Eur J Appl Physiol (2010) 109:1017–1025
DOI 10.1007/s00421-010-1447-1

ORIGINAL ARTICLE

# Physiological effects of wearing graduated compression stockings during running

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Accepted: 17 March 2010 / Published online: 31 March 2010

**Abstract** This study examined the effect of wearing different grades of graduated compression stockings (GCS) on physiological and perceptual measures during and following treadmill running in competitive runners. Nine males and one female performed three 40-min treadmill runs (80 ± 5% maximal oxygen uptake) wearing either control (0 mmHg; CON), low (12–15 mmHg; LO-GCS), or high (23–32 mmHg; HI-GCS) grade GCS in a double-blind counterbalanced order. Oxygen uptake, heart rate and blood lactate were measured. Perceptual scales were used pre- and post-run to assess comfort, tightness and any pain associated with wearing GCS. Changes in muscle function, soreness and damage were determined pre-run, immediately after running and 24 and 48 h post-run by measuring creatine kinase and myoglobin, counter-movement jump height, perceived soreness diagrams, and pressure sensitivity. There were no significant differences between trials for oxygen uptake, heart rate or blood lactate during exercise. HI-GCS was perceived as tighter ($P < 0.05$) and more pain-inducing ($P < 0.05$) than the other interventions; CON and LO-GCS were rated more comfortable than HI-GCS ($P < 0.05$). Creatine kinase ($P < 0.05$), myoglobin ($P < 0.05$) and jump height ($P < 0.05$) were higher and pressure sensitivity was more pronounced ($P < 0.05$) immediately after running but not after 24 and 48 h. Only four participants reported muscle soreness during recovery from running and there were no differences in muscle function between trials. In conclusion, healthy runners wearing GCS did not experience any physiological benefits during or following treadmill running. However, athletes felt more comfortable wearing low-grade GCS whilst running.

**Keywords** Muscle function · Muscle soreness · Athletic apparel · Endurance athletes · Perceptual responses

## Introduction

Graduated compression stockings (GCS) create compressive pressure around muscle, bone and connective tissue and are tightest at the ankle and gradually decay up to the point where the stocking ends just beneath the knee (Lawrence and Kakkar 1980). The garments were originally developed to treat deep vein thrombosis (DVT; Byrne 2001) and venous insufficiencies (Jonker et al. 2001; van Geest et al. 2003). In more recent years athletes from various sporting codes have used GCS as a training aid; the rationale being that they may help the skeletal muscle pump (Kraemer et al. 2000), increase deep venous velocity, and/or decrease blood pooling in the calf veins (Sigel et al. 1975). Claims made by manufacturers of GCS include performance gains, enhanced perception, and improvements in various physiological responses; however, there is

Communicated by Niels Secher.

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a lack of research supporting these assertions in an athletic setting.

Running economy is shown to improve for athletes wearing GCS by diminishing the oxygen uptake $\left(\dot{V}O_2\right)$ slow component at 12 km h$^{-1}$, but not at 14 or 16 km h$^{-1}$ (Bringard et al. 2006). However, running at 12 km h$^{-1}$ would be too slow to provide performance benefits to highly trained athletes unless they were competing in ultra-marathon distances. GCS are postulated to reduce cardiovascular load by enhancing the skeletal muscle pump. However, Ali et al. (2007) found no significant difference in heart rate for moderately trained athletes wearing GCS compared with a control condition over paced 10-km runs. Nevertheless, both were field trials encompassing moderately trained athletes; athletes specifically trained for endurance running may not gain the same physiological benefits.

Wearing GCS during exercise has also been advocated to alleviate exercise-induced muscle damage (Noonan and Garrett 1999). GCS may lessen inflammation (Armstrong et al. 1991) and reduce lower leg volume and gastrocnemius vein diameter after a half marathon run (Benigni et al. 2001). Leg pain and delayed onset muscle soreness (DOMS) were also alleviated 24 h after 10-km running (Ali et al. 2007) and high-intensity cycling (Chatard et al. 2004). Wearing a compression garment during training or racing that causes considerable loss of muscle function or muscle damage may help an athlete return to training more rapidly. However, it remains to be seen whether there are physiological benefits in terms of muscle repair and recovery or whether GCS simply have perceptual advantages that aid an athlete's comfort.

Investigations have used medical-grade GCS (18–30 mmHg at the ankle) designed to treat patients with venous deficiencies (e.g. Ali et al. 2007; Bringard et al. 2006). Clinical studies have shown that optimum compression level for DVT patients is 20 mmHg at the ankle dissipating to 10 mmHg at the calf (Lawrence and Kakkar 1980). Increasing compression at the ankle to 30 mmHg created too much compression and decreased subcutaneous tissue flow and deep vein velocity (Lawrence and Kakkar 1980). Though clinical trials recommend compression at the ankle between 15 and 30 mmHg that dissipates to the knee this may not be appropriate for healthy athletes. No study has compared different levels of compression to determine which (if any) is the most beneficial for running. Furthermore, no study has utilised an appropriate control garment to examine the effects of graduated compression per se.

The aim of this study was to examine the physiological and perceptual responses to wearing GCS during fast-paced running in a controlled laboratory environment. Furthermore, we wished to investigate whether manufacturers' claims regarding the use of GCS during exercise were substantiated, whether benefits shown by others (e.g. improved running economy; Bringard et al. 2006) were relevant in competitive runners, and whether there were any 'dose–response' issues related to wearing various grades of GCS. This study will also utilise a non-graduated compression stocking to offset any 'placebo' effects. The null hypothesis is that there will be no impact of wearing GCS during running on physiological and perceptual responses.

