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The effect of post-exercise application of either graduated or uniform compression socks on the mitigation of delayed onset muscle soreness

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Abstract

A series of studies were conducted to test the hypothesis that compression socks (uniform or graduated compression) worn after exercise mitigate exercise-induced pain. Fifty-nine (59) participants took part in three separate exercise protocols to induce a degree of muscle soreness from low to severe. Participants wore either ankle height socks with no compression (NoCo), knee height socks with uniform (UNI) or graduated compression (GRAD) for 8 h/day following exercise. Before, immediately after and during recovery, we measured muscle strength, flexibility and the perception of pain. The three exercise protocols were as follows. (1) Hike: compared the effects of GRAD and NoCo socks following a 10-km treadmill hike with a 1000 m ascent and descent. (2) Trail Run: compared the effect of GRAD and UNI following a 14-km trail run with 250 m ascent and descent. (3) Calf Exercise: compared the effect of GRAD and UNI socks with a predominately eccentric calf exercise. GRAD socks significantly mitigated the perception of calf pain compared to NoCo (Hike). The UNI socks were superior to the GRAD socks in mitigating the perception of pain during recovery in the Trail Run. No statistical difference was noted between UNI and GRAD socks after the Calf Exercise. Compression socks mitigated the perception of calf muscle pain (Hike trial), with UNI providing more benefit compared to GRAD socks (Trail Run trial). No differences between the UNI and GRAD socks were observed in the Calf Exercise trial. Compression socks aid in the perception of recovery following low to moderate pain from delayed onset muscle soreness.

Keywords

compression socks, uniform compression profile, graduated compression profile, recovery, delayed onset muscle soreness

Exercise training, sporting competition and recreational activities may result in exercise-induced muscle damage defined as delayed onset muscle soreness (DOMS). The magnitude of muscle damage that an individual may experience following exercise is influenced by the duration, intensity and type of exercise performed. In addition, the individual's prevailing training status will also play a role in DOMS susceptibility or protection,[1,2] with eccentric muscle contractions providing the greatest stimulus for DOMS.[3] Whilst all sporting activities involve some degree of eccentric muscle contraction, activities with a higher contribution of eccentric muscle contraction (e.g. downhill walking/running and weight lifting) result in extensive muscle damage. DOMS is characterised by structural damage to the sarcomeres in the muscle, which in turn leads to an inflammatory response.[3]

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This structural damage is a normal response to training and is an important component of the training cycle, because in the days that follow the damaging bout of exercise, the muscle adapts and becomes more resilient to further damage.[4] This pattern of overload and recovery is the physiological principle behind improving performance in all sporting and athletic activities. The symptoms associated with DOMS include decreased muscle strength, decreased range of motion (ROM), swelling, pain, a temporary reduction in exercise performance and a prolonged recovery phase.[2,5–7] These symptoms may last from 24 to 96 h with a maximum perceived at 48 h following exercise, which may negatively impact subsequent training sessions. As a result, methods to reduce the negative symptoms associated with DOMS are of particular interest, since this may potentially reduce recovery time following training and/or competition.

The effects of compression socks worn during exercise have been studied extensively and a review of the current literature that is available reveals conflicting results, with some studies showing no benefit.[8] More recently, compression socks have gained popularity as a method of potentially enhancing recovery from exercise.[9–11] Additionally, studies have reported that the compression provided by socks may enhance recovery by reducing the space available for swelling, consequently, the perception of pain associated with the swelling,[12] augmenting tissue oxygenation[13] and enhancing blood flow, which in turn may augment an immediate clearance of blood lactate[10] markers of muscle damage and inflammation.[14] The above-mentioned effects are reportedly achieved through the mechanical pressure applied to the calf muscles by the compression socks, which leads to an increased intramuscular pressure and reduced cross-sectional area of compliance vessels (i.e. veins), thereby enhancing venous return.[14,15]

While there is a growing body of research concerned with investigating the impact of compression garments on recovery from exercise and competition, the benefit of compression socks, however, remains equivocal.[8] A systematic review and meta-analysis of this literature concludes that compression garments worn after exercise effectively ameliorate the perception of DOMS and the loss of strength and power that occur with muscle damaging exercise.[17] The mechanisms proposed to be responsible for this are associated with the mechanical pressure applied by the compression garment, which reduces the osmotic pressure and the space available for swelling. This, in turn, may reduce the inflammatory response and perception of pain.[18] The mechanical pressure may also improve circulation and venous return, which may augment the clearance of metabolites and enhance the repair of the damaged muscle.[18] However, the exact mechanism(s) by which compression socks mitigate DOMS and enhance recovery after exercise remain to be fully elucidated. The differential results from various studies are likely due to differences in the type, duration and intensity of exercise included in the study designs, the initial training status of the participants, the physiological variables measured during and post exercise, the type of compression garment worn, the length of time the garment was worn and the pressure applied by the garment.[2,8,19] Further, there are differences between the textiles utilised in garment construction for comfort to avoid skin irritation and for the maintenance of sufficient elasticity and compression. The type of fabric utilised in a compression garment can affect the non-linear stretch/strain characteristics of the garment. Training was provided by the company regarding donning the sock to ensure that compression and stretch characteristics were not altered by inappropriate fit. As such, it can be difficult to draw recommendations as to the most appropriate and practical use of compression garments.

Methodology

The present study assessed the efficacy of two types of compression strategies following exercise on functional and perceived recovery: (i) knee high graduated-compression socks (GRAD) and (ii) knee high uniform compression socks (UNI). The former induced a higher level of compression at the ankles (21 ± 0.7 mmHg: 2.8 ± 0.1 kPa) compared to the calf (13.2 ± 1.9 mmHg: 1.8 ± 0.3 kPa), whereas the latter exert a uniform compression along the length of the lower leg (i.e. the level of compression is the same at the ankle and calf) (ankle: 20.5 ± 2.2 mmHg: 2.7 ± 0.3 kPa; calf: 21.0 ± 2.4 mmHg: 2.8 ± 0.3 kPa).

Three separate studies assessing the utility of compression socks following exercise have been combined to address the following issues.

(I) Does the use of compression socks after moderate exercise activity affect the perception of DOMS?
(II) Does the manner in which compression is applied (i.e. uniform or graded) have an effect on post-exercise perception of DOMS?
(III) Are graded and uniform socks capable of mitigating DOMS after severe exercise?

Although these were separate studies, the protocols were similar.

Experimental details

Participants

A total of 59 participants (39 male and 20 female) participated in three separate trials (some subjects participated in more than one trial) investigating the effect of the application of compression socks after an activity on the perception of DOMS, ankle flexibility (AF) and muscle strength. The three trials took place between January and May 2016, allowing for at least 1 month of recovery for those reprised participants. Participants were included if they were physically healthy, aged 18–60 years, regularly active (2–3 h per week), able to declare their willingness to participate in the entire study and provide a signed informed consent form. Participants were excluded from the study if they were injured or recovering from an injury, had chronic back pain or were taking any medication that could interfere with the interpretation of the results (e.g. non-steroidal anti-inflammatories, such as aspirin or ibuprofen, corticosteroids, sedatives or other prescription medications). Well trained participants, those partaking in more than five exercise sessions per week, were excluded from the study as they would likely have muscular characteristics that would be more resistant to the DOMS-inducing exercises and intensities within these experiments when compared to their less trained counterparts. Active participants who take part in three exercise sessions per week were included in this study because they have the physical fitness and ability to complete the exercises within these experiments, but have undergone less adaptations to training and were unfamiliar with the heavy eccentric loading of our experiment and so were likely to experience DOMS. Participants were required to abstain from exercise and alcohol for 24 h prior to the testing and from caffeine 2 h prior to testing. Participants were asked to refrain from any excessive (intensity greater than usual) physical activity in the week prior to the study. Furthermore, the participants were required to avoid any exercise during the four days of recovery, including stretching and/or massage. Several participants were unable to complete the experimental protocols due to time availability and in two cases medical reasons; this resulted in uneven participant numbers per experimental study. In addition, while we strove to include equal numbers of male and female participants this was not always achievable, again due to time, medical or logistic issues. Therefore, a total of 59 participants, whose physical characteristics are presented in Table 1, took part in this experimental series.

