Investigation of the Impact of Below-Knee Compression Garments on Markers of Exercise-Induced Muscle Damage and Performance in Endurance Runners: A Prospective Randomized Controlled Trial

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Background: Compression garment utilization is very popular among runners despite a lack of consensus in the literature regarding a beneficial impact. The aim of the study was to investigate the impact of training and competing with compression garments on exercise-induced muscle damage and performance in ultramarathon runners.

Hypothesis: Compression garments will reduce the severity of exercise-induced muscle damage and improve performance in long-distance runners compared with control conditions.

Study Design: Prospective, randomized controlled trial.

Level of Evidence: Level 1.

Methods: The study was conducted in healthy, uninjured endurance runners ($n = 41$) participating in a 56-km ultramarathon. The experimental group ($n = 20$; 14 males, 6 females) trained for 6 weeks and participated in the race wearing below-knee compression garments while the control group ($n = 21$; 15 males, 6 females) did not. Participants were tested on 4 occasions for various markers of exercise-induced muscle damage and running performance.

Results: Ankle circumference measurements increased significantly less ($P = 0.01$, Cohen $d = 0.9$) in the experimental group from immediately after until 2 days post-race compared with the control group. No further statistically significant changes were detected over time in midcalf circumferences, muscle architecture, or race performance. Selected pain ratings were statistically significant and worse in the experimental group.

Conclusion: There are limited indications of a beneficial impact of compression garments with improvements in ankle circumference measurements. No ergogenic impact was detected.

Clinical Relevance: There is limited evidence to support the continued utilization of commercially available below-knee compression garments during running for the purpose of muscle recovery or as a performance aid.

Keywords: compression garments; running; exercise-induced muscle damage; performance

It is well established that running, as a form of aerobic exercise, is associated with various health benefits.⁵⁰ Conversely, long-distance running may be associated with acute and/or chronic neuromusculoskeletal injuries.⁴⁴ The most

common consequence of endurance running is exercise-induced muscle damage (EIMD) predominantly after unaccustomed exercise with various manifestations.^{16,18,26,29} Signs and symptoms of EIMD include a reduction in muscle

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force production, enhanced passive muscle tension with decreased range of motion (ROM), swelling/edema, muscle pain, and increased levels of various blood proteins and inflammatory markers^{18,25,29} along with reduced subsequent running performance.³³

To encourage continued participation in running and the associated health benefits, various methods have been considered to decrease the potential detrimental impact of EIMD.⁴⁵ Compression garments (CGs) have become prominent in running in recent years with the twofold aim of reducing EIMD and promoting running performance.³² It is suggested that compression may function therapeutically by decreasing edema, inflammation, and pain sensitivity, while promoting circulatory cytokine dissipation post-exercise.²⁹ However, based on available research, it is unclear if CGs have a beneficial impact over and above usual sporting attire to justify their popularity.^{8,32,34}

Previous literature reviews have demonstrated improvements in subjective measures such as ratings of pain, rating of perceived exertion, and comfort in the majority of studies.^{2,5,10,24,43} Objective measures such as swelling and blood/serum testing demonstrated limited beneficial effects with none detected for cardiopulmonary measures.^{6,10,12,46} Performance benefits have been limited to time-to-exhaustion, energy cost, workload, and other variables during treadmill testing^{6,10,12,27,46} with no significant changes in the majority of performance outcome measures.^{2,5,19,21,36,48,49} It appears that there is balance in evidence in favor of wearing CGs during recovery as opposed to during exercise alone.⁸ The overall efficacy of CGs has not been established conclusively.^{2,5,10,24,43}

The aim of this research was to determine the impact of below-knee CGs on lower leg EIMD and performance in runners before, during, and after an ultramarathon road race. It was anticipated that if CGs decreased muscle damage, changes may only become apparent after prolonged periods of exercise. Nonetheless, a prior study performed at a marathon did not detect statistically significant results.⁵ This study pioneered a 6-week training period in preparation for a popular 56-km ultra-distance road race.

