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# Compression Garments Reduce Muscle Movement and Activation during Submaximal Running

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*[1]Institute for Health and Sport (iHeS), Victoria University, VIC, AUSTRALIA; [2]Australia Institute of Sport, ACT, AUSTRALIA; [3]Physiology Department, New South Wales Institute of Sport, NSW, AUSTRALIA; [4]First Year College, Victoria University, VIC, AUSTRALIA; [5]School of Behavioral and Health Sciences, Australian Catholic University, VIC, AUSTRALIA; and [6]School of Medical and Health Sciences, Edith Cowan University, WA, AUSTRALIA*



**ABSTRACT**

BROATCH, J. R., N. BROPHY-WILLIAMS, E. J. PHILLIPS, S. J. O'BRYAN, S. L. HALSON, S. BARNES, and D. J. BISHOP. Compression Garments Reduce Muscle Movement and Activation during Submaximal Running. *Med. Sci. Sports Exerc.*, Vol. 52, No. 3, pp. 685–695, 2020. **Purpose:** The purpose of this study was to investigate the effectiveness of sports compression tights in reducing muscle movement and activation during running. **Methods:** A total of 27 recreationally active males were recruited across two separate studies. For study 1, 13 participants (mean ± SD = 84.1 ± 9.4 kg, 22 ± 3 yr) completed two 4-min treadmill running bouts (2 min at 12 and 15 km·h$^{-1}$) under two conditions: a no-compression control ($CON_1$) and compression (COMP). For study 2, 14 participants (77.8 ± 8.4 kg, 27 ± 5 yr) completed four 9-min treadmill running bouts (3 min at 8, 10, and 12 km·h$^{-1}$) under four conditions: a no-compression control ($CON_2$) and three different commercially available compression tights (2XU, Nike, and Under Armor). Using Vicon 3D motion capture technology, lower limb muscle displacement was investigated in both study 1 (thigh and calf) and study 2 (vastus lateralis + medialis [VAS]; lateral + medial gastrocnemius [GAS]). In addition, study 2 investigated the effects of compression on soft tissue vibrations (root-mean-square of resultant acceleration, RMS $A_r$), muscle activation (iEMG), and running economy (oxygen consumption, $\dot{V}O_2$) during treadmill running. **Results:** Wearing compression during treadmill running reduced thigh and calf muscle displacement as compared with no compression (both studies), which was evident across all running speeds. Compression also reduced RMS $A_r$ and iEMG during treadmill running, but it had no effect on running economy (study 2). **Conclusion:** Lower limb compression garments are effective in reducing muscle displacement, soft tissue vibrations, and muscle activation associated with the impact forces experienced during running. **Key Words:** PERFORMANCE, OSCILLATION, DAMPING, CLOTHING

Repetitive ground impact forces that occur at heel strike during running are indirectly transmitted to the soft tissues (fat, muscle, and skin) via the skeleton (1). The resultant movement and vibration of these tissues relative to the underlying bone is thought to serve a protective role (2) by attenuating potentially injurious impact forces (3), which can be up to three times body mass during running (4). However, repeated and/or long-term exposure to vibrations can have detrimental effects on soft tissue, including pain and loss of function (5), reductions in motor unit firing rates and muscle contraction force (6), as well as decreases in nerve conduction velocity and attenuated sensory perception (7). Furthermore, the mass of lower extremity soft tissue is directly related to peak shock experienced during running (8) as well as the development of lower extremity injuries as reported in basketball, soccer, and track and field athletes (9), hypothetically implicating soft tissue movement and vibrations in the development of lower extremity injuries. As such, quantifying the degree of soft tissue vibrations during running may provide a better understanding of their role in injury prevention (3).

A potentially effective method to attenuate soft tissue movement and vibration experienced during dynamic activities (e.g., running and jumping) is the use of sports compression garments (10–12). The external pressure applied by compression garments has been reported to attenuate the movement of thigh musculature during countermovement jumps (10,11), and preliminary evidence suggests a similar response during running (12). Consequently, compression garments are thought to aid

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muscle function and running efficiency, as well as offset the detrimental effects of fatigue on technique and joint sense. For example, it has been suggested that compression-induced reductions in muscle movement may optimize the contraction direction of muscle fibers favoring mechanical efficiency (4), thus reducing energy loss and muscle fatigue (13). In a study by Bringard et al. (13), compression garments lowered the $\dot{V}O_2$ slow component when running, which was attributed to an attenuation in muscle vibrations. In further support of this, compression shorts have been reported to reduce the rectus femoris EMG–torque ratio during isokinetic knee extensions, indicating that knee extensor force production may be maintained with recruitment of fewer rectus femoris motor units (14).