## Methods

Nine males and one female provided informed consent to take part in this study approved by the University's Human Ethics Committee. The participants competed regularly in 5–42 km races and Ironman triathlon distances (mean ± SD) 36 ± 10 years old, 72.9 ± 13.2 kg body mass, and 1.80 ± 0.08 m in stature, with a mean $\dot{V}O_2$ max of 70.4 ± 6.1 mL kg$^{-1}$ min$^{-1}$. Run training time ranged from 6 to 16 h per week, interspersed with competitive events. All participants completed and signed health screening questionnaires before beginning any exercise tests.

### Measurements

GCS were individually fitted for the levels of compression based on the manufacturer's recommendations (Julius Zorn GmbH, Aichach, Germany). Participants were required to perform each trial with one of three grades of compression garments. The control garment (CON) was designed to have no compression at the ankle or calf (0 mmHg). The other two garments were low (LO-GCS; 15 mmHg at ankle and 12 mmHg at knee) and high (HI-GCS; 32 mmHg at ankle and 23 mmHg at knee) grade GCS. The different compression grades at the ankle and calf were achieved by the length, width, and weave of the garment.

A pressure bladder was used to assess the pressure of the GCS for each participant for each trial. The bladder was attached by tubing to a pressure meter (Kikuhime BG3792, Advancis Medical; Nottingham, UK) and was placed between the skin and GCS above the lateral malleolus and on the lateral aspect of the widest circumference of the calf muscle. Participants were asked to stand and wait at least 5 s for the digital meter to settle before recording the measurement.

Counter-movement jumps (CMJ) were measured pre- and post-run to estimate leg power. Participants were instructed to step onto a mat (Just Jump, Just Run; Probotics inc. 8602 Esslinger CT Huntsville, AL), place their hands on their hips, and use a counter-movement to optimise jump height. When participants were ready they performed three maximal-effort jumps separated by at least 10 s. Leg power was inferred from jumping height using the following formula for peak power (Johnson and Bahamonde 1996):

$$\mathrm{PP} = (78.6 \times \mathrm{CMJ}) + (60.3 \times \mathrm{mass}) - (15.3 \times \mathrm{height}) - 1308$$

where PP is peak power (W), CMJ is counter-movement jump (cm), mass is body mass (kg) and height is stature (cm).

Muscle soreness was assessed by participants drawing on an anatomical diagram differentiated into major muscle group regions (Ali et al. 2007; Thompson et al. 1999). Participants were asked to indicate muscle soreness by shading any regions that felt sore and assigning a level of muscle soreness to it (Thompson et al. 1999).

Lower limb soreness was assessed before and after treadmill running using an algometer (Force Dial FDK 60, Wagner Instruments; Greenwich, CT) to apply pressure and measure changes in sensitivity (Bailey et al. 2001). Six anatomical landmarks were selected to quantify muscle soreness: vastus lateralis muscle 20 cm above distal end of the lateral aspect of the femur, vastus medialis muscle 10 cm above distal end of the medial aspect of the femur, biceps femoris muscle 20 cm above the popliteal line, centre of the medial gastrocnemius muscle belly, centre of lateral gastrocnemius muscle belly and tibialis anterior muscle 10 cm above proximal aspect of lateral malleolus. Up to 11 kg $\mathrm{cm}^{-2}$ (110 N) of pressure was applied to each site using the algometer with a metal probe covered by a rubber tip. Participants were asked to verbally indicate when the force became ‘uncomfortable’ and this value was recorded. If no indication of discomfort was given, soreness at that site was considered ‘not present’ (Bailey et al. 2001). Each site was pressure tested for muscle soreness twice and the mean taken. If measurements were different by greater than 1 kg $\mathrm{cm}^{-2}$ a third measurement was completed and the median taken.

A number of scales were used during treadmill running. The ratings of perceived exertion scale (RPE; Borg 1973) was used to quantify exercise effort. The FS (Hardy and Rejeski 1989) indicates level of pleasure or displeasure using an 11-point scale ranging from $-5$ (very bad), 0 (neutral), to $+5$ (very good) with markers at each odd integer. The felt arousal scale (FAS; Svebak and Murgatroyd 1985) was used to measure perceived activation or arousal. The scale ranges from 1 (low arousal) to 6 (high arousal). A number of Likert scales were used to assess the comfort, tightness, and any associated pain from wearing GCS during running (Ali et al. 2007). Responses for each variable range from 1 (very uncomfortable, slack/loose, no pain) through to 10 (very comfortable, very tight, very painful).

### Preliminary procedures

Participants completed a maximal oxygen uptake ($\dot{V}O_2$ max) and lactate test protocol prior to the first trial. The experimental procedures were explained and leg measurements were taken to ensure participants received the correct stocking size for each time trial run. The GCS worn during the trials were determined by a counterbalanced design that was blinded to the participants and experimenters.

### Experimental procedures

Participants performed three 40-min running trials on a treadmill (Woodway, ELG70; Munich, Germany), in a randomised double-blind counterbalanced design, with each trial separated by 7 days of recovery. Participants were asked to record their food and drink consumption for the day prior to trial 1 and then replicate intake prior to the other trials; they were also instructed to refrain from training the day prior to each trial.