METHODS

Distance runners aged between 20 and 45 years participating in a local ultramarathon were recruited for inclusion in this prospective randomized controlled experimental study. Participants with a minimum average training distance of 50 km per week and who completed at least 1 marathon/ultramarathon in the 18 months preceding data collection were eligible for inclusion.

Participants with preexisting musculoskeletal injuries to the lower limb in the 3 months prior to enrollment (based on a self-developed screening tool and verified by the Nordic Musculoskeletal Questionnaire); and/or with a history of underlying chronic or acute medical conditions that may have an impact on safety of participation and/or performance (based on screening with the Physical Activity Readiness Questionnaire);

and/or who were routinely using CGs and/or unwilling to train and/or compete with or without CGs were excluded.

The participants were matched based on sex, age, and personal best marathon times before being randomly allocated to the experimental or control group (using Microsoft Excel, 2013 simple randomization).

With a selected confidence level of 95%, a power of detectability of 80%, a hypothesized difference of 1.8, and a variance of 4 (based on data from a previous study by K. E. Welman, PhD, unpublished data, 2011),⁵¹ the required sample size was calculated as 19 participants per group. This is similar to the calculations in a prior doctoral dissertation for a study performed to test CG use during a 56-km race in which some significant differences were reported (K. E. Welman, PhD, unpublished data, 2011).⁵¹

A minimum of 38 participants (ie, 19 per group) were required to ensure adequate statistical power. Twenty-three participants were initially included for each group in this study.

The initial data collection (visit 1) was performed 6 weeks prior to the race and involved screening, body mass and stature measurements, ultrasound imaging of the medial gastrocnemius, midcalf, and figure-of-8 ankle circumferences. Participants were instructed to refrain from analgesics, nonsteroidal anti-inflammatory drugs, excessive alcohol consumption, sports massage, foam rolling, extensive stretching,^{7,26,36,37} and other muscle recovery strategies as far as possible from 1 week prior to Old Mutual Two Oceans 56-km ultramarathon (OMTOM) until the final visit. In the 3 days prior to the race (visit 2), these measurements were repeated. At the finish line of the OMTOM (visit 3), circumference measurements and visual analogue scale (VAS) pain ratings were repeated at the medical facilities. Two days after the event (visit 4), circumference measurements, ultrasound imaging, and VAS pain ratings were obtained. Electronic results (based on RaceTec timing values) were obtained for each participant's finish time and 42-km split times. In addition, a self-developed questionnaire was used to assess records of CG utilization, recovery modalities, and training details during the 6-week training period.

For group descriptive purposes, the body mass index was calculated based on body mass (with a calibrated digital scale—Detecto, UWE-BW-150, No. 1) and stature measurements (with a mechanical stadiometer—Detecto, UWE-BW-150).

Ultrasound Imaging

Ultrasound can be used to obtain a representation of muscle damage after a precipitating event. For example, it has been used to assess muscle damage in male runners after induction of delayed-onset muscle soreness (DOMS)⁵³ and to investigate structural changes over time in the medial gastrocnemius muscle.⁵³ Significantly increased ($P < 0.05$) muscle thickness and pennation angles were detected at 48 hours compared with baseline and started to decrease by 72 hours after DOMS induction.⁵³ Based on these findings, the peak changes compared with baseline should be observed by 48 hours after a race. Ultrasound has not previously been included as an

outcome measure in research on CG utilization in runners, but results with resistance training indicated its potential for inclusion in subsequent research.²⁸

Diagnostic ultrasound has high inter- and intrarater reliability for measuring pennation angle and muscle thickness in the medial gastrocnemius muscle.^{17,36} In addition, muscle thickness measurements were similar between ultrasonography, magnetic resonance imaging, and computed tomography scans,²² making ultrasound an affordable, convenient, and suitable alternative measure to obtain a representation of possible muscle damage.