Protocol

To test the effects of these compression strategies on recovery we conducted three trials, each comprising different modes of exercise and intensity, all of which were designed to induce varying degrees of DOMS in the calf muscles. The protocols of this study series were approved by the Committee for Medical Ethics at the Ministry of Health (Republic of Slovenia) and participants gave their informed consent to participate in the study. The three exercise trials were simulated hike on a treadmill, a trail run (field study) and calf exercise. The protocols of these trials are outlined below.

Criterion measurements

Visual analog scale for perceived muscle pain. Participants were requested to provide subjective ratings of their perceived level of muscle pain of their calves, that is,

Table 1. Physical characteristics of participants in the Hike, Trail Run and Calf Exercise trials. Male (M) and female (F) participant breakdowns are presented under sex

Trial	Sock type and/or experimental Group	Sex	Age (years)	Height (m)	Weight (Kg)	Body Mass Index (kg.m^{-2})
Hike	NoCo	M = 6 F = 4	27.20 ± 12.15	1.75 ± 0.06	69.87 ± 8.45	22.85 ± 1.9
	GRAD	M = 6 F = 4	23.90 ± 5.61	1.75 ± 0.09	71.90 ± 13.31	23.46 ± 3.28
Trail Run	UNI	M = 6 F = 3	41.56 ± 15.56	1.76 ± 0.09	79.61 ± 11.22	25.84 ± 3.27
	GRAD	M = 6 F = 3	43.44 ± 18.05	1.74 ± 0.07	70.16 ± 9.2	23.09 ± 1.52
Calf Exercise	UNI	M = 7 F = 3	27.60 ± 4.86	1.76 ± 0.10	76.55 ± 17.23	24.53 ± 4.59
	GRAD	M = 8 F = 3	26.09 ± 5.7	1.79 ± 0.06	74.33 ± 8.62	23.20 ± 1.94

Note: data are presented as means ± SD.
NoCo: no compression; GRAD: graduated compression; UNI: uniform compression.

both soleus and gastrocnemius muscles, using a visual analog scale (VAS). The VAS questionnaire is a 10 cm (10-point) visual scale with anchors of 0 meaning no pain and of 10 representing maximal pain. Subjective ratings were obtained before (Pre) and after (Post) each activity and in the morning and late afternoon on Days 1, 2, 3 and 4 (D1, D2, D3 and D4) after the activity. Following statistical analysis, the morning and afternoon ratings were then combined and median values are presented for the VAS ratings of perceived muscular pain/DOMS. The explanation and scale were provided in the Slovene language, for clarity and the benefit of the Slovene participants.

Flexibility. The participants' flexibility was measured using the two tests outlined below. Both tests were repeated thrice and 30 s rest was allowed between repetitions.[20] The maximal distance achieved in any of the three attempts was taken as the best score.

a. Sit and reach test (S&R): this test was carried out before the maximal strength test to avoid any confounding factors. The participants sat on the ground, with their bare feet against the sit and reach box. The box had an overhanging lip of 15 cm toward the participant. The start of this lip was marked as 0 cm and the toe line as 15 cm. The participants were instructed to keep their legs straight and to slide a ruler (starting at 0 cm) gently and continuously across the top of the sit and reach box, as far as they could. The participants were instructed to avoid bouncing and that both hands were required to push the ruler simultaneously to complete this test.
b. Ankle Flexibility (AF): AF was tested with the knee-to-wall test. The participants began this test with both their knee and toe touching the wall. They were instructed to draw their foot backward away from the wall, while keeping the knee in contact with the wall at all times. At the furthest point at which the participant could still maintain heel contact with the ground, the distance between the wall and the greater toe was measured.

Muscle function and strength testing. Muscle strength was measured with an isokinetic dynamometer in the Hike Trial and with a modified force platform in the Run and Calf Exercise trials.

a. Hike trial. Maximal strength of the calf muscles was assessed with an isokinetic dynamometer (Biodex System 4 Pro, Biodex Medical Systems, USA). The participants were instructed to conduct maximal plantar and dorsiflexions at three separate speeds: 60, 90 and 120°.s^{-1}. The participants were secured to the Biodex chair with chest and waist straps. The knee angle was set at 120° during the test and securely fastened. The participants were familiarised with the testing procedure and had multiple attempts at the exercise prior to formal testing. The ROM of the ankle joint was set within the participants' limits. The participant was instructed to perform a maximal effort contraction from one limit of the ROM (full dorsiflexion) to the other limit of their ROM (full plantarflexion). The participants were allowed a 30 s recovery between exertions. The participants performed three maximal exertion repetitions at each of the speeds in the following order: 60, 90 and 120°.s^{-1}. There was a rest period of 1 min between the different velocities.
b. Calf Exercise and Trail Run trials. Maximal voluntary contraction (MVC) of the calf muscles was assessed in the same manner as described by Moraux et al.[21] Participants were seated and placed their feet centrally on a Leonardo force platform (Novotec Medical GmbH, Pforzheim, Germany) with knee and ankle angles maintained at 90°. A padded bar was secured across the knees, limiting the vertical movement of the lower leg during the maximal plantar flexion. Participants were instructed to maximally plantar flex their foot for 5 s, pushing against the fixed plate. The peak force generated by both feet simultaneously was taken as the maximum.

Calf measurement and determination of sock size. Participants' sock sizes were determined according to manufacturer's recommendations, utilising a combination of both calf and foot sizes. The calf circumference was measured using a measuring tape in accordance with anthropometric standards.[22] During the measurement, participants were seated with their calf muscles relaxed and the knee maintained at an angle of 100°. The widest circumference of the calf was measured in duplicate to assure the correct dimensions. In addition, the measurement of calf circumference before and after exercise and during recovery was carried out and used as an indicator of any swelling/oedema in the leg.

In all three trials, the participants were provided with a test pair of socks (UNI or GRAD), which they were requested to wear for 8 h on the day of exercise during the daytime and during the daytime on the following 3 days (D1, D2 and D3) following the DOMS-inducing exercise. The participants were specifically instructed not to wear the socks during sleep.

Evaluation of sock compression

Two types of compression socks (GARD and UNI) were knitted by the manufacturer, Intersocks, from Tactel ® fiber, the composition of which was 94% polyamide and 6% elastane. The yarn and fiber composition provide a smooth and soft sock, yet was strong enough to create and maintain sufficient pressure. For each GRAD and UNI sock, the level of compression was assessed on two separate socks in each size (i.e. S, M and L). The compression assessment was repeated three times for accuracy and repeatability. The assessment was carried out using the model MST MK IV (Salzmann Group, Switzerland) compression measurement device. An inflatable plastic strip containing pressure sensors was taped to a wooden last (foot manikin), which allowed for the determination of pressure at two locations along its length. Following placement of the pressure sensors, the sock was donned onto the appropriate size last. The inflatable plastic strip was then connected to the control unit, which initiated inflation of the strip/balloon. During the inflation, the control unit measured the pressure required to inflate the balloon to a predetermined volume. The pressure required to inflate the balloon was recorded at the ankle (Salzmann level B) and calf (Salzmann level C) on the Salzmann apparatus. The results of the compression analysis indicated that the average pressures at the ankle (Salzmann B) and calf (Salzmann C) of the GRAD socks were 21 ± 0.7 mmHg: 2.8 ± 0.1 kPa and 13.2 ± 1.9 mmHg: 1.8 ± 0.3 kPa, respectively. In contrast, the pressure in the UNI sock was the same at the ankle (Salzmann B: 20.5 ± 2.2 mmHg: 2.7 ± 0.3 kPa) and calf (Salzmann C: 21 ± 2.4 mmHg: 2.8 ± 0.3 kPa).