Compression garments may also minimize the detrimental effects of impact forces during running by altering muscle activation. Muscle activity in the lower limb during running responds to the excitation frequency of the impact shock at heel strike (15), in a process called muscle tuning. In this regard, muscle tuning is composed of increased muscle activation to dampen soft tissue vibrations, as demonstrated by an adjustment of muscle activity to vibrations during running (16). Considering compression has been implicated in reducing soft tissue vibrations (10,11,17), it has also been implicated in reducing the reliance of muscle tuning. For example, below-knee compression socks have been reported to reduce cumulative shank muscle activity during submaximal running (speeds between 8 and 14 km·h$^{-1}$) (18), as well as reduce gastrocnemius EMG activity when running at 75% maximal aerobic speed (19).

A potential implication of compression-induced reductions in muscle activation is an improvement in running economy. Increased muscle activity of the lower limbs has been reported as a potential mechanism behind increasing oxygen consumption and is thus seen as detrimental to running economy (20). For example, decreases in the ratio of eccentric–concentric activity of the knee extensors (i.e., increased activity during propulsion/concentric phase) have been associated with higher energetic costs of running and reduced running economy (21,22), thus implicating compression-induced reductions in muscle activity as a means to improve running economy. This response may be most profound in the calf musculature; the gastrocnemius and the soleus are the greatest contributors to forward propulsion during running (23), and the reduced activity of these muscles may imply greater muscle efficiency during this phase of running (19).

Apart from preliminary evidence (12), the effects of compression tights on lower limb soft tissue movement and muscle activation during running have not been quantified. In addition, no study has compared the effects of different garment brands on these variables, or the effect this has on running economy. As such, the purpose of this study was to investigate the effectiveness of three different commercially available lower limb sports compression garments in reducing muscle displacement, soft tissue vibrations, and muscle activation during running. We hypothesized that compression garments would be effective in damping soft tissue movement, which would be inversely correlated to the level of external pressure applied to the limb. In addition, we hypothesized that compression-reduced reductions in soft tissue movement would decrease the reliance on muscle activation and subsequently improve running economy.

## METHODS

### Participants

A total of 27 recreationally active male participants were recruited across two separate studies (Table 1). The first study investigated the effects of commercially available compression tights on thigh and calf muscle movement during treadmill running. This study aimed to investigate whether compression garments reduce lower limb muscle movement, as measured by 3D motion capture technology. The second study expanded on the first study by investigating the effects of three different commercially available compression tights on thigh and calf muscle movement, as well as soft tissue vibrations, muscle activation, and running economy, during treadmill running. Sample sizes (both studies) were calculated from previously reported changes in anterior–posterior thigh muscle displacement (compression vs no compression) during drop jumps (10). Written informed consent was obtained before participation, and all participants were screened for cardiovascular risk factors that may increase the risk of an adverse event occurring during exercise. All procedures were approved by the Australian Institute of Sport (study 1) and Victoria University (study 2) Human Research Ethics Committees.

### Overview: Study 1

A total of 13 amateur Australian-Rules footballers (Table 1) reported to the laboratory on two separate occasions. The first session was a familiarization trial of the treadmill running protocol, in which participants performed a 4-min treadmill (Trackmaster TMX 55; Full Vision Inc., Newton, KS) running bout (2 min at 12 km·h$^{-1}$ and 2 min at 15 km·h$^{-1}$) with the Vicon markers in place (discussed below). Also during this session, a series of girth and skinfold measurements were performed on the dominant lower limb to provide anthropometric characterization of the participants' lower limb, performed according to the international standard for anthropometric measurements (24). With the subjects standing, an Executive steel tape measure (Lufkin Executive; Apex Tool Group, Albury, NSW, Australia) was used to measure the midthigh and calf girth measurements. In addition, skinfold calipers (Harpenden Skinfold Caliper;

TABLE 1. Participant characteristics.