Pennation angle is defined as the angle created between the deep aponeurosis and the muscle fascicles' attachment.³⁹ Ultrasound imaging can be used to visualize muscle architecture and consequently calculate the degrees of angulation between the deep aponeurosis and the muscle fascicles.³⁸ Pennation angles may be related to muscle strength as greater pennation angles allow for larger quantities of contractile muscle tissue to be contained within a certain volume with a consequent enhancement of force production.⁴⁰ After induction of DOMS, pennation angles have been found to increase transiently for 48 hours before starting to return to normal.⁵³ Theoretically, this may relate to EIMD-related swelling, exerting pressure on muscle fibers, which may cause an increase in angulation. Furthermore, it was found that pennation angles tend to increase as muscles shorten.¹⁵ Thus considering the temporary reduction in ROM with EIMD, pennation angles may subsequently increase.

The measurement of pennation angle with ultrasound imaging is considered reliable ($r > 0.8$) if performed by the same investigator under the same conditions⁵² and has been used with high inter- and intrarater reliability to measure pennation angles in the medial gastrocnemius muscle.^{17,38} SEM values of 0.1° to 1.2° have been reported for pennation angles determined by ultrasonography.³⁰

Muscle thickness is defined as the space between the superficial and deep aponeuroses.³⁸ It is also an important muscle strength predictor since greater muscle thickness relates to enhanced force production.³⁸ In endurance runners, muscle thickness may increase slightly compared with controls, but tends to be smaller than in sprinters.¹ After inducing DOMS, muscle thickness has been found to increase compared with baseline,⁵³ which may be due to EIMD-related swelling.

The measurement of muscle thickness with ultrasound imaging has been found to be highly reliable ($r > 0.88$) when performed by the same investigator and same conditions.⁵² Ultrasound imaging has been used with high inter- and intrarater reliability in measuring muscle thickness in the medial gastrocnemius muscle.^{17,38} SEM values of 0.1 to 0.4 cm have been reported for medial gastrocnemius muscle thickness with ultrasonography.⁹

Pennation angle and muscle thickness of the medial gastrocnemius was determined using a Siemens ACUSONX150 diagnostic ultrasound machine using previously reported settings.¹³ The right legs of participants were tested in prone position with the ankle maintained at 90° plantarflexion with a

Figure 1. Ultrasound scan of medial gastrocnemius muscle (original photo by investigator). MT, muscle thickness; PA, pennation angle.

firm footplate. Participants were instructed to relax the muscle during imaging. Scans were performed at the midpoint between the proximal and distal musculotendinous junctions.¹³ Pennation angle was calculated as the angle between the muscle fascicles and the deep aponeurosis while thickness was calculated as the distance between the superficial and deep aponeuroses with measurements taken perpendicularly at the middle of each image. Each measurement was performed twice and average values recorded. The same investigator performed all measurements.

An example of pennation angles and muscle thickness measurements can be seen in Figure 1.

Circumferences With Tape Measurement

Tape measurements have been used with high reliability in midcalf circumference.³¹ The figure-of-8 ankle tape measurement has been used with high validity in detecting edema with high inter- and intrarater reliability of measurement.^{35,42} SEM of 0.5 cm has been reported for midcalf circumferences¹⁴ and 0.47 cm⁴⁰ for ankle circumferences.

Midcalf and figure-of-8 ankle circumferences were determined with a tape measure. Participants were positioned in a sitting posture with feet extending over the edge of the plinth. The ankle circumference was taken with the right ankle in a relaxed neutral position with a standardized figure-of-8 method.⁴² The midcalf measurement was taken at the widest girth section (standardized protocol⁵¹) between the ankle malleoli and the fibular head. Each measurement was performed twice and average values recorded. The same investigator performed all measurements.