Participants consumed 250 mL of water when they arrived at the laboratory followed by a venous blood sample and measurements including muscle soreness diagrams, pressure sensitivity measures, CMJ height, and perceptual scales. Participants then donned a pair of stockings (CON, LO-GCS, or HI-GCS) and also wore running socks over the garments. Participants were instructed to slide the stocking over their foot inside out, and then roll it up their leg to fit the stocking flush at the bottom of their knee without any bunching at the ankle or calf. Participants performed a standardised warm-up on the treadmill for 5–10 min starting at 8 km $\mathrm{h}^{-1}$ and increasing to 90% of 10 km personal best speed at 1% incline (80 ± 5% $\dot{V}O_2$ max; Jones and Doust 1996). Following the warm-up participants were fitted with a downloadable heart rate chest strap (S400, Polar; Kempele, Finland) and a head strap and face mask (Hans Rudolph Inc; Kansas City, MO). The face mask was connected to a turbine and gas sampling line (Cortex, 2.3; Leipzig, Germany) to measure expired ventilatory volumes and gas concentrations during treadmill running. Resting gas analysis was measured before commencing the test to ensure correct values were obtained. Heart rate and blood lactate concentration ($\mathrm{La}^-$) were measured after the warm-up to indicate baseline data.

Heart rate and $\dot{V}O_2$ were monitored during the run. Finger prick blood samples were taken for measurement of $\mathrm{La}^-$ (Lactate Pro, Arkray Ltd, Kyoto, Japan) during running. RPE was expressed every 5 min during and immediately after the treadmill run. Perceptual scales, CMJ height, muscle soreness diagrams, pressure sensitivity measures and a venous blood sample were completed immediately following the run and 24 and 48 h after the treadmill test.

### Blood sampling and analyses

A 10-mL venous blood sample was drawn from an antecubital vein and stored in vacutainers containing EDTA (BD Diagnostic Systems; Sparks, MD) at 4°C or on ice for a maximum of 2 h. Samples were centrifuged at 3,500 rpm for 7 min at 4°C (Heraeus Labofuge 400R; DJB Healthcare Ltd, Buckinghamshire, England) and then duplicate aliquots of 500 μL plasma were transferred to plastic tubes and stored at −20°C. The plasma samples were later analysed for creatine kinase (CK) and myoglobin using a Vitalab Flexor clinical chemistry analyser (Vital Scientific NV, The Netherlands) using assay kits for CK (Roche Diagnostics GmbH, Mannheim, Germany) and myoglobin (Randox Kit, Vitalab Flexor E, AC Dieren, The Netherlands).

### Statistical analyses

Data collected were compared between each GCS intervention worn using one-way or two-way repeated measures analysis of variance (ANOVA, SPSS version 15.0). Values between groups comparing pre- and post-run measures were also identified using one-way ANOVA. When significant differences between interventions were identified Student's *t* test, using the Holm–Bonferroni adjustment, were performed. Correlations between variables were verified using linear regression equations and reported as Pearson's correlation co-efficient. Data are presented as means ± SD (unless otherwise indicated). Statistical significance was accepted at $P < 0.05$.

## Results

The level of compression measured for LO-GCS and HI-GCS were similar to the manufacturer's ratings. The mean compression for LO-GCS was 11 ± 2 mmHg at the ankle and 8 ± 1 mmHg at the calf, whereas the HI-GCS garment was 26 ± 3 mmHg at the ankle and 15 ± 2 mmHg at the calf. The CON garment applied a consistent level of compression throughout the lower leg (4 ± 1 mmHg).

### Muscle function

There was a main effect of time for CMJ height and estimated peak power. Athletes jumped higher and produced more peak power immediately post-run compared to all other time points ($P < 0.001$). However, there were no significant differences in jump height or peak power between trials (Table 1).

The most frequent regions where muscle soreness occurred were the calf muscles. However, only 4 out of 10 participants reported soreness at any one particular location. A small number of participants indicated muscle soreness with three participants feeling no muscle soreness for any trials. Upper body soreness was rare and unrelated to running. There were no differences in muscle soreness between trials (Fig. 1a–c).

There was a main effect of time for pressure sensitivity ($P < 0.05$; Fig. 2). Ratings were higher immediately post-run compared with pre-run ($P < 0.05$), remained lower after 24 h post-run ($P < 0.05$) but recovered after 48 h post-run ($P > 0.05$). There was a trend for an interaction effect ($P = 0.07$) with participants expressing a lower-pressure sensitivity wearing HI-GCS. There was no significant difference between pressure sensitivity measured at the left and right leg.

### Physiological data

There was a main effect of time for $\dot{V}O_2$ ($P < 0.05$) with values increasing from 5 (3.8 ± 0.6 L min$^{-1}$) to 40 min (4.1 ± 0.6 L min$^{-1}$) of treadmill running. However, there were no differences in $\dot{V}O_2$ between CON (3.9 ± 0.1 L min$^{-1}$), LO-GCS (3.9 ± 0.1 L min$^{-1}$) and HI-GCS (4.0 ± 0.1 L min$^{-1}$) trials (Table 2). Heart rate increased at each 5-min interval during running (main effect of time, $P < 0.05$) but there were no differences between CON (159 ± 7 beat min$^{-1}$), LO-GCS (160 ± 7 beat min$^{-1}$) or HI-GCS (160 ± 8 beat min$^{-1}$) trials. Blood La$^{-}$ did not increase from 5 (2.4 ± 0.9 mmol L$^{-1}$) to 40 min (3.6 ± 1.7 mmol L$^{-1}$) of treadmill running. There were no differences in La$^{-}$ between CON (2.6 ± 0.7 mmol L$^{-1}$),