Hike. Participants ($N = 20$; 12 males and 8 females) were requested to visit the Nordic Centre (NC) Planica (Rateče, Slovenia) on two separate occasions. On the first visit the participants completed the baseline criterion tests (assessment of muscle strength and function, AF, S&R, calf circumference and perception of muscle pain (VAS)). Following the baseline tests, participants performed a 10 km walk on a treadmill (Woodway Desmo HP, Germany). The participants were also required to visit NC Planica 48 h post exercise (Day 2: D2) to repeat the criterion tests. The 10 km walk was performed in two phases; firstly, a 5 km uphill phase, during which a altitude gain of 1000 m was conducted, and a downhill phase, during which a descent of 1000 m of over 5 km was simulated. To achieve this, the treadmill was set at an angle of 11.5° or 20% gradient for both ascent and descent phases. The participants were allowed to self-select a walking pace between 4 and 6 $km.h^{-1}$ for the ascent and 5 $km.h^{-1}$ for the descent. The participants had a 5 min rest between the uphill and downhill phases. After the simulated hike, participants were randomly assigned by a blinded researcher to two groups: one group wore ankle-high no compression socks (NoCo) and the other wore GRAD socks, after the hike. The researcher made sure to include even numbers of males and females in each experimental group.

Trail Run

Participants ($N = 18$; 12 males and 6 females) completed a 14 km trail run from the NC Planica to Lagho di Fusini (Italy) and back. The course offered mixed terrain over a 14 km distance with 250 m ascent and descent covering snow, gravel, forest trails, grass and a section of road. The participants self-selected their running pace and were requested to maintain a competition (race) pace. Global Positioning System (GPS) data was recorded using a Garmin Forerunner 305, collecting data from several participants that were later verified with a fitness tracking app, such as Mapmyrun or Strava, which was collected from the remaining participants. Total run time was also recorded. One group wore GRAD socks while the other wore UNI socks. All were regularly active individuals capable of running 10 km in under 1 h. The participants were requested to visit NC Planica on three occasions. On the first occasion, they completed the criterion tests; thereafter, the participants set out on the 14 km run either by themselves or in groups. Immediately on completion of the run, the participants returned to the laboratory where they repeated the criterion tests. The participants were then randomly assigned either the uniform (UNI) or graduated (GRAD) compression socks. The participants returned to NC Planica on D1 and D2 to repeat the criterion measures.

Calf Exercise

Participants ($N = 21$; 15 males and six females) completed a calf exercise using a standing calf raise machine. Participants were assigned to one of two groups, who wore either the GRAD or UNI compression socks after exercise. The participants were required to visit NC Planica on three occasions. The first visit involved baseline criterion measures and the DOMS-inducing exercise. The criterion measures were repeated on D1 and D2.

The baseline criterion tests were followed by a calf exercise comprising a three-repetition maximum (3RM) test. An experienced researcher performed a demonstration of the exercise prior to the participants using the exercise equipment. Following a warm up with a light weight (10 repetitions), the weight was gradually increased until the participant could only perform a maximum of three repetitions. The weight lifted a maximum of three times safely and with good technique was recorded as the participants' 3RM and was set as the workload to be used for six sets of 10 repetitions in the trial.

During the main calf exercise, the participants received the load (100% 3RM) at full plantar flexion and then proceeded to lower the weight over a 3-s period through a full range of movement to full plantar extension. Following each repetition, the weight was raised back to the starting position by two research assistants, where once again the participant would receive the load at full plantar flexion, thus allowing the participants to complete a large number of eccentric contractions at a high intensity without the fatiguing aspect of the concentric phase. To avoid inter- and intra-individual variation due to leg dominance, the DOMS provocation protocol was carried out on both legs simultaneously. If the participants were unable to maintain the eccentric contraction throughout the 3-s period, the load was decreased until the lift was possible with the correct technique. The participants repeated the criterion measures immediately after the completion of the calf raise exercise and were then provided with either UNI or GRAD compression socks.

Statistical analysis

Comparison of median (VAS) and average values of all tests completed within the three trials was conducted using the statistical package SPSS version 21.0 (Statistical Package for the Social Sciences 2012). The subjective ratings of muscle soreness obtained from the VAS were analyzed using a Mann–Whitney U nonparametric and a Wilcoxon nonparametric test. An alpha level of significance was set a priori at $p < 0.05$.

Results

The compression socks were randomly assigned to the participants following each of the exercises. Both the participants and the investigator conducting the tests and the analysis of the results were naïve regarding the type of socks that were being worn by the participants during the recovery phase (either UNI, GRAD).

There were no statistically significant differences between the groups of participants in terms of their physical characteristics (Table 1), $p > 0.05$, in any of the three studies.

Hike Trial

The participants self-selected a walking speed of 4 km.h^{-1} at the onset of the hike (i.e. during the ascent phase) and increased their velocity to 5 km.h^{-1} during the last 30 min of ascent. As a result, the NoCo group ascended at an average speed of 4.4 ± 0.6 km.h^{-1} and the GRAD group at 4.5 ± 0.5 km.h^{-1}. The descent pace for both groups was 5 km.h^{-1}. The average time taken for both groups on ascent was 1 h and 8 min to complete the 5 km distance and 1000 m ascent. The average time taken for both groups for the descent was 1 h. Heart rate was also similar for the two groups (NoCo: ascent: 148 ± 17 bpm; descent: 110 ± 15 bpm; GRAD: ascent 153 ± 7 bpm; descent: 116 ± 15 bpm). These results, based on speed, time of ascent and heart rate, indicate that the level of exertion for both the GRAD and NoCo groups was the same.

There was no difference in the calf circumference between groups (NoCo Pre: 39.5 ± 1.4 cm and GRAD Pre: 39.5 ± 2.7 cm), $p > 0.05$. In addition, following 48 h of recovery (D2), calf circumference was not different from Pre in either group and there was no difference in calf circumference between groups (NoCo D2: 38.9 ± 1.9 cm and GRAD D2: 39.4 ± 2.9 cm), indicating an absence of oedema or swelling in both groups, $p > 0.05$.

AF did not change during the 48-h (D2) post-exercise recovery period in either group (Table 2). While participants may have reported stiffness and pain in the leg, this was not evident in the measurement of flexibility. Finally, there was also no statistical difference in the AF between the groups, $p > 0.05$. The S&R test of flexibility did not reveal any change in flexibility during the 48-h post-exercise recovery period in either group; in addition, there was also no difference between groups, $p > 0.05$ (Table 2).

Calf muscle strength was assessed at three different speeds through a safe ROM within each participant's limits of ankle dorsiflexion to plantarflexion. There was no difference in the maximal force generated at any velocity between groups (Figure 1). Further, there was no change in strength from the baseline criterion testing (Pre) to 48 h (D2) following the treadmill hike, $p > 0.05$, indicating there was no effect of the exercise on MVC.