Visual Analogue Scale for Pain Ratings

The VAS questionnaire was administered for subjective pain ratings on a scale of 0 to 10 with 0 representing no pain and 10 representing the worst pain imaginable. The numerical VAS was adapted and applied to evaluate pain at rest and during active nonweightbearing lower limb movements.

Compression Garments

Commercially available below-knee CGs produced locally were used in the study. The composition of these garments is 68% polyamide, 30% Drynamix (containing predominantly polyester), and 2% elastane fabric. The manufacturers were not financially involved in the study. CGs were used during running only (ie, training sessions and during the ultramarathon) and not during the subsequent recovery period.

Statistical Analysis

All data are presented as mean $\pm$ SD unless otherwise indicated. All statistical analysis was performed with Statistica software (Statistica13; 2017) and Microsoft Excel (2013). Statistical significance was accepted as $P < 0.05$.

The Shapiro-Wilk tests for normality were conducted to determine if data were normally distributed (normal distribution accepted as $P > 0.05$). Means and SDs were calculated and t test for independent samples was performed to determine if there were any statistically significant differences between groups for descriptive measures, race performance, circumference, and muscle architecture parameters. Frequencies and medians of VAS ratings were determined and Mann-Whitney-U tests performed to assess for statistically significant differences between groups.

Effect sizes for absolute and proportional changes over time and between variables at each visit were calculated using the Cohen formula: $(\text{mean}_1 - \text{mean}_2)/\text{SD}_{\text{pooled}}$.²³ Values of >0.2 were considered a “small” effect size, >0.5 a “medium” effect size, and >0.8 a “large” effect size.⁴¹ Values smaller than 0.2 were considered trivial. The smallest worthwhile change (SWC) was determined as “(SD)(0.2).” These values were compared with SEM values to assess relevance. Values considered of practical significance refer to a large difference (in effect size) that exceeds SWC and therefore may be considered to have practical significance regardless of statistical significance.

Ethical Considerations

The study adheres to the principles of the Declaration of Helsinki (2013). It was approved by the University of Cape Town’s Faculty of Health Sciences Human Research Ethics Committee (HREC REF: 872/2016). Informed consent was obtained from each participant prior to enrollment, and participants’ rights were protected.

RESULTS

To recruit participants, a bulk email was sent to OMTOM 56-km entrants ($n = 1685$) aged between 20 and 45 years. Ninety-eight responses were received with 53 possibly eligible based on preliminary screening. A further 7 were excluded with the majority ($n = 5$) due to musculoskeletal injuries and the remaining of personal nature. One participant withdrew after group allocation and an additional four withdrew during the course of the study. Only the data of those participants who completed the study were included in the final report of findings.

Descriptive Characteristics

Group descriptive measures of the 41 participants who completed the study are presented in Table 1. There were no significant differences between groups. Analysis of covariance revealed no significant differences in descriptive characteristics between males and females.

At the initial data collection, 6 weeks prior to the race, circumference measurements and muscle architecture of the medial gastrocnemius muscles were similar for the experimental and control group with a normal distribution of data. There were no statistically significant differences between groups, although a trend to statistical significance was observed in muscle architecture parameters. Baseline outcome measures are presented in Table 2.

Changes Over Time of Main Outcomes

Circumference Measurements

Over the period from 6 weeks pre-race until 2 days post-race, there were no significant changes in midcalf ($P = 0.75$) or figure-of-8 ankle ($P = 0.34$) measurements between groups.

Midcalf circumference. The midcalf measurements remained virtually unchanged over the training period with a $0.05\% \pm 1.5\%$ average increase in the experimental group compared with a $0.3\% \pm 1.8\%$ decrease in the control group. After the race, values decreased on average $1.4\% \pm 1.3\%$ in the experimental group compared with $0.9\% \pm 1.7\%$ in the control group. Two days after the race, these values increased on average $1.8\% \pm 1.2\%$ in the experimental group compared with $1.5\% \pm 1.2\%$ in the control group. There were no statistically significant differences between groups in terms of proportional changes in midcalf measurements during the training period ($P = 0.54$); from shortly pre-race until immediately post-race ($P = 0.26$) or 2 days post-race ($P = 0.64$); nor from immediately post-race until 2 days post-race ($P = 0.35$). None of these relative (%) changes to midcalf measurements were statistically significant over time between the 2 groups ($P > 0.05$).