**Table 1** Countermovement jump (CMJ) height and estimated peak power output [based on formula of Johnson and Bahamonde (1996)] pre-run and 0, 24 and 48 h post-run in all trials

| | Pre | 0 h Post | 24 h Post | 48 h Post |
|---|---|---|---|---|
| Jump height (cm) | | | | |
| CON | 42.3 ± 9.8 | 47.7 ± 10.7 | 41.9 ± 11.1 | 41.0 ± 10.8 |
| LO-GCS | 42.0 ± 9.1 | 47.8 ± 10.2 | 41.7 ± 10.1 | 40.7 ± 9.5 |
| HI-GCS | 41.2 ± 8.9 | 47.7 ± 11.6 | 41.7 ± 12.0 | 40.5 ± 8.5 |
| Estimated peak power (W) | | | | |
| CON | 3,659 ± 1,106 | 4,082 ± 1,172 | 3,628 ± 1,207 | 3,556 ± 1,180 |
| LO-GCS | 3,638 ± 1,047 | 4,093 ± 1,134 | 3,612 ± 1,128 | 3,535 ± 1,078 |
| HI-GCS | 3,571 ± 1,035 | 4,082 ± 1,246 | 3,615 ± 1,279 | 3,516 ± 1,005 |

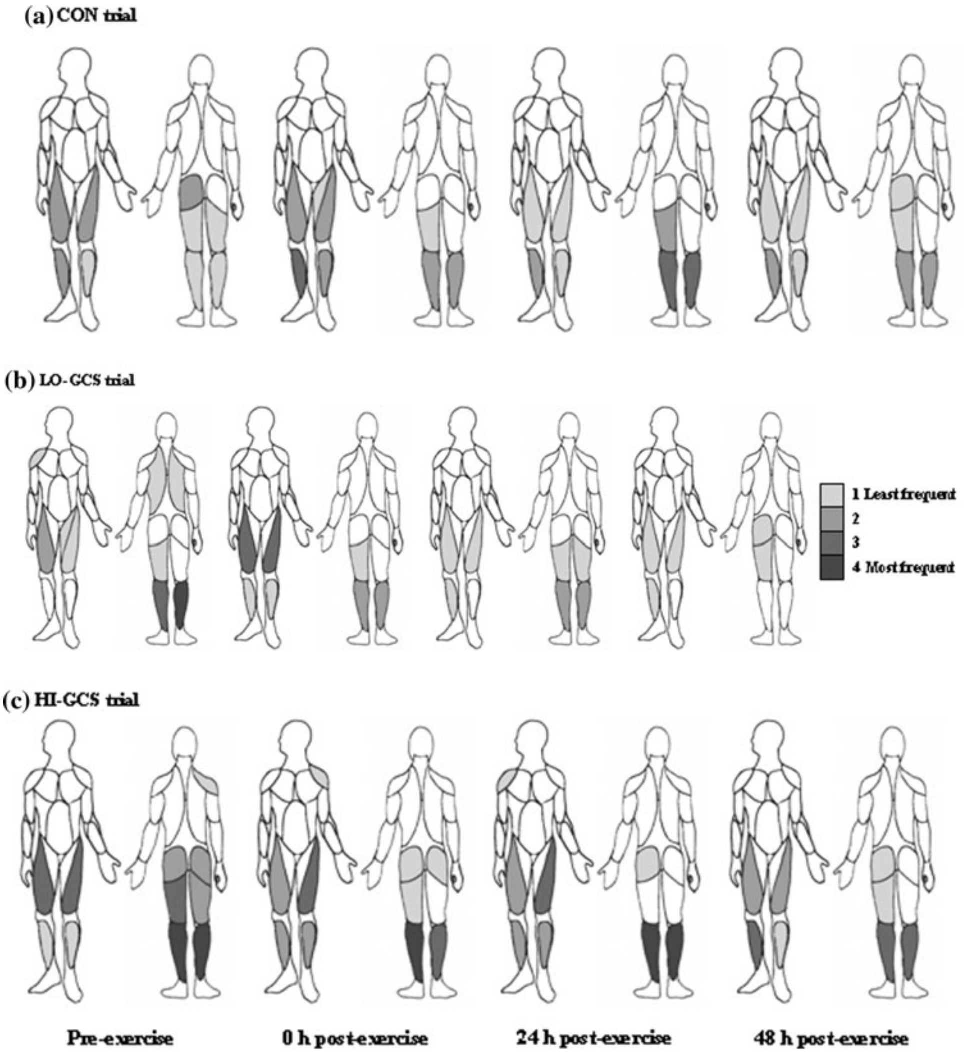

**Fig. 1** Location and frequency of perceived muscle soreness pre-run and 0, 24 and 48 h post-run in **a** control (*CON*), **b** low-grade graduated compression stockings (*LO-GCS*) and **c** high-grade graduated compression stockings (*HI-GCS*) trials