The subjective ratings of muscular pain (VAS) in the calf are presented in Figure 2. The participants rated a significant increase in the level of perceived pain as a consequence of the treadmill Hike (Post) in both groups, $p < 0.05$. While there was an increase in pain noted in both groups, as evident in Figure 2, the participants who did not wear compression socks (NoCo) during the recovery phase reported a significantly greater level of pain in the calf on D2 compared to those who wore compression socks

Table 2. Ankle flexibility (AF) and the sit and reach test (S&R) before and immediately following the trail run and 24 h (Day 1) and 48 h (Day 2) later

Trial	Test	Experimental group/ sock type	Pre	Post	Day 1	Day 2
Hike	AF	NoCo	13.4 ± 3.1	/	/	13.2 ± 2.5
		GRAD	13.3 ± 2.8	/	/	13.2 ± 2.8
Trail Run	AF	UNI	12.1 ± 6.7	12.5 ± 4.8	11.3 ± 3.6	13.4 ± 5.9
		GRAD	11.8 ± 3.2	11.9 ± 3.4	10.9 ± 3.1	11.9 ± 4.1
Calf Exercise	AF	UNI	*12.7 ± 2.8	*12.7 ± 4.9	*12.2 ± 4.2	*12.6 ± 4.4
		GRAD	15.7 ± 2.8	15.3 ± 2.5	16.1 ± 2.6	15.6 ± 2.2
Hike	S&R	NoCo	26.5 ± 10.6	/	/	26.0 ± 10.7
		GRAD	25.7 ± 6.5	/	/	25.0 ± 6.9
Trail Run	S&R	UNI	25.7 ± 10.4	24.9 ± 11.3	26.0 ± 10.0	25.9 ± 11.5
		GRAD	24.6 ± 8.8	25.4 ± 9.4	24.9 ± 9.0	24.2 12.2
Calf Exercise	S&R	UNI	27.0 ± 12.4	26.9 ± 12.0	27.0 ± 11.9	27.3 ± 11.3
		GRAD	30.1 ± 4.3	30.1 ± 4.1	28.7 ± 5.2	29.4 ± 4.9

Note: Units are cm for all data which are presented as means ± SD.
/ indicates time periods measurements were not included.
*indicates a significant difference between groups.
NoCo: no compression; GRAD: graduated compression; UNI: uniform compression.

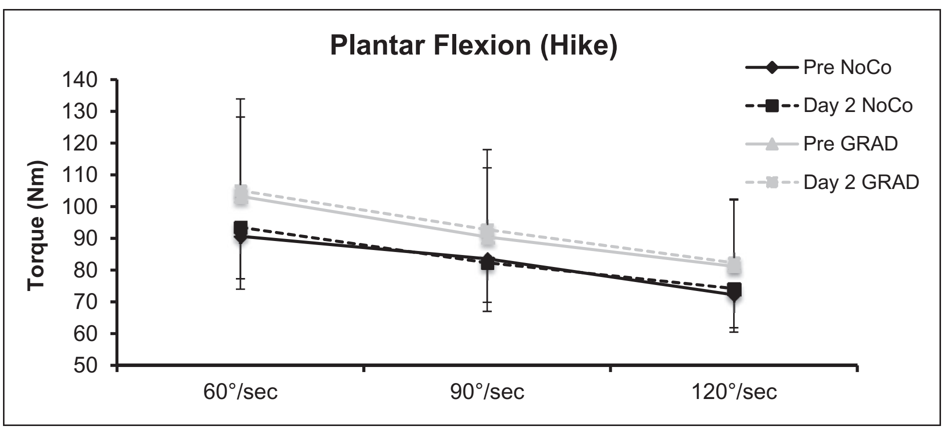

Figure 1. Average (±SD) torque (Nm) during calf plantar flexion at three velocities (60, 90 and 120°.s^{-1}) before (Pre: solid lines) and 48 h (Day 2: dashed lines) following the Hike Trial for the no compression (NoCo: black lines) and graduated compression (GRAD: grey lines) socks.

(GRAD), $p < 0.05$. In addition, the participants in the GRAD group reported a significant improvement in their perceived pain levels from D1 to D2, $p < 0.05$.

In summary, graduated compression socks (GRAD) applied immediately after the simulated treadmill hike, which induced significant muscular pain in the legs, mitigated the subjective perception of muscle pain on D2 of recovery.

Trail Run

The participants were on average older than the other two groups; however, they were within the 20–60 year age range acceptable for inclusion and were healthy and recreationally fit, so their age did not have a bearing on the results.

The time taken to complete the trail course varied, which was to be expected given the age range and gender distribution (Table 1). The slowest participant completed the 14 km trail run in 1 h 26 min and the fastest participant completed the run in 1 h 2 min. The time differential between participants was indicative of fitness level rather than exertion, as upon completion of the run all participants rated the run as a vigorous effort.

There was a difference in the calf circumference between groups at Pre (GRAD: 37.2 ± 2.1 cm; UNI: 40.9 ± 2.5 cm), Post (GRAD: 36.8 ± 1.9 cm; UNI: 40.5 ± 2.1 cm), Day 1 (GRAD: 37.1 ± 1.9 cm;

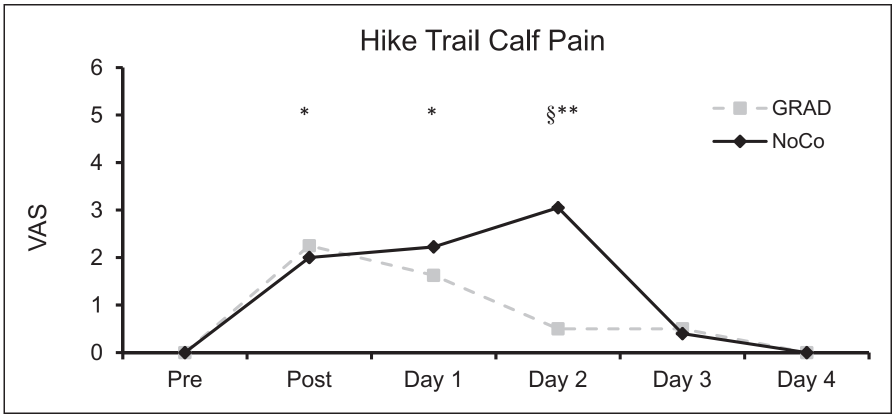

Figure 2. Median ratings of perceived pain reported by the participants in their calves before the treadmill hike (Pre), immediately following the Hike (Post) and on Days 1, 2, 3 and 4 following the exercise. The black line represents the participants in the NoCo group and the grey dashed line the participants in the GRAD group. * signifies a difference compared to Pre for both conditions while ** notes a difference to Pre for NoCo only. § denotes a difference between conditions.