There were small effect sizes from 6 weeks pre-race until shortly pre-race in proportional (Cohen $d = 0.3$) and absolute (Cohen $d = 0.2$; SWC = -0.1 cm) values; from shortly pre-race until immediately post-race in proportional (Cohen $d = 0.4$) and absolute (Cohen $d = 0.4$; SWC = -0.1 cm) values; from immediately post-race until 2 days post-race in proportional (Cohen $d = 0.3$) and absolute (Cohen $d = 0.4$; SWC = 0.06 cm) change; and in proportional (Cohen $d = 0.2$) and absolute (Cohen $d = 0.4$, SWC = 0.1 cm) change from shortly pre-race until 2 days post-race. The SWC and differences in means were smaller than the SEM of 0.5 cm,^{14,25} hence it is considered nonsignificant. The effect size of the absolute change in midcalf measurements from tapering baseline until 2 days post-race was trivial (Cohen $d = 0.1$).

Ankle circumference. The figure-of-8 ankle measurements remained virtually unchanged over time in the experimental group with an average reduction of $0.6\% \pm 1.2\%$ over the training period, a further minimal decrease of $0.2\% \pm 1.9\%$ until

Table 1. Descriptive data

	Experimental Group	Control Group	Difference
Total, n	20	21	
Males, n	14	15	
Females, n	6	6	
Best marathon pace in past 18 months, min:s/km	06:04 ± 00:37	06:04 ± 00:45	$P = 0.98$
Age, y, mean ± SD	34 ± 4.8	34 ± 6.4	$P = 0.57$
Mass, kg, mean ± SD	72.1 ± 10.5	76.6 ± 9.9	$P = 0.17$
Stature, m, mean ± SD	1.7 ± 0.9	1.8 ± 0.09	$P = 0.18$
BMI, kg/m ² , median (interquartile range)	24.3 (18.0-28.8)	23.8 (20.8-29.0)	$P = 0.78$

BMI, body mass index.

Table 2. Baseline outcome measures

Baseline	Experimental Group	Control Group	Difference	P	Effect Size d	Descriptor
Ankle circumference, cm, mean ± SD (n = 38)	54.6 ± 3.9 (n = 19)	55.3 ± 3.1 (n = 19)	0.7	0.56	0.2	“Small”
Midcalf circumference, cm, mean ± SD (n = 38)	38.8 ± 3.2 (n = 19)	39.4 ± 2.3 (n = 19)	0.6	0.39	0.3	“Small”
Pennation angle, deg, mean ± SD (n = 41)	18.6 ± 1.3 (n = 20)	19.8 ± 2.4 (n = 21)	1.2	0.06	0.6	“Medium”
Thickness, cm, mean ± SD (n = 41)	1.70 ± 0.2 (n = 20)	1.82 ± 0.2 (n = 21)	0.12	0.05	0.6	“Medium”

immediately post-race, and $0.3\% \pm 1.2\%$ until 2 days post-race. The control group also remained virtually unchanged over the training period with a $0.2\% \pm 2.2\%$ decrease over the 6-week period. These values decreased a further $1\% \pm 2.6\%$ until immediately post-race and increased $0.8\% \pm 1.5\%$ by 2 days after the race. There were no significant differences in proportional changes of ankle measurements over the training period ($P = 0.48$) or from tapering baseline to immediately post-race ($P = 0.31$) or 2 days post-race ($P = 0.5$). However, from immediately post-race until 2 days post-race, the absolute ankle measurements ($P = 0.01$) and the proportional difference ($P = 0.01$) changed significantly over time in the 2 groups, with higher values in the control group.