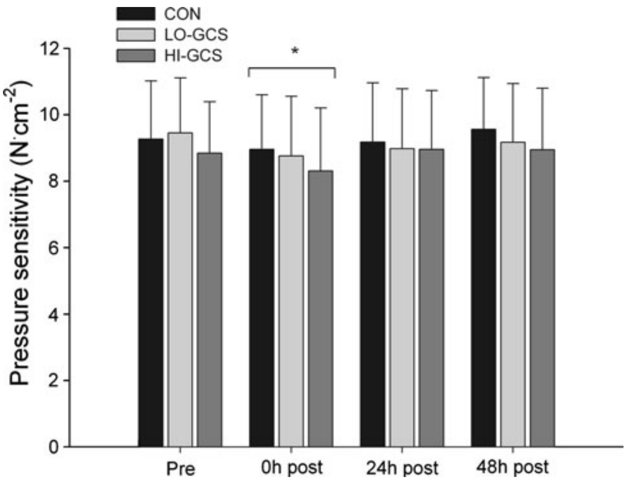

**Fig. 2** Ratings of pressure sensitivity as measured by pressure algometer pre-run and 0, 24 and 48 h post-run in all trials (left and right legs combined for each trial; *main effect of time, significantly lower than pre-exercise and 24 h post-exercise, $P < 0.05$)

LO-GCS (3.1 ± 0.8 mmol $L^{-1}$), and HI-GCS (3.3 ± 0.7 mmol $L^{-1}$) trials.

There was a main effect of time for CK activity ($P < 0.001$; Fig. 3). CK was higher immediately post-run compared with pre-run ($P < 0.05$) but there were no differences between pre-run and 24 and 48 h post-run. There was no difference in CK activity between trials. There was a main effect of time for myoglobin concentration ($P < 0.001$; Fig. 4); specifically, myoglobin immediately post-run was elevated compared with other time points ($P < 0.05$). There were no differences in myoglobin between trials.

## Perceptual data

Ratings of perceived exertion (RPE) increased during running ($P < 0.05$) but there were no differences between CON (13.4 ± 1.2), LO-GCS (13.8 ± 1.0), and HI-GCS (13.9 ± 1.1) trials. Ratings of pleasure–displeasure were not

**Table 2** Heart rate (HR), blood lactate ($La^-$) and oxygen uptake $\left(\dot{V}O_2\right)$ measurements during each 5-min interval of running in all trials

| | Exercise time (min) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 |
| Heart rate (beat $min^{-1}$) | | | | | | | | |
| CON | 148 ± 9 | 156 ± 10 | 159 ± 9 | 160 ± 10 | 162 ± 10 | 165 ± 10 | 167 ± 10 | 168 ± 9 |
| LO-GCS | 149 ± 9 | 157 ± 10 | 160 ± 10 | 162 ± 11 | 165 ± 10 | 167 ± 9 | 169 ± 8 | 171 ± 7 |
| HI-GCS | 146 ± 11 | 156 ± 11 | 159 ± 11 | 161 ± 10 | 164 ± 10 | 166 ± 11 | 168 ± 11 | 170 ± 10 |
| Blood lactate (mmol $L^{-1}$) | | | | | | | | |
| CON | 2.4 ± 0.6 | 2.3 ± 0.5 | 2.4 ± 0.5 | 2.8 ± 0.5 | 2.9 ± 0.4 | 2.9 ± 0.5 | 3.6 ± 0.5 | 3.3 ± 1.0 |
| LO-GCS | 2.1 ± 0.7 | 2.4 ± 0.5 | 2.8 ± 0.4 | 2.2 ± 0.4 | 3.1 ± 0.4 | 3.2 ± 0.7 | 3.6 ± 0.6 | 3.9 ± 1.4 |
| HI-GCS | 2.6 ± 0.6 | 2.4 ± 0.4 | 2.6 ± 0.7 | 3.1 ± 0.4 | 2.1 ± 0.5 | 3.2 ± 0.7 | 3.6 ± 0.7 | 3.6 ± 0.7 |
| Oxygen uptake (L $min^{-1}$) | | | | | | | | |
| CON | 3.8 ± 0.7 | 4.1 ± 0.6 | 4.1 ± 0.7 | 4.1 ± 0.6 | 4.0 ± 0.6 | 4.1 ± 0.6 | 4.1 ± 0.6 | 4.1 ± 0.6 |
| LO-GCS | 3.8 ± 0.7 | 4.0 ± 0.7 | 4.0 ± 0.7 | 4.0 ± 0.7 | 4.1 ± 0.7 | 4.0 ± 0.7 | 4.1 ± 0.6 | 4.1 ± 0.6 |
| HI-GCS | 3.8 ± 0.6 | 4.1 ± 0.6 | 4.1 ± 0.7 | 4.1 ± 0.7 | 4.1 ± 0.7 | 4.1 ± 0.6 | 4.1 ± 0.6 | 4.1 ± 0.6 |

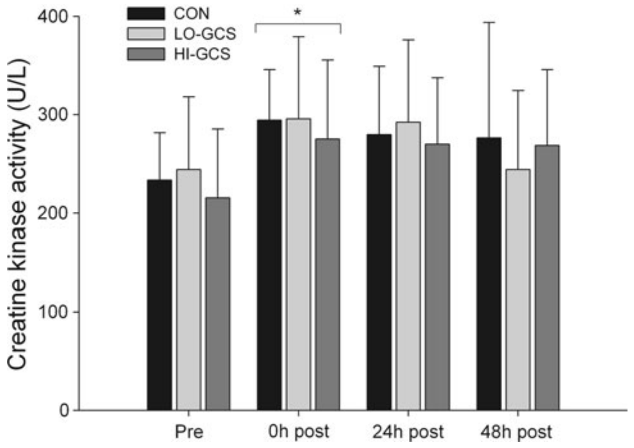

**Fig. 3** Creatine kinase (CK) activity pre-run and 0, 24 and 48 h post-run in all trials (*main effect of time, significantly higher than all other time points, $P < 0.05$)