| Variable | Study 1 (*N* = 13) | Study 2 (*N* = 14) |
|---|---|---|
| Age (yr) | 22 ± 3 | 27 ± 5 |
| Height (cm) | 185.0 ± 5.5 | 180.9 ± 7.3 |
| Body mass (kg) | 84.1 ± 9.4 | 77.8 ± 8.4 |
| Exercise (min·wk$^{-1}$) | 395 ± 110 | 294 ± 155 |
| Thigh girth (cm) | 54.0 ± 4.5 | 53.1 ± 3.1 |
| Thigh skinfold (mm) | 11.6 ± 4.2 | 11.5 ± 4.9 |
| Calf girth (cm) | 38.3 ± 1.4 | 38.3 ± 3.2 |
| Calf skinfold (mm) | 7.8 ± 2.6 | 5.8 ± 2.1 |

Values are presented as mean ± SD. Exercise was classified as moderate- to vigorous-intensity aerobic exercise.

Baty International, West Sussex, UK) were used to measure midthigh and medical calf skinfolds.

Approximately 48 h after the familiarization, participants again reported to the laboratory for the main testing session. This session followed a within-subject crossover design, in which participants completed two 4-min treadmill running bouts separated by 30 min of passive rest. Participants performed the treadmill running bouts under two conditions, a no-compression control ($CON_1$; loose-fitting running shorts) and with compression tights (COMP; 2XU Elite Tights, Melbourne, Australia) covering the lower limb from waist to ankle. Garment fabric was composed of 72%/28% (front) and 65%/35% nylon and elastane (back) and were fitted according to manufacture guidelines (i.e., height and weight). Participants performed both running trials wearing the same running shoes. The order in which participants performed these conditions was randomized and counterbalanced for the first 12 participants, with the 13th participant performing the $CON_1$ condition first and the COMP condition second. All participants were asked to be well fed (last meal <2 h) and hydrated, and to refrain from strenuous exercise (<24 h) and caffeine (<12 h), before the main testing session, which was verified by a 24-h training and dietary recall. During each trial, thigh and calf muscle movement was measured (as detailed below).

## Testing Protocols: Study 1

**Muscle displacement.** Gait characteristics during treadmill running were captured using a 10-camera Vicon MX motion capture system (Vicon, Oxford, UK), sampled at 250 Hz using Vicon Nexus 2.5 Software. Before completing the trial, 14-mm reflective markers were attached to the skin overlying the anterior and posterior superior iliac spines of both left and right pelvic segments, left and right femoral condyles of the dominant leg, and medial and lateral malleoli of the dominant leg. These markers (bony markers) served to provide kinematic information of the dominant leg during running as well as provide reference segments by which muscle movement were determined. Two additional markers (soft tissue markers) were placed on the skin overlying the thigh (midline of the thigh, halfway between the head of the patella and the natural fold of the hip) and calf (most posterior point on the line of maximal calf girth) soft tissue compartments, corresponding to the underlying *vastii* (VAS) and *gastrocnemii* (GAS) muscles. Vicon markers placed on top of compression garments have previously been reported to accurately identify soft tissue motion experienced under a compression garment (25). All markers were attached using a double-sided adhesive, and congruence with the underlying soft tissues was improved by using stretch adhesive tape. To minimize intrasubject variability, all Vicon markers were set up by the primary investigator (all participants and both conditions) according to the international standard for anthropometric measurements (24). Muscle displacement (mm) was calculated as the difference between the maximum and the minimum displacement of the soft tissue markers relative to the segment of interest (i.e., femur for the quadriceps marker and shank for the calf marker) and is reported in the medial–lateral, anterior–posterior, and vertical planes. In addition, acceleration ($m \cdot s^{-2}$) was calculated from the displacement data using a 20-ms averaging time window, which was used as a marker of muscle movement during running. For the 4-min treadmill running bouts, displacement and acceleration data were analyzed during the stance phase (i.e., heel strike to toe off) only, with the average of 8 to 10 gait cycles (starting from 90 s into each 2-min stage) used for analysis. Muscle displacement and acceleration were used as markers of muscle movement and vibration during treadmill running.