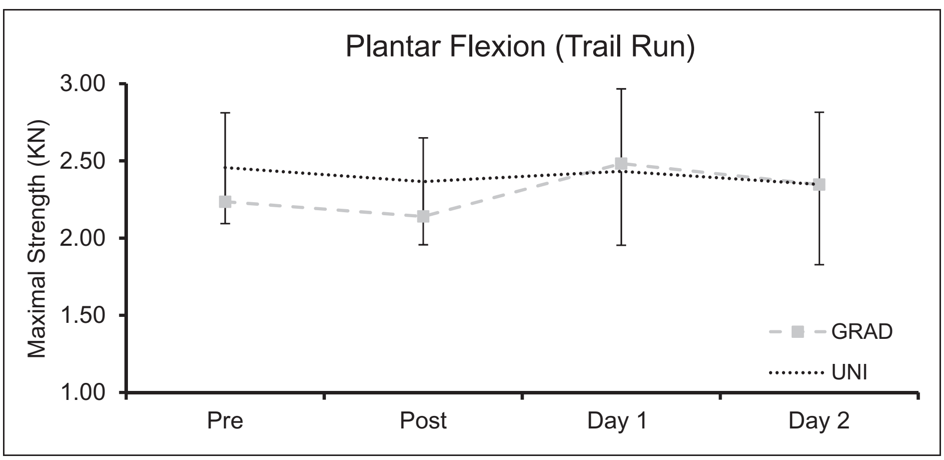

Figure 3. Average (±SD) maximal isometric strength in the calf before the Trail Run (Pre), immediately after the run (Post), 24 h (Day 1) and 48 h (Day 2) later. The black dotted line represents the participants in the UNI group and the grey dashed line the participants in the GRAD group.

UNI: 40.5 ± 2.1 cm) and Day 2 (GRAD: 37.3 ± 1.2 cm; UNI: 40.2 ± 2.1 cm). However, there was no statistical effect of time in either group, indicating no effect of the compression sock on calf circumference.

There was also no statistical difference between the groups with regard to AF. AF did not change from Pre to Post, or during the recovery on D1 or D2 in either group (Table 2). Similar to the Hike trial, participants reported stiffness and leg pain, but this was not evident in the measurement of flexibility. The S&R test of flexibility did not reveal any change in flexibility during the 48-h post-exercise recovery period in either GRAD or UNI groups (Table 2, $p > 0.05$).

There was no change in MVC of the calf as a result of exercise (Post) and thereafter in recovery on D1 or D2. In addition, maximal strength of the calf muscles (Figure 3) was not different between groups.

There was a statistically significant ($p < 0.05$) increase in the reported levels of pain in the calf by both groups from prior to the Trail Run to Post run and D1 (Figure 4). Analyzing the median values of the VAS ratings revealed a significant difference ($p < 0.05$) on D2 between groups. In this case, the GRAD group reported significantly more pain than the UNI group for the same time point.

In summary, the participants reported significantly lower perceived pain in the calf muscles when using the UNI socks during the 4-day post-exercise recovery period.

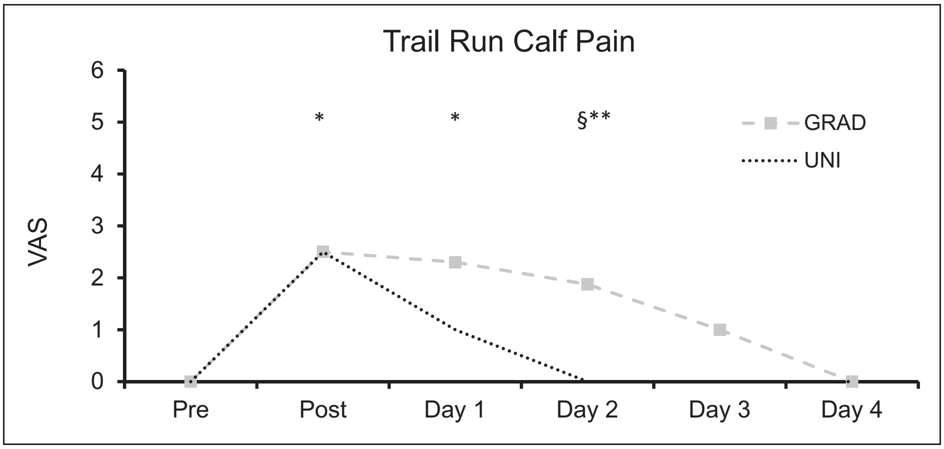

Figure 4. Participants' median ratings of perceived pain in the calf muscles. Perception of pain was determined before the Trail Run (Pre), after the Trail Run (After Ex) and on days 1, 2, 3 and 4 following the exercise. The black dotted line represents the participants in the UNI group and the grey dashed line the participants in the GRAD group. *signifies a difference compared to Pre for both conditions while **notes a difference to Pre for GRAD only. § denotes a difference between conditions. VAS: visual analog scale.

Calf Exercise

The physical characteristics of the participants (Table 1) who took part in this experiment were not significantly different within either group (UNI or GRAD). Similar to the Hike and the Trail Run trials, there were no differences in either the AF or S&R (Table 2; $p > 0.05$) across time; however, AF was different at all time points. The difference between groups in AF remained stable across time and was not affected by compression garment.

Calf circumference, regardless of condition, was larger Post exercise compared to Pre, D1 and D2, indicating increased muscle perfusion, $p < 0.05$. Pre, D1 and D2 were not different between groups or within groups, indicating an absence of swelling or oedema. The calf circumferences were Pre (GRAD: 37.7 ± 2.5 cm; UNI: 38.6 ± 3.5 cm), Post (GRAD: 38.6 ± 2.7 cm; UNI: 39.8 ± 3.3 cm), D1 (GRAD: 38.1 ± 2.6 cm; UNI: 38.6 ± 3.3 cm) and D2 (GRAD: 37.7 ± 1.8 cm; UNI: 38.6 ± 3.5 cm).

The Calf Exercise had no effect on MVC immediately following the DOMS-inducing exercise (Post) or on D1 and D2 of recovery. The participants in both groups were able to maintain maximal strength at all time points (Figure 5).

The Calf Exercise induced a significantly greater perception of DOMS than the Hike and Trail Run trials (see Figure 6). There was a significant increase in the perceived pain in the calf from Pre to Post and to D1 and D2 of the recovery period, $p < 0.05$. However, there were no differences in this level of pain reported between the GRAD and UNI groups, $p > 0.05$.

In summary, while there were no differences reported in the perceived pain levels between the two compression strategies (UNI versus (Grad), it is likely that the level of pain perceived by the participants reaches a level where neither compression strategy has a benefit over the other.

Discussion

The exercises performed by the participants in the current series of three studies induced a significant level of perceived DOMS in the calf muscles. As is typical and expected,[23,24] the participants indicated that their level of perceived pain peaked on D2 (48 h) post-exercise and subsided thereafter. Despite the significant DOMS induced by the different exercises in these studies, the participants maintained their peak maximal voluntary force and flexibility. The compression socks mitigated the perception of DOMS after the Hike Trial and Trail Run, or low to moderate levels of pain/DOMS. Compression socks did not mitigate the perception of DOMS in the calf Exercise trial, or moderate to high levels of pain.

Magnitude of exercise-induced DOMS

The three studies were designed to represent activities ranging from low strain recreational (Hike Trial), moderate (Trail Run) and moderate to strenuous training (Calf Exercise) activities. Consequently, the magnitude of the muscle damage varied between these studies, as did the magnitude of the self-reported DOMS. The lowest VAS scores for DOMS were reported in the Hike Trial, where the participants performed the simulated mountain ascent and descent. The descent phase of the walk was controlled at $5\,km.h^{-1}$ in order to standardize the effect of the

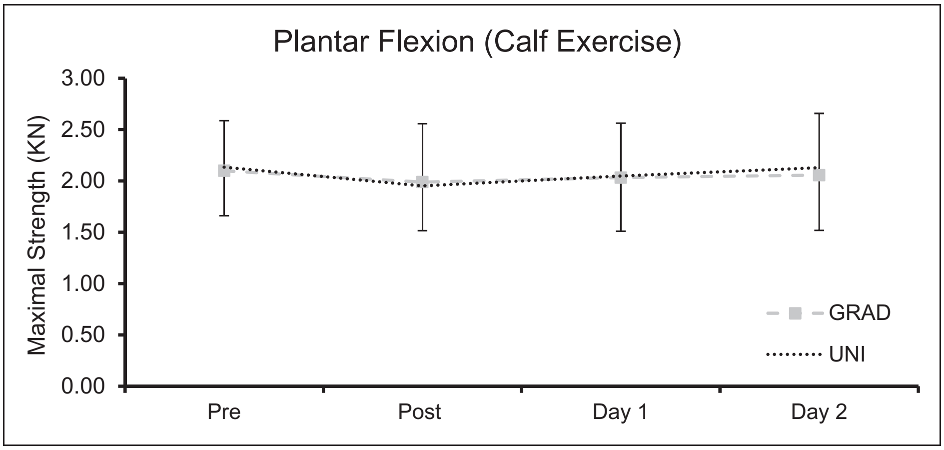

Figure 5. Average (±SD) maximal isometric strength in the calf before the Calf Exercise (Pre), immediately after the exercise (Post), 24 h (Day 1) and 48 h (Day 2) later. The black dotted line represents the participants in the UNI group and the grey dashed line the participants in the GRAD group.