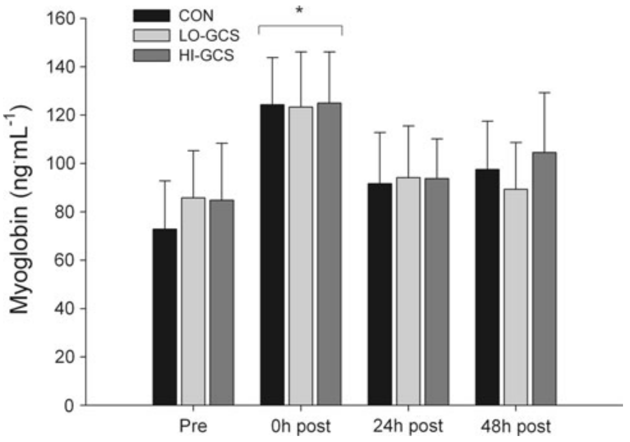

**Fig. 4** Myoglobin concentration pre-run and 0, 24 and 48 h post-run in all trials (*main effect of time, significantly higher than pre-exercise, $P < 0.05$)

different between CON (2.3 ± 1.4), LO-GCS (1.8 ± 1.9), and HI-GCS (1.8 ± 1.9) trials. Ratings of arousal/activation were also unchanged between CON (3.8 ± 1.2), LO-GCS (3.5 ± 1.1), and HI-GCS (3.6 ± 0.8) trials.

There was a main effect of treatment for perceived GCS comfort ($P < 0.05$; Fig. 5a). CON was rated as more comfortable than HI-GCS ($P < 0.05$) but there were no differences between CON and LO-GCS or LO-GCS and HI-GCS. Ratings of comfort remained the same throughout each trial indicating there was no effect of time. There was a main effect of treatment for perceived tightness of GCS ($P < 0.001$; Fig. 5b). HI-GCS were perceived as tighter than CON ($P < 0.05$) and LO-GCS ($P < 0.05$); however, there was no main effect of time from pre- to post-run. There was a main effect of treatment for perceived pain wearing GCS ($P < 0.05$; Fig. 5c). HI-GCS were rated as inducing more pain than the other trials ($P < 0.05$). As with the ratings of comfort and tightness, there was no main effect of time for ratings of perceived pain.

## Discussion

This study investigated the effects of wearing various grades of GCS on physiological and perceptual measures during and following high-intensity treadmill running in competitive runners. There were no differences in $\dot{V}O_2$, HR or $La^-$ during exercise between trials. In this cohort, GCS did not have an impact on muscle function or muscle soreness in the days following exercise. Ratings of perceived comfort were greater for low level compression (4–12 mmHg) than higher grades (23–32 mmHg) of

