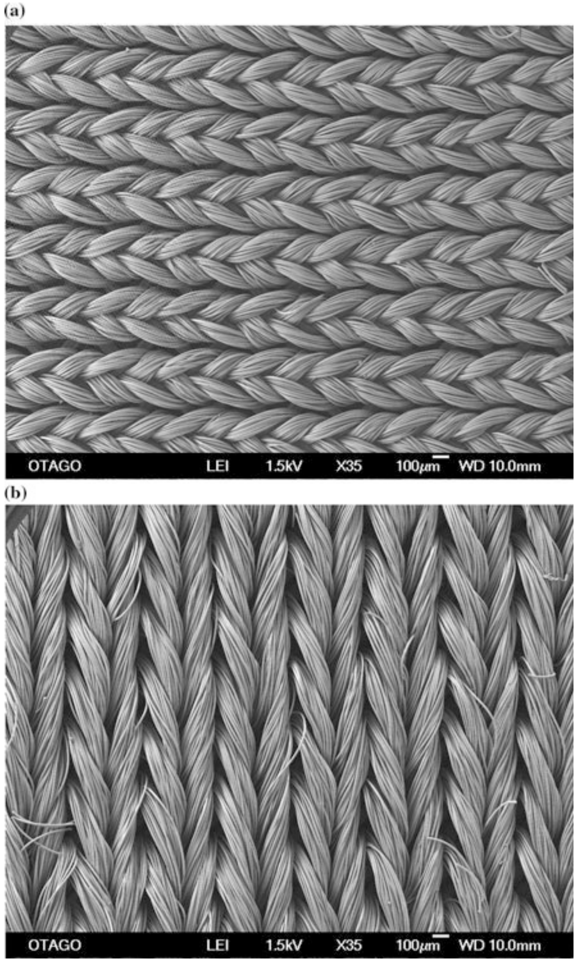

Fig. 1 Scanning electron microscope images of the fabric from a common sporting compression garment at X35 magnification; fabric outer (**a**) and inner (**b**) surfaces as used in the garment

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,