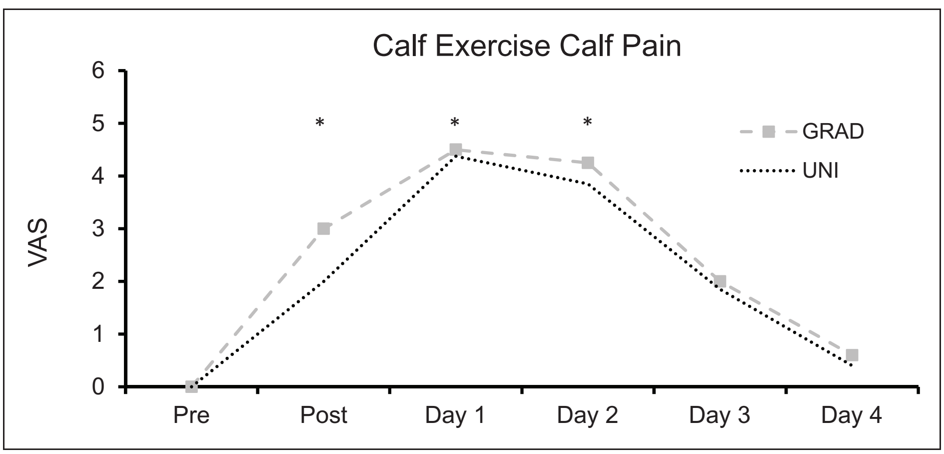

Figure 6. Median ratings of perceived pain in the calf prior to the Calf Exercise (Pre), immediately after (Post) and on Days 1, 2, 3 and 4 following the exercise. The black dotted line represents the participants in the UNI group and the grey dashed line the participants in the GRAD group. *signifies a difference compared to Pre for both conditions. VAS: visual analog scale.

eccentric workload across groups. In addition, it was felt that at this speed the participants would have a prolonged eccentric contraction phase during the gait cycle, increasing the level of physical stress. However, as the results indicate, the hike exhibited the lowest levels of DOMS; perhaps, therefore, a faster descent or a self-paced descent may have created higher forces and a greater level of DOMS. Participants' ratings of DOMS following the Trail Run were on average higher than those in the Hike Trial but lower than within the Calf Exercise. Based on the subjective ratings of muscle soreness, the calf raises conducted in the Calf Exercise trial induced the highest DOMS scores, with some individuals reporting severe pain during the recovery period.

Textile properties

All garments have a combination of properties, some of which will be considered comfortable and others as inducing discomfort. Compression garments vary in their composition and these variations can impact the level of comfort experienced by the wearer. These particular compression socks were knitted with a fiber composition of 94% polyamide and 6% elastane. The primary yarn used in the construction of the compression socks was the Tactel ® fiber, which is designed to create garments that are soft, smooth, breathable and lightweight, but also strong. The finish applied to the compression socks involved washing them for 15 min at 30°C to fix the size and avoid further shrinkages; they were then dried and ironed, which fixed the density of fabric per square cm. The characteristics of the compression socks created a balance between stiffness and elasticity to facilitate comfortable movement when worn while also staying in place. Anecdotally, the participants reported that the garments were indeed comfortable to wear, although some also reported a perception of slight thermal discomfort, which was described as too much heat being produced/stored by wearing the socks. However, it may be of note that the current studies were conducted in the northern hemisphere spring. Summer conditions may exacerbate this thermal discomfort and lead to non-compliance. Non-compliance (i.e. not wearing the compression socks) due to discomfort will obviously affect the mitigation of DOMS and have an effect on the rate of post-exercise recovery. These factors may play an important role in participant compliance when using compression socks. In addition, the relationship between the textile and the skin will provide comfort or discomfort to the user: mechanical irritation and perception of wettedness will lead to discomfort. The current socks being tested utilise a yarn and construction designed to overcome this. Finally, other skin irritants as a result of the textile composition must be taken into consideration during sock design and construction.[25]

Effect of compression pressure and pattern on mitigation of DOMS

The two pairs of socks offered for testing by the company Intersocks were identically knitted with the same composition of fiber. In addition, the socks were knitted in single batches, so that defects or differences in manufacturing thresholds between machines were kept to a minimum with the test socks. The only difference between the UNI and GRAD sock was the compression force experienced at the calf level. Although specific compression pressures are considered to offer benefits to specific user populations, this is not supported by any experimental data. Thus, for example, the application of compression socks is often promoted during exercise. Compression socks available on the market offer a range of compression pressures, for example, Reich-Schupke et al.[26] carried out a comparative study of five brands of compression socks utilized for sport. They noted the pressures of five sports socks at the ankle of between 11.7 and 25.6 mmHg. Three of those socks had pressures of 25.6, 23.2 and 20.8 mmHg, indicating that the pressure applied by the compression socks (GRAD and UNI) from Intersocks was in line with those in the industry. However, the fiber content was different, with a higher percentage of polyamide noted in the Intersocks socks; CEP running (86% polyamide) had the next highest content. How the restriction of blood flow and resultant decrease in the supply of oxygen to the working muscle might benefit performance is unknown. Further, Sperlich et al.[27] noted that applying 37 mmHg to the thigh while wearing compression breeches reduced superficial and deep blood flow. Similarly, during the post-exercise period, the compression force must be sufficient to counteract any oedema, but must not impede blood flow. Moreover, users of compression garments may not be using appropriately sized garments and thus the compression effect may not be optimal. Brophy-Williams et al.[28] reported pressure differences across landmark sites in relation to the fit of the garment, which in turn was related to the sizing of the garment. Finally, the manufacturer – Intersocks – informed us while testing the garment pressures utilising the wooden last, that an even fit of the sock on the last was essential: any folds, creases or twisting in the sock would disrupt the pressure gradient. Thus, an inappropriately sized or incorrectly fitted sock would not maintain and distribute the applied compression correctly. In addition, it is clear from our results that the type of compression (GRAD versus UNI) also plays a role in mitigating the perception of DOMS. This is a small but perhaps noteworthy caveat in the use of compression garments in the field. The above-mentioned factors must be taken into consideration when it comes to recommending that athletes wear compression garments during exercise, as this could negatively impact on performance[29] or following exercise, where recovery may be hampered.