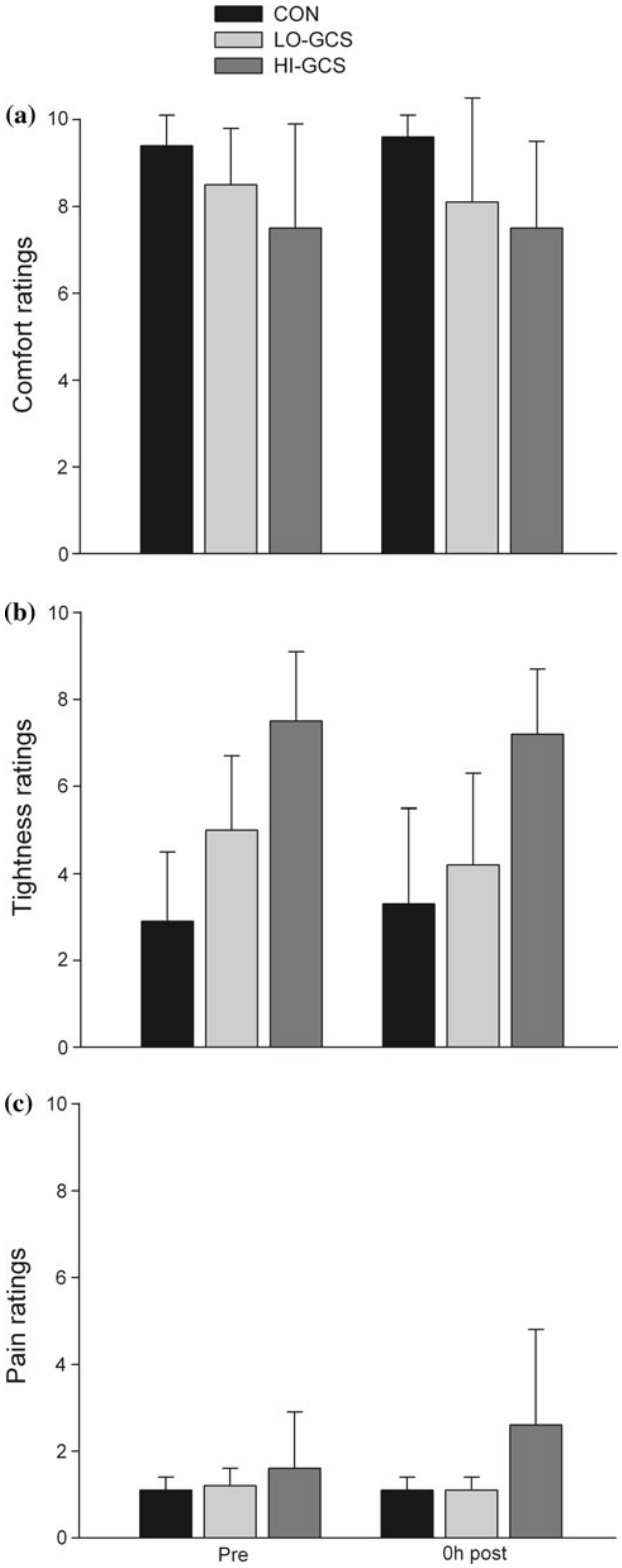

**Fig. 5** Ratings of perceived **a** comfort, **b** tightness and **c** pain from wearing compression garments pre-run and immediately post-run in all trials

compression. In addition, ratings of perceived pain were greater in the HI-GCS trial.

Muscle function (inferred from CMJ and estimated peak power) was expected to be affected at 24 and 48 h post-run due to acute muscle damage leading to DOMS. However, these indices were well maintained post-run (Table 1) and probably due to the athletes being accustomed to the exercise (Kuipers et al. 1989). The higher CMJ and peak power immediately post-run may have been due to a ‘warm-up’ effect (Shellock and Prentice 1985). Nevertheless, there were no differences in muscle function between trials which contrast with earlier findings (Ali et al. 2010). In that study participants running 10-km time trials on an outdoor track were better able to maintain CMJ performance when wearing low (10–12 mmHg) and medium (18–22 mmHg) grade GCS compared with a control (0 mmHg) garment. The athletes may have experienced reduced muscle oscillation (Kraemer et al. 1996) and/or reduced mechanical stress (Armstrong et al. 1991) in the GCS trials (Ali et al. 2010). Athletes ran on a treadmill with a suspension system and the ground reaction forces were lower relative to running on a rubberised outdoor track. Further, they were only exercising at 90% of their personal best 10 km times as opposed to maximal effort in the field study.

There were no differences in muscle soreness indices between trials. Pressure sensitivity was highest immediately post-run ($P < 0.05$), remained high at 24 h ($P < 0.05$) and returned to pre-run levels at 48 h post-exercise (Fig. 2). These ratings (8.5–9.5) indicate “just noticeable” soreness 1 and 2 days after the run. Moreover, Fig. 1 shows that few participants indicated soreness at any specific body part and this was not different between trials.

Training status and training volume were critical aspects differentiating this study with investigations that have included athletes unaccustomed to high volumes (Bringard et al. 2006; Chatard 1998; Duffield and Portus 2007). For example, Ali et al. (2007), using games players, found that 13 out of 14 participants reported soreness in the calf area 24 h following a 10-km run (cf. the highest frequency reported was 4 out of 10). The high volume of running that the participants regularly completed may have developed training adaptations that improved the muscles’ capacity to recover for the next training session (Kuipers et al. 1989). The treadmill protocol caused immediate-onset muscle soreness (Fig. 2) and damage (Figs. 3, 4) immediately post-run. However, pressure sensitivity, CK and myoglobin levels recovered within 24 h. The reason why GCS may not have had an impact on recovery from exercise was because the exercise protocol was not strenuous enough to induce significant amount of DOMS.

Bringard et al. (2006) reported considerable improvements in oxygen economy when running at 12 km $h^{-1}$ using GCS. The mechanisms proposed for the better economy were improved muscle fibre support in the same contraction direction and improved circulation by assisting the skeletal muscle pump. However, $\dot{V}O_2$ was not different between time points in any of the trials (Table 2) and the results do not support wearing GCS improves running economy in competitive athletes. Participants in this study ran at 80 ± 5% of their $\dot{V}O_2$ max, the same relative intensity as the athletes in the study by Bringard et al. (2006), but at a higher running speed (14 ± 1.4 km $h^{-1}$ compared with 12 km $h^{-1}$). Bringard et al. (2006) found that oxygen economy was not different at higher speeds (14 and 16 km $h^{-1}$) thus the discrepancies between studies could relate to the training status of participants.

Heart rate increased during the treadmill runs for all GCS conditions (Table 2). GCS have been postulated to assist the skeletal muscle pump and possibly enhance venous return (Mayberry et al. 1991) which could lower HR during the constant pace exercise. However, there were no differences in HR between trials, indicating venous return was not altered since athletes have an adequate blood flow from the lower leg to the heart during intense exercise (Kuipers et al. 1989).

Another purported benefit of wearing GCS during exercise is its ability to remove $La^-$. Berry and McMurray (1987) showed a decrease in venous $La^-$ both during exercise and recovery whilst wearing GCS; possibly due to lower production of $La^-$ and/or the greater blood flow removing and oxidising $La^-$. However, based on our results we conclude that GCS do not have any impact on $La^-$ clearance in competitive runners.

There was no difference in perceptions of pleasure–displeasure, arousal/activation and exertion between trials. However, CON were rated as more comfortable than HI-GCS ($P < 0.05$; Fig. 5a) with a trend for LO-GCS to be more comfortable than HI-GCS. HI-GCS caused minor but more pain than LO-GCS and CON ($P < 0.05$; Fig. 5c). Pain increased for some participants in the second half of the run that began as a dull ache and progressed to numbness or 'pins and needles'. This may have been due to the excessive compression around the foot which may have impeded blood flow (Lewis et al. 1976). Anecdotal comments from the athletes indicated they felt that the HI-GCS impeded their ability to maintain a steady pace. This contradicts Bringard et al. (2006) who stated that athletes ran more economically when compression was 23.5 mmHg compared with 5 mmHg.