## Overview: Study 2

A total of 14 recreationally active participants (Table 1) reported to the laboratory on two separate occasions. The first session was a familiarization trial of the treadmill running protocol, in which participants performed a 9-min treadmill (Instrumented Tandem Treadmill; Advanced Medical Equipment Inc., MA) running bout (3 min at 8 $km \cdot h^{-1}$, 3 min at 10 $km \cdot h^{-1}$, and 3 min at 12 $km \cdot h^{-1}$) with the Vicon markers in place (discussed below). Also during this session, a series of girth and skinfold measurements were performed on the dominant lower limb (as described in study 1). Approximately 48 h after the familiarization, participants again reported to the laboratory for the main testing session. This session followed a within-subject crossover design, in which participants completed 4 × 9-min continuous treadmill running trials separated by 30 min of passive rest. Trials were performed under four conditions: 1) a no-compression control ($CON_2$; loose-fitting running shorts); 2) 2XU MCS Compression Tights (2XU, Melbourne, Australia), composed of 72%/28% (front) and 65%/35% nylon and elastene (back); 3) Nike Pro Zonal Compression Tights (Nike, Beaverton, OR), composed of 83%/17% (body/center-front lining) and 84%/16% (mesh) polyester and elastene; or Under Armor (UA) Charged Compression Tights (Under Armor, Baltimore, MD), composed of 78%/22% polyester and elastene. These garments were chosen for their targeted support of lower limb muscles during exercise and covered the participant's lower limb from waist to ankle. Garments were fitted according to manufacture guidelines (i.e., height and weight for 2XU, and waist and hip circumference for Nike and UA). Participants performed all running trials wearing the same running shoes.

The order in which participants performed these conditions was randomized and counterbalanced for the first 12 participants, with the order for the 13th and 14th participants randomly allocated. During each trial, muscle movement, soft tissue vibrations, muscle activation, and running economy were measured (as detailed below). Garment pressure was assessed before the treadmill running protocol for each compression garment condition as described below. All participants were asked to be well fed (last meal <2 h) and hydrated, and refrain from strenuous exercise (<24 h) and caffeine (<12 h), before the main testing session, which was verified by a 24-h training and dietary recall.

### Testing Protocols: Study 2

**Garment pressure.** For each compression condition, pressure measurements were made using a Kikuhime pressure monitor (Kikuhime Pressure Monitor; mediGroup, Melbourne, Australia) at six landmarks on the lower limb. These landmarks were 5 cm proximal to the distal border of the medial malleolus (A), 5 cm proximal to A (B), on the medial aspect of the maximal calf girth (C), on the anterior aspect of the thigh 10 cm below landmark E (D), on the midpoint between the inguinal crease and the superior–posterior border of the patella (E), and 5 cm proximal to landmark E (F) (Fig. 1). These measurements were used as an indication of the pressure exerted by the compression garments on participants' lower limbs.

**Muscle displacement.** For study 2, gait characteristics during treadmill running were captured using a 14-camera Vicon MX motion capture system (Vicon, Oxford, UK), also sampled at 250 Hz using Vicon Nexus 2.5 Software. Bony markers were set up and used in the same manner as described for study 1. Soft tissue markers were placed on top of EMG electrodes (detailed below) at four muscle sites of the participant's dominant leg, including vastus lateralis (VL), vastus medialis (VM), lateral gastrocnemius (LG), and medial gastrocnemius (MG). Average displacement values were obtained for the *vastii* (VL + VM = VAS) and *gastrocnemii* (MG + LG = GAS) due to their similar functional roles during running (23). To minimize intrasubject variability, all bony markers were set up by the primary investigator (all participants and conditions) according to the international standard for anthropometric measurements (24), and all soft tissue markers were placed directly on top of the EMG electrodes (and over the garment for the three compression conditions) at the corresponding muscle. Acquisition of muscle displacement data was performed in the same manner as described for study 1. Displacement data were collected during the stance phase (i.e., heel strike to toe off) of 10 individual strides, commencing at 90 s into the 3-min stages. Data analysis was performed using individual strides as opposed to the average of 10 strides (as performed for study 1). Muscle displacement was used as a marker of muscle movement during treadmill running.

**Soft tissue vibrations.** For calculation of soft tissue vibrations during treadmill running, displacement data for each of the four muscle sites were first converted into acceleration data using a 20-ms averaging time window. To quantify the amount of soft tissue vibrations during running, acceleration signals were analyzed in the time domain during the entire stance phase. Resultant acceleration ($A_r$) was calculated from the three acceleration components (medial–lateral, anterior–posterior, and vertical), following which a root-mean-square of the $A_r$ (i.e., RMS $A_r$) was calculated, as previously described (17). As per the displacement data, the RMS $A_r$ values of individual strides were used for analysis of soft tissue vibrations, and comparisons were made between $CON_2$ and the three compression conditions. In addition, soft tissue vibration data are reported using VAS and GAS averages.


**FIGURE 1—Landmarks A (5 cm proximal to the distal border of the medial malleolus), B (5 cm proximal to A), C (medial aspect of the maximal calf girth), D (anterior aspect of the thigh 10 cm below landmark E), E (midpoint between the inguinal crease and the superior–posterior border of the patella), and F (5 cm proximal to landmark E) where garment pressure measurements were taken.**

**Muscle activation.** A wireless receiver (Telemyo DTS wireless; Noraxon Inc., Scottsdale, AZ) recorded raw surface EMG signals during treadmill running from VL, VM, LG, and MG of the dominant leg, at 1500 Hz (MyoResearch software, Noraxon Inc.). Before placement of electrodes, the skin was prepared by shaving all hair, lightly abrading, and cleaning with alcohol swab. Disposable pregelled Ag-AgCl electrodes (Blue sensor N; Ambu, Ballerup, Denmark) were attached to the skin with an interelectrode distance of 20 mm and aligned parallel to the underlying muscle fibers in accordance with SENIAM guidelines (26).

Raw EMG signals were processed offline using Spike2 software (version 7.13; Cambridge Electronic Design, Cambridge, UK). Signals were high-pass filtered at 20 Hz (fourth-order Butterworth high-pass filter) to remove movement artifact (27) and then root-mean-squared over a 40-ms window (28). For analysis, an EMG burst for each stride (the same 10 strides analyzed for muscle displacement) and muscle was identified from a rising and falling threshold of +13 SD above the minimal EMG value (28), and the integral for each burst (iEMG) was calculated. Average iEMG values were obtained for the VAS and GAS and were used as indicators of *vastii* and *gastrocnemii* activation during treadmill running. All iEMG values were normalized to the initial 60 s of data recorded during $CON_2$ and at a running speed of 8 $km \cdot h^{-1}$ (total number of bursts = 113 ± 5). For the compression garment conditions, the sample size was reduced by $n = 3$ for GAS and by $n = 2$ for VAS due to artifact in the signal. For the remaining samples included in the analysis, no differences in the minimal EMG value between the control and the compression garment conditions were reported for VAS or GAS ($P > 0.05$). Moreover, reliability analysis of the minimal EMG value during running and between the conditions reported typical error of ≤0.7% for both muscle groups.

**Running economy.** During the entire test, participants wore a mask covering the nose and mouth (Hans Rudolph, Kansas City), and breath-by-breath expired gases were an analyzed by a portable metabolic cart (COSMED Indirect Calorimeter, Rome, Italy). The $O_2$ and $CO_2$ gas analyzers (AEI Technologies, Bastrop, TX) were calibrated to known gas concentrations before each test. Expired gas values were averaged over the 1-min period that Vicon data was collected for determination of oxygen consumption ($\dot{V}O_2$, $L \cdot min^{-1}$) as a marker of running economy.

**Statistical analyses.** Muscle displacement/acceleration, soft tissue vibrations, muscle activation, and running economy data were analyzed with a linear mixed model using IBM SPSS Statistics V19 (IBM Corporation, Armonk, NY). A random intercept for subjects was included to account for intraindividual dependencies and interindividual heterogeneity. This also allowed for individual baseline adjustment. Fixed effects for condition, muscle (VAS vs GAS), and interaction (condition–muscle) were analyzed for muscle displacement/acceleration, soft tissue vibrations, and muscle activation for each running speed. For the whole-body measure of oxygen consumption, fixed effects for condition, running speed, and interaction (condition–running speed) were analyzed. All models were estimated using restricted maximum likelihood. Compression data were analyzed with a one-way ANOVA at each landmark. The level of significance was set at $P < 0.05$. Data are presented as mean estimates and 95% confidence intervals, unless otherwise stated.

## RESULTS

### Study 1

**Muscle displacement.** There were no interaction effects for displacement at 12 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.994$), anterior–posterior ($P = 0.297$), or vertical ($P = 0.370$) axes. There were no condition effects for displacement at 12 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.282$), anterior–posterior ($P = 0.265$), or vertical ($P = 0.089$) axes. There was a muscle effect for displacement at 12 $km \cdot h^{-1}$ in the vertical axis ($P = 0.000$), but not in the medial–lateral ($P = 0.537$) or anterior–posterior ($P = 0.117$) axes. Specifically, displacement at 12 $km \cdot h^{-1}$ was significantly higher for the thigh as compared with the calf.