Compression socks have been reported to provide relief from exercise-induced muscle damage and to promote a faster recovery,[9,10] particularly when the sock is worn during the recovery phase.[30] In addition, several studies[14,17,31,32] have shown the potential for compression garments to either reduce perceived pain or facilitate recovery. The results of the Hike Trial support these findings, namely, that participants wearing compression socks reported significantly lower scores for DOMS compared to participants wearing socks offering no compression (NoCo). The Trail Run and Calf Exercise trials were designed to assess differences in the mitigation of the progression of post-exercise DOMS afforded by different compression strategies, uniform (UNI) or graduated (GRAD) compression socks. The reason for this is that uniform compression and progressive compression socks (those with higher calf pressures) have been shown to improve chronic venous insufficiency and reduce leg pain and were reported to be easier to don.[33] Mosti and Partsch[34,35] suggest that the pressure of the compression garment at the calf has more relevance than that at the ankle due the ejection fraction of blood volume from the calf. However, it must be noted that there is a limit; high-compression garment calf pressure (30 mmHg) may increase deep venous flow, but can limit subcutaneous flow; further increases in garment pressure can also limit deep blood flow.[27,36] The eccentric calf exercise performed in the Calf Exercise trial induced the highest DOMS scores and there was no difference in the progression of post-exercise DOMS between the UNI and GRAD trials. In contrast, the results of the Trail Run trial demonstrated a significant reduction in the participants' perception of post-exercise DOMS scores in the UNI compared to the GRAD trials. This may be the result of the differences in the magnitude of the compression pressure at the calf. The GRAD socks offered a compression pressure of 13.2 ± 1.9 mmHg, compared to the UNI socks, which had a compression pressure of 21 ± 2.4 mmHg. It would therefore appear that in the case of moderate DOMS the compression pressure or profile offered by the GRAD sock is not as effective as the UNI compression profile, which creates a greater pressure around the calf. Secondly, the difference in the results of Trail Run and Calf Exercise trials might suggest that once the perception of DOMS is moderate to severe, as it was in the Calf Exercise trial, an 8 mmHg difference in compression pressure is not sufficient to provide any benefits in terms of the mitigation of DOMS. It is noteworthy that many studies evaluating the effects of compression socks fail to report the magnitude of the compression pressure and whether it is applied in a uniform or graduated manner. In view of the significant effect that these two characteristics (pressure and pressure profile) have on the progression of the post-exercise perception and development of DOMS, comparisons of our results to the literature and between studies are difficult. Nevertheless, two studies by the same authors[34,35] indicate that the level of compression induced at the calf level rather than the profile of compression (GRAD versus UNI) may play an important role in enhancing venous return. This may explain why the UNI sock (calf pressure: 21.0 ± 2.4 mmHg) was more effective at mitigating the perceived DOMS in the Trail Run trial.

Rate of recovery from exercise

The present series of studies did not elucidate whether compression socks would improve the rate of recovery from exercise, only whether the perception of recovery had improved 48 h following exercise. The criterion tests in the present paper focused on maximal muscle strength and joint flexibility. Future experiments should ideally investigate the benefits of compression socks on functional recovery, a performance test, hopping performance, muscular fatigue and more dynamic movements. Furthermore, testing periods would be increased to take into account a time line of athletic recovery. It has been suggested that the reduction of pain due to the application of compression garments improves performance. Indeed, Driller and Halson[37] indicate that wearing compression tights for 1 h between exercise bouts will reduce pain and subsequent performance decrement in the second exercise session when compared to those not wearing non-compression garments. In addition, Chatard et al.[10] found that wearing compression garments for an 80-min recovery phase lead to a 2.1% performance improvement in 63-year-old participants. The reported calf pressure of 24 hPa (18 mmHg) is more than our GRAD sock but less than the UNI sock, suggesting further potential benefits at different calf pressures, although too low (17 hPa or 12 mmHg) a pressure may not be beneficial to muscular recovery in the short term.[38] Due to the reported moderate effects of the application of compression socks following exercise on recovery rate and perceived pain,[39] such garments should be given consideration for use by athletes following moderate but not strenuous exercise.

While the present studies have demonstrated the potential for compression socks to reduce perceived post-exercise muscle pain levels, there was no indication of an effect on an improved rate of recovery in terms of muscle function. In the present study, the only test of muscle performance was that of muscle strength and this was not affected by the exercise. Therefore, due to there being no effect of the exercise on maximal muscle strength, no improvements could be anticipated in the recovery period. However, a systematic review of the literature that is available concludes that strength and power recover at a faster rate in subjects wearing compression garments.[17] An investigation into the potential effect of using compression socks on the rate of recovery and performance is warranted. Previous research investigating the benefits of compression socks on DOMS has found decreases in functional or performance tests[14,37,40] following a muscle damage inducing exercise with some benefit of compression garments. In addition, some studies have reported that there has been no decrease in functional performance following the muscle damaging exercise[41] or conflicting results.[42] It is possible that the choice of 3–5 s MVC as a measure of muscle function was not suitable to indicate muscle damage, whereby the participants' voluntary drive was not sufficiently blunted to affect the outcome of the MVC. A more dynamic or prolonged measure of muscle function may have shown muscle damage. Despite this, the participants themselves rated the perception of pain as significantly increasing in all three studies and therefore any change or improvement in their perception warrants investigation. Finally, following 30 min of downhill walking, Trenell et al. found a significant increase in the level of pain perceived by the participants but no difference in cellular function.

Duration of post-exercise application of compression socks

In the present study, we requested that the socks be worn during the daytime for 4 days, including the day of the DOMS-inducing exercise. This was to ensure that any benefits of compression were sustained throughout the period during which DOMS prevails. Whether the application of compression socks for shorter periods would have the same effect cannot be discerned from the present study. Several studies[31] have used similar durations of post-exercise application of compression socks as in the present study, but some also used extended periods.[14] Kraemer et al.[14] found that wearing a compressive sleeve for 5 days following eccentric exercise maintained elbow ROM and decreased the participants' subjective rating of pain. Perrey et al.[31] reported that compression garments worn for 72 h after a 30 min backward downhill walk alleviated DOMS pain in the triceps surae by day 3 compared to the condition where no compression garment was worn. They speculated that there is a local effect of tissue compression and a reduction of structural damage, which allows recovery of force production at a faster rate than without the compression garment. However, this recovery of force production was not corroborated by Duffield et al.,[43] where participants wore compression garments for 24 h post exercise.

Conclusions

The current set of exercise trials supports the findings that compression socks reduce perception of muscle soreness after muscle damaging exercise. More specifically, graduated compression socks offer pain relief following low-intensity exercise compared to no compression garment (Hike Trial) and uniform compression socks are more effective in mitigating DOMS following moderate intensity exercise compared to graduated compression socks (Trail Run). The current set of results will apply only to socks with a compression perssure of 21 and 13 mmHg at the calf; further research is required to broaden these pressure ranges. Finally, a reduction in the perception of muscle soreness may allow an individual to return to training at a faster rate. Whether the individual is physiologically ready to train again will require further research. The current data sets and study series can be summarised alongside our original questions as follows:

(I) *Does the use of compression socks after moderate exercise activity affect the perception of DOMS? Yes*

(II) *Does the manner in which compression is applied (i.e. uniform or graded) have an effect on post-exercise perception of DOMS? Yes*

(III) *Are graded and uniform socks capable of mitigating DOMS after severe exercise? Probably not; further research is required to understand this point.*

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References

1. Connolly DAJ, Sayers SE and McHugh MP. Treatment and prevention of delayed onset muscle soreness. *J Strength Condition Res* 2003; 17: 197–208.
2. Tee JC, Bosch AN and Lambert MI. Metabolic consequences of exercise-induced muscle damage. *Sports Med* 2007; 37: 827–836.
3. Clarkson PM and Sayers SP. Etiology of exercise-induced muscle damage. *Can J Appl Physiol* 1999; 24: 234–248.
4. Warren GL, Ingalls CP, Lowe DA, et al. Excitation-contraction uncoupling: major role in contraction-induced muscle injury. *Exercise Sport Sci Rev* 2001; 29: 82–87.
5. Proske U and Allen TJ. Damage to skeletal muscle from eccentric exercise. *Exercise Sport Sci Rev* 2005; 33: 98–104.
6. Cleak MJ and Eston RG. Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *Br J Sports Med* 1992; 26: 267–272.
7. Byrne C, Twist C and Eston R. Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. *Sports Med* 2004; 34: 49–69.
8. MacRae BA, Cotter JD and Laing RM. Compression garments and exercise: garment considerations, physiology and performance. *Sports Med* 2011; 41: 815–843.
9. Armstrong SA, Till ES, Maloney SR, et al. Compression socks and functional recovery following marathon running: a randomized controlled trial. *J Strength Condition Res* 2015; 29: 528–533.