## Conclusions

Competitive runners did not gain any benefits from wearing GCS during fast-paced running. Though the treadmill running trials were stressful enough to cause changes in muscle damage markers and pressure sensitivity the participants were able to recover within 24 h. These runners experienced no physiological benefits while wearing GCS from enhanced $La^-$ clearance, improved running economy, or reduced HR. The runners favoured low-grade garments (4–12 mmHg) and reported that high-grade GCS (23–32 mmHg) caused discomfort.

**Acknowledgments** The authors would like to thank Invista International S.à.r.l. (Geneva, Switzerland) for funding this study and Julius Zorn GmbH (Aichach, Germany) for providing the compression garments used by the participants. We would also like to thank all the participants involved in this study and the research assistants who assisted with data collection. The authors declare that they have no conflicts of interest.

## References

Ali A, Caine MP, Snow BG (2007) Graduated compression stockings: physiological and perceptual responses during and after exercise. J Sports Sci 25:413–419

Ali A, Creasy RH, Edge JH (2010) The effect of graduated compression stockings on running performance. J Strength Cond Res (in press)

Armstrong RB, Warren GL, Warren JA (1991) Mechanisms of exercise-induced muscle fibre injury. Sports Med 12:184–207

Bailey DM, Davies B, Young IS, Hullin DA, Seddon PS (2001) A potential role for free radical-mediated skeletal muscle soreness in the pathophysiology of acute mountain sickness. Aviat Space Environ Med 72:513–521

Benigni JP, Sadoun S, Schadeck M, Rastel D (2001) Marathon runners, veins, and compression stockings. Phlebologie 54:171–217

Berry MJ, McMurray RG (1987) Effects of graduated compression stockings on blood lactate following an exhaustive bout of exercise. Am J Phys Med Rehab 61:121–132

Borg GAV (1973) Perceived exertion: a note on 'history' and methods. Med Sci Sports Exerc 5:90–93

Bringard A, Perrey S, Belluye N (2006) Aerobic energy cost and sensation response during submaximal running exercise—positive effects of wearing compression tights. Int J Sports Med 27:373–378

Byrne B (2001) Deep vein thrombosis prophylaxis: the effectiveness and implications of using below-knee or thigh-length graduated compression stockings. Heart Lung 30:277–284

Chatard JC (1998) Elastic bandages, recovery and sport performance. In: Proceedings of the Techtextil symposium. Health and protective textiles, Lyon, France, pp 79–84

Chatard JC, Atlaoui D, Farjanel J, Louisy F, Rastel D, Guezennec CY (2004) Elastic stockings, performance and leg pain recovery in 63-year-old sportsmen. Eur J Appl Physiol 93:347–352

Duffield R, Portus M (2007) Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players. Br J Sports Med 41:409–414

Hardy CJ, Rejeski WJ (1989) Not what, but how one feels: the measurement of affect during exercise. J Sport Exerc Psychol 11:304–317

Johnson DL, Bahamonde R (1996) Power output estimate in university athletes. J Strength Cond Res 10:161–166

Jones AM, Doust JH (1996) A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci 14:321–327

Jonker MJ, de Boer EM, Adèr HJ, Bezemer PD (2001) The oedema-protective effect of Lycra® support stockings. Dermatology 203:294–298

Kraemer WJ, Bush JA, Bauer JA et al (1996) Influence of compression garments on vertical jump performance in NCAA Division I volleyball players. J Strength Cond Res 10:180–183

Kraemer WJ, Volek JS, Bush JA et al (2000) Influence of compression hosiery on physiological responses to standing fatigue in women. Med Sci Sports Exerc 32:1849–1858

Kuipers H, Janssen GME, Bosnan F, Frederik PM, Guerten P (1989) Structural and ultrastructural changes in skeletal muscle associated with long-distance training and running. Int J Sports Med 10:S156–S159

Lawrence D, Kakkar VV (1980) Graduated, static, external compression of the lower limb: a physiological assessment. Br J Surg 67:119–121

Lewis CE, Antoine J, Meuller C et al (1976) Elastic compression in the prevention of venous stasis. Am J Surg 132:739–743

Mayberry JC, Moneta GL, DeFrang RD, Porter JM (1991) The influence of elastic compression on deep venous hemodynamics. J Vasc Surg 13:91–99

Noonan TJ, Garrett WE (1999) Muscle strain injury: diagnosis and treatment. J Am Acad Orthop Surg 7:262–269

Shellock FG, Prentice WE (1985) Warming up and stretching for improved physical performance and prevention of sports-related injuries. Sports Med 2:267–278

Sigel B, Edelstein AL, Savitch L (1975) Type of compression for reducing venous stasis. Arch Surg 110:171–175

Svebak E, Murgatroyd S (1985) Metamotivational dominance: a multimethod validation of reversal theory constructs. J Personal Soc Psychol 48:107–116

Thompson D, Nicholas CW, Williams C (1999) Muscular soreness following prolonged, intermittent, high-intensity shuttle running. J Sports Sci 17:387–395

van Geest AJ, Franken CPM, Neumann HAM (2003) Medical elastic compression stockings in the treatment of venous insufficiency. Curr Probl Derm 31:98–107