There were no interaction effects for displacement at 15 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.958$), anterior–posterior ($P = 0.402$), or vertical ($P = 0.509$) axes. There were no condition effects for displacement at 15 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.489$), anterior–posterior ($P = 0.484$), or vertical ($P = 0.089$) axes when running at 15 $km \cdot h^{-1}$. There was a muscle effect for displacement at 15 $km \cdot h^{-1}$ in the vertical axis ($P = 0.000$), but not in the medial–lateral ($P = 0.315$) or anterior–posterior ($P = 0.058$) axes. Specifically, displacement at 15 $km \cdot h^{-1}$ was significantly higher for thigh as compared with calf.

There was an interaction effect for acceleration at 12 $km \cdot h^{-1}$ in the anterior–posterior axis ($P = 0.048$), but not the medial–lateral ($P = 0.303$) or vertical ($P = 0.725$) axes. Specifically, compression significantly reduced acceleration at 12 $km \cdot h^{-1}$ in the thigh but had no effect on acceleration at 12 $km \cdot h^{-1}$ in the calf. There was a condition effect for acceleration at 12 $km \cdot h^{-1}$ in the medial–lateral axis ($P = 0.009$), but not the vertical ($P = 0.195$) axis. Specifically, acceleration at 12 $km \cdot h^{-1}$ was significantly lower for COMP as compared with $CON_1$. There were muscle effects for acceleration at 12 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.000$) and vertical ($P = 0.000$) axes. Specifically, acceleration at 12 $km \cdot h^{-1}$ was significantly higher for thigh as compared with calf in the medial–lateral and vertical axes.

There were no interaction effects for acceleration at 15 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.598$), anterior–posterior ($P = 0.251$), or vertical ($P = 0.971$) axes (Table 2). There were no condition effects for acceleration at 15 $km \cdot h^{-1}$ in the medial–lateral ($P = 0.163$), anterior–posterior ($P = 0.157$), or vertical

TABLE 2. Peak muscle displacement (mm) and acceleration ($m \cdot s^{-2}$) of the thigh and calf soft tissues during treadmill running (study 1) in the medial–lateral, anterior–posterior axis, and vertical axes.

| | 12 $km \cdot h^{-1}$ | | 15 $km \cdot h^{-1}$ | |
|---|---|---|---|---|
| Variable | $CON_1$ | COMP | $CON_1$ | COMP |
| Displacement (mm) | | | | |
| Thigh | | | | |
| Medial–lateral | 9.6 ± 3.6 | 8.5 ± 3.4 | 10.8 ± 5.0 | 10.0 ± 3.6 |
| Anterior–posterior | 10.2 ± 3.6 | 10.1 ± 3.7 | 11.1 ± 4.7 | 11.2 ± 3.3 |
| Vertical | 16.0 ± 4.1 | 12.9 ± 5.5 | 13.4 ± 1.8 | 14.2 ± 4.7 |
| Calf | | | | |
| Medial–lateral | 9.7 ± 3.6 | 8.4 ± 3.7 | 9.6 ± 3.8 | 8.7 ± 3.8 |
| Anterior–posterior | 9.7 ± 2.7 | 7.8 ± 1.4 | 10.0 ± 2.4 | 8.4 ± 2.3 |
| Vertical | 8.5 ± 3.6** | 7.5 ± 3.1** | 9.2 ± 3.0** | 8.7 ± 3.3** |
| Acceleration ($m \cdot s^{-2}$) | | | | |
| Thigh | | | | |
| Medial–lateral | 13.4 ± 7.6 | 8.2 ± 4.8* | 13.8 ± 8.2 | 10.4 ± 4.8 |
| Anterior–posterior | 10.3 ± 6.7 | 5.6 ± 3.1*** | 13.4 ± 8.7 | 8.8 ± 4.4 |
| Vertical | 13.8 ± 8.7 | 10.8 ± 7.8 | 16.3 ± 9.1 | 15.3 ± 8.9 |
| Calf | | | | |
| Medial–lateral | 6.4 ± 3.4** | 4.1 ± 2.1*,** | 8.7 ± 5.7** | 7.2 ± 4.0** |
| Anterior–posterior | 7.0 ± 2.6 | 7.2 ± 3.2 | 9.9 ± 4.5 | 9.4 ± 4.9 |
| Vertical | 6.2 ± 4.2** | 4.5 ± 3.1** | 8.3 ± 5.2** | 7.2 ± 3.9** |

Data are presented as mean ± 95% confidence interval of the control ($CON_1$) and compression (COMP) conditions.
*Significant condition effect as compared with $CON_1$.
**Significant muscle effect.
***Significant interaction effect.