There were small effect sizes from 6 weeks until shortly pre-race in proportional (Cohen $d = 0.2$) and absolute (Cohen $d = 0.3$; SWC = 0.2 cm) change; from shortly pre-race until immediately post-race in proportional (Cohen $d = 0.3$) and

absolute (Cohen $d = 0.4$; SWC = 0.2 cm) change; and from shortly pre-race until 2 days post-race in proportional (Cohen $d = 0.4$) and absolute (Cohen $d = 0.2$; SWC = 0.2 cm) change. These small effect sizes are unlikely to be significant, as the changes in the means and SWC are smaller than the SEM of 0.4 cm.³² However, there was a large effect size from immediately post-race until 2 days post-race in proportional (Cohen $d = 0.9$) and absolute (Cohen $d = 1.1$; SWC = 0.1 cm) change, with the change in means (-0.7 cm) exceeding the SEM.

The absolute circumference measurement changes over time are presented in Figures 2 and 3.

Muscle Architecture Values

Over the period from 6 weeks pre-race until 2 days post-race, there were no significant changes in pennation angles ($P = 0.46$) or muscle thickness ($P = 0.91$) measurements between groups.

Figure 2. Midcalf circumference means over time.

Figure 3. Ankle circumference means over time.

Muscle thickness. Muscle thickness of the medial gastrocnemius increased on average $4.3\% \pm 7.9\%$ in the experimental group and $4.8\% \pm 7.7\%$ in the control group

from 6 weeks pre-race until shortly pre-race. There were no statistically significant changes between the 2 groups ($P = 0.83$) for proportional (%) changes in muscle thickness over the

Figure 4. Medial gastrocnemius muscle thickness changes over time.

6-week period. A further increase was detected in both groups from shortly pre-race until 2 days post-race, with an average increase of $1.1\% \pm 4.6\%$ in the experimental group and $0.8\% \pm 5.9\%$ in the control group. This proportional (%) change was not statistically significant ($P = 0.86$) between groups from shortly pre-race until 2 days post-race. Effect sizes were trivial for average muscle thickness proportional (Cohen $d = -0.06$) and absolute (Cohen $d = 0.1$) change from 6 weeks pre-race until shortly pre-race; as well as from shortly pre-race until 2 days post-race in proportional (Cohen $d = 0.05$) and absolute (Cohen $d = 0.03$) values.

Pennation angle. Pennation angles increased from the first until the final data collection in both groups. The experimental group's pennation angles increased marginally with an average of $0.5\% \pm 8.8\%$ from 6 weeks until tapering baseline, whereas the control group increased $4\% \pm 10.7\%$ on average over the training period. There were no significant proportional changes between the 2 groups over the training period ($P = 0.25$). A further average increase of $3\% \pm 7.6\%$ was observed from tapering baseline until 2 days after the race in the experimental group compared with an average of $2.6\% \pm 9.4\%$ increase in the control group. This change from tapering baseline to 2 days post-race was also not statistically significant between groups ($P = 0.89$). There was a small effect size in average proportional (Cohen $d = 0.3$) and absolute (Cohen $d = 0.4$; SWC = 0.4°) pennation angle changes from 6 weeks pre-race until shortly pre-race. However, this is unlikely to be of significance since the change in the means was smaller than the SEM of 0.1° to 1.2° .²⁹ Effect sizes from shortly pre-race until 2 days

post-race was trivial in proportional (Cohen $d = 0.04$) and absolute (Cohen $d = 0.04$; SWC = 0.2°) pennation angle changes.

The absolute muscle architecture measurement changes over time are presented in Figures 4 and 5.