10. Chatard JC, Atlaoui D, Farjanel J, et al. Elastic stockings, performance and leg pain recovery in 63-year-old sportsmen. *Eur J Appl Physiol* 2004; 93: 347–352.
11. Trenell MI, Rooney KB, Sue CM, et al. Compression garments and recovery from eccentric exercise: a (31)P-MRS study. *J Sports Sci Med* 2006; 5: 106–114.
12. Ali A, Caine MP and Snow BG. Graduated compression stockings: physiological and perceptual responses during and after exercise. *J Sports Sci* 2007; 25: 413–419.
13. Agu O, Baker D and Seifalian AM. Effect of graduated compression stockings on limb oxygenation and venous function during exercise in patients with venous insufficiency. *Vascular* 2004; 12: 69–76.
14. Kraemer WJ, Bush JA, Wickham RB, et al. Continuous compression as an effective therapeutic intervention in treating eccentric-exercise-induced muscle soreness. *J Sport Rehabil* 2001; 10: 11–23.
15. Ibegbuna V, Delis KT, Nicolaides AN, et al. Effect of elastic compression stockings on venous hemodynamics during walking. *J Vasc Surg* 2003; 37: 420–425.
16. Maton B, Thiney G, Dang S, et al. Human muscle fatigue and elastic compressive stockings. *Eur J Appl Physiol* 2006; 97: 432–442.
17. Hill J, Howatson G, van Someren K, et al. Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. *Br J Sports Med* 2014; 48: 1340–1346.
18. Kraemer WJ, French DN and Spiering BA. Compression in the treatment of acute muscle injuries in sport: review article. *Int Sport Med J* 2004; 5: 200–208.
19. Ali A, Creasy RH and Edge JA. Physiological effects of wearing graduated compression stockings during running. *Eur J Appl Physiol* 2010; 109: 1017–1025.
20. Freitas SR, Vaz JR, Bruno PM, et al. Are rest intervals between stretching repetitions effective to acutely increase range of motion? *Int J Sports Physiol Perform* 2015; 10: 191–197.
21. Moraux A, Canal A, Ollivier G, et al. Ankle dorsi- and plantar-flexion torques measured by dynamometry in healthy subjects from 5 to 80 years. *BMC Musculoskel Disord* 2013; 14: 104.
22. Lohman TG, Roche AF and Martorell R. *Anthropometric standardization reference manual*. Champaign, IL: Human Kinetics Books, 1988.
23. Cheung K, Hume PA and Maxwell L. Delayed onset muscle soreness. *Sports Med* 2003; 33: 145–164.
24. Armstrong RB. Mechanisms of exercise-induced delayed onset muscular soreness: a brief review. *Med Science Sports Exercise* 1984; 16: 529–538.
25. Wollina U, Abdel-Naser MB and Verma S. Skin physiology and textiles - consideration of basic interactions. *Curr Probl Dermatol* 2006; 33: 1–16.
26. Reich-Schupke S, Surhoff S and Stucker M. Pressure profiles of sport compression stockings. *J German Soc Dermatol* 2016; 14: 495–506.
27. Sperlich B, Born DP, Kaskinoro K, et al. Squeezing the muscle: compression clothing and muscle metabolism during recovery from high intensity exercise. *PLoS One* 2013; 8: e60923.
28. Brophy-Williams N, Driller MW, Shing CM, et al. Confounding compression: the effects of posture, sizing and garment type on measured interface pressure in sports compression clothing. *J Sports Sci* 2015; 33: 1403–1410.
29. Rider BC, Coughlin AM, Hew-Butler TD, et al. Effect of compression stockings on physiological responses and running performance in division III collegiate cross-country runners during a maximal treadmill test. *J Strength Condition Res* 2014; 28: 1732–1738.
30. Mizuno S, Morii I, Tsuchiya Y, et al. Wearing compression garment after endurance exercise promotes recovery of exercise performance. *Int J Sports Med* 2016; 37: 870–877.
31. Perrey S, Bringard A, Racinais S, et al. *Graduated compression stockings and delayed onset muscle soreness (P105). The Engineering of Sport 7*. Paris: Springer, 2008, pp.547–554.
32. Hill JA, Howatson G, van Someren KA, et al. Influence of compression garments on recovery after marathon running. *J Strength Condition Res* 2014; 28: 2228–2235.
33. Couzan S, Leizorovicz A, Laporte S, et al. A randomized double-blind trial of upward progressive versus degressive compressive stockings in patients with moderate to severe chronic venous insufficiency. *J Vasc Surg* 2012; 56: 1344–1350.
34. Mosti G and Partsch H. Compression stockings with a negative pressure gradient have a more pronounced effect on venous pumping function than graduated elastic compression stockings. *Eur J Vasc Endovasc* 2011; 42: 261–266.
35. Mosti G and Partsch H. Improvement of venous pumping function by double progressive compression stockings: higher pressure over the calf is more important than a graduated pressure profile. *Eur J Vasc Endovasc* 2014; 47: 545–549.
36. Lawrence D and Kakkar VV. Graduated, static, external compression of the lower limb: a physiological assessment. *Br J Surg* 1980; 67: 119–121.
37. Driller MW and Halson SL. The effects of wearing lower body compression garments during a cycling performance test. *Int J Sports Physiol Perform* 2013; 8: 300–306.
38. Goto K, Mizuno S and Mori A. Efficacy of wearing compression garments during post-exercise period after two repeated bouts of strenuous exercise: a randomized crossover design in healthy, active males. *Sports Med Open* 2017; 3: 25.
39. Born DP, Sperlich B and Holmberg HC. Bringing light into the dark: effects of compression clothing on performance and recovery. *Int J Sports Physiol Perform* 2013; 8: 4–18.
40. Perrey S, Bringard A, Racinais S, et al. *Graduated compression stockings and delayed onset muscle soreness. The*

Engineering of Sport 7: Vol 1. Paris: Springer Paris, 2008, pp.547–554.

41. Chan V, Duffield R and Watsford M. The effects of compression garments on performance of prolonged manual-labour exercise and recovery. *Appl Physiol Nutrit Metabol* 2016; 41: 125–132.
42. Serinken MA, Gençoğlu C and Kayatekin BM. The effect of eccentric exercise-induced delayed-onset muscle soreness on positioning sense and shooting percentage in wheelchair basketball players. *Balk Med J* 2013; 30: 382–386.
43. Duffield R, Cannon J and King M. The effects of compression garments on recovery of muscle performance following high-intensity sprint and plyometric exercise. *J Sci Medicine Sport Sports Med Aust* 2010; 13: 136–140. 2.