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TABLE 3. Pressure measurements for garments used in study 2.

| Garment | Pressure (mm Hg) A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 2XU | 13.2 ± 2.9 | 17.2 ± 6.2 | 21.8 ± 6.0 | 12.0 ± 2.2 | 12.1 ± 2.3 | 10.7 ± 2.9 |
| Nike | 9.1 ± 2.5* | 14.6 ± 4.9 | 21.5 ± 5.1 | 11.3 ± 2.1 | 12.9 ± 2.7 | 12.7 ± 2.1 |
| UA | 7.7 ± 3.1* | 11.4 ± 4.7* | 18.9 ± 6.3 | 13.3 ± 3.1 | 13.2 ± 3.1 | 12.6 ± 2.9 |

Data are presented as mean ± SD. Garment pressure measurements (mm Hg) 5 cm proximal to the distal border of the medial malleolus (A), 5 cm proximal to A (B), on the medial aspect of the maximal calf girth (C), on the anterior aspect of the thigh 10 cm below landmark E (D), midpoint between the inguinal crease and the superior–posterior border of the patella (E), and 5 cm proximal to landmark E (F).
*Significantly lower than 2XU.

($P$ = 0.632) axes. There were muscle effects for acceleration at 15 km·h$^{-1}$ in the medial–lateral ($P$ = 0.024) and vertical ($P$ = 0.001) axes, but not in the anterior–posterior ($P$ = 0.438) axis. Specifically, acceleration at 15 km·h$^{-1}$ was significantly higher for thigh as compared with calf in the medial–lateral and vertical axes.

## Study 2

**Garment pressure measurements.** There were no condition effects for pressure applied to the limb at landmark C ($P$ = 0.392), landmark D ($P$ = 0.165), landmark E ($P$ = 0.540), or landmark F ($P$ = 0.112). However, there was a condition effect for pressure applied to the limb at landmark A ($P$ = 0.000) and landmark B ($P$ = 0.028). Specifically, the pressure applied to limb at landmarks A ($P$ = 0.000) and B ($P$ = 0.008) was significantly higher in 2XU as compared with UA. In addition, the pressure applied to the limb at landmark A was significantly higher ($P$ = 0.001) in 2XU as compared with Nike (Table 3).

**Muscle displacement.** There were interaction effects for muscle displacement at 8 km·h$^{-1}$ in the medial–lateral ($P$ = 0.000) and vertical ($P$ = 0.000) axes, but not the anterior–posterior ($P$ = 0.537) axis. Specifically, Nike ($P$ = 0.000) and UA ($P$ = 0.001) were more effective in reducing medial–lateral displacement in the VAS than the GAS muscles at 8 km·h$^{-1}$ as compared with $CON_2$. In the vertical axis, 2XU ($P$ = 0.026) and Nike ($P$ = 0.000) were more effective in reducing displacement in the VAS than the GAS muscles at 8 km·h$^{-1}$ as compared with $CON_2$. There were condition effects for muscle displacement at 8 km·h$^{-1}$ in the medial–lateral ($P$ = 0.000) and vertical ($P$ = 0.000) axes, but not the anterior–posterior ($P$ = 0.050) axis (Fig. 2A–C). As compared with $CON_2$, medial–lateral displacement at 8 km·h$^{-1}$ was significantly lower for 2XU in the VAS ($P$ = 0.000) and GAS ($P$ = 0.001). In addition, vertical displacement at 8 km·h$^{-1}$ was significantly lower for 2XU in the VAS only ($P$ = 0.000) as compared with $CON_2$. There were muscle effects for muscle displacement at 8 km·h$^{-1}$ in the anterior–posterior ($P$ = 0.000) and vertical ($P$ = 0.000) axes, but not the medial–lateral axis ($P$ = 0.093). Specifically, muscle displacement at 8 km·h$^{-1}$ was significantly higher for VAS and compared with GAS in both anterior–posterior and vertical axes.

There was an interaction effect for muscle displacement at 10 km·h$^{-1}$ in the medial–lateral ($P$ = 0.000) axis, but not the anterior–posterior ($P$ = 0.135) or vertical ($P$ = 0.911) axes.