Race Performance

Both groups demonstrated a slower running pace per kilometer during the final 25% of the race compared with the first 75%. However, there were no significant changes between groups at any point in time; nor for overall race pace ($P = 0.97$). Effect sizes were trivial in both proportional (Cohen $d = 0.02$) and absolute (Cohen $d = 0.04$) changes in pace from 0 to 42 km compared with 42 to 56 km pace between the groups.

The race paces to 42 km and during the final 14 km are presented in Figure 6.

Subjective Pain Ratings

The control group had a significantly greater improvement in median VAS pain rating during dorsiflexion ($P = 0.03$) and during knee flexion ($P = 0.04$) of the right leg, although this was not reciprocated in the left leg. There was a trend for decreased pain rating by 2 days post-race, yet no other statistically significant changes were detected over time.

The relative change in rating from immediately post-race until 2 days post-race are presented in Figure 7.

Self-Reported Descriptive Data

During the 6-week training period, no significant differences ($P > 0.05$) were reported in the training history of the experimental and control groups. The majority of participants in

Figure 5. Medial gastrocnemius muscle pennation angle changes over time.

Figure 6. Average race pace during different stages of the 56-km Old Mutual Two Oceans 56-km ultramarathon (OMTOM) race.

Figure 7. Difference in pain ratings from immediately until 2 days post-race.

the experimental group reported using the CGs 3 to 4 times per week, whereas the control group confirmed that CGs were not used during this period.

DISCUSSION

Only limited statistically significant changes over time in measures of EIMD and race performance were found between runners training and participating in the ultramarathon with CGs compared with usual attire. No changes were detected in muscle architecture or calf and ankle circumferences in the 6-week training period, therefore there were no discernible anatomical changes as a result of CG use. However, reduced ankle circumferences were detected 2 days post-race in runners who used the CGs during the ultramarathon in keeping with their mode of action. Paradoxically, pain scores were lower in the control group.

The overall trend for ankle and midcalf measurements in both groups of an initial decrease post-race followed by an increase in the subsequent 2 days is similar to prior studies that demonstrated an immediate reduction in lower limb volume after a marathon distance⁴ and subsequently increased volume until 72 hours after an ultramarathon (K. E. Welman, PhD, unpublished data, 2011).⁵¹ The initial decrease coincided with body mass losses, which is likely to be an indication of reduced hydration status as expected immediately post-race.²⁰

The statistically significant ($P = 0.01$) increase and large effect size (Cohen $d = 1.1$) in figure-of-8 ankle circumference measurements in the control group compared with the experimental group from immediately post-race until 2 days after the race implies that the control group may have had a larger degree of swelling related to EIMD¹⁸ compared with the experimental group by 2 days post-race. A prior study⁵¹ detected significantly smaller increases in midcalf and ankle circumference measurements at 24, 48, and 72 hours post-race when below-knee CGs were used during the 56-km race and during recovery compared with placebo socks. Ankle circumferences in this prior study were measured as the narrowest section adjacent to the malleoli. The figure-of-8 ankle measurements in our study may present a more encompassing presentation of ankle swelling.⁴² Our study, in contrast to the prior, did not detect any significant changes in midcalf circumference measurements from immediately post-race until 2 days after the race. Similarly, in another study,⁵ no significant changes were detected pre- and postmarathon running in lower leg volume assessed by water displacement. In contrast, Bovenschen et al¹¹ assessed lower leg volume with a perometer after a 10-km race and found significant reductions with CG use immediately after the run, but this effect vanished 5 minutes post-run. Because of the large number of participants tested in the medical tent at the finish line of the current study, it was not

possible to test each participant immediately as he or she finished, and some had a short waiting period. Considering reduced measurements in a prior study had disappeared by 5 minutes post-race,¹¹ even a short waiting period could potentially have affected the results obtained. Based on our findings and that of previous studies, there appears to be some evidence that CGs may help reduce measures of swelling in the ankle and/or lower leg after a running event.^{11,51}

The trend for muscle thickness to increase from 6 weeks pre-race until the tapering baseline shortly prior to the race in both groups may indicate improved calf muscle strength after the training period, as muscle thickness is positively associated with muscle strength.⁴⁰ Although the mean tapering baseline muscle thickness was significantly higher in the control group compared with the experimental group ($P = 0.03$), the lack of significant effect and trivial effect size over time between the 2 groups indicates that it is unlikely to relate to CG utilization or lack thereof. The trend toward statistical significance between values at the 6-week pre-race baseline data collection point also implies that the control group most likely had stronger calf musculature prior to the race.⁴⁰

Previous research has demonstrated significant increases in pennation angles by 48 hours after DOMS induction.⁵³ Our study involved highly trained runners, thus the extent of EIMD may have been attenuated. Two days post-race, significantly higher post-race pennation angles ($P = 0.01$) were detected in the control group compared with the experimental group, which could possibly indicate a higher degree of EIMD in the control group. However, as for the muscle thickness values, there was a trend toward statistical significance at both pre-race sessions, accompanied by medium (6 weeks baseline) and large (tapering baseline) effect sizes and no significant changes over time, thus this may indicate a pre-existing difference rather than an effect of CG use.

The significantly lower VAS ratings post-race and over time in selected regions in the control group compared with the experimental group are different from the majority of prior studies that reported improved VAS pain ratings after various running events when CGs were used compared with conventional clothing. For example, runners using CGs during exercise reported lower VAS pain ratings in the lower leg compared with control group runners both shortly after and 24 hours after a 10-km race² and a 5-km race.⁴³

In contrast, higher ratings of discomfort have been reported in runners using high- and medium-level CGs compared with low-pressure CGs and conventional socks.^{3,4} It is possible that the higher pain ratings in the shins at rest in the current study could relate to discomfort caused by the socks, rather than being an indication of DOMS.

The current findings challenge those of previous research (which generally consisted of much smaller sample sizes) that suggested subjectively reduced pain ratings with CG use during running compared with conventional clothing.

The lack of significant changes in race pace and finish times is similar to a previous randomized controlled trial testing CGs conducted at the 56-km OMTOM.⁵¹ Likewise, many other

studies failed to detect any significant changes in running performance over a range of distances and terrains (from 400-m track to a 15-km trail run) when using CGs compared with control conditions.^{2,43,47,48} The current study reinforced previous findings that it is unlikely that CGs have any impact on running performance, including in ultra-endurance events.

Further Possible Contributing Factors

The dropout rate of participants after baseline measurements was the same in each group, with 2 participants not completing the study per group. Only 1 of these was related to CG use, with the concerned participant complaining that it caused thermal discomfort.

Study Limitations and Future Directions

Recovery modalities were used by a few participants in both groups pre-race, during the race, and post-race, and although there were no statistically significant differences between groups, it may confound results obtained. More stringent restriction of alternative recovery modalities should be implemented in future studies.

CONCLUSION

This study pioneered the inclusion of a 6-week training period prior to competition to allow for familiarization with the product in addition to assessing if the impact changed after routine utilization. In addition, it was the first to use diagnostic ultrasound to detect structural changes in muscle architecture parameters with CG use in endurance runners. Selected measurements suggest a possible protective impact with a reduction in ankle circumferences (both with statistical significance and large effect size), possibly related to attenuated swelling, detected over time after the race. However, further measures considered showed no or minimal statistically significant differences between groups indicating a relative lack of effect. Conversely, CGs may be associated with more discomfort in the shins than control conditions. Moreover, the only improvements detected occurred in the 48 hours after the race, with no significant impact detected during training and the race itself. Furthermore, it seems extremely unlikely that CGs can be considered an effective ergogenic aid. There is relatively limited evidence to support the utilization of commercially available below-knee CGs during long-distance running events for the purpose of muscle recovery; therefore, the popularity of utilization should be revisited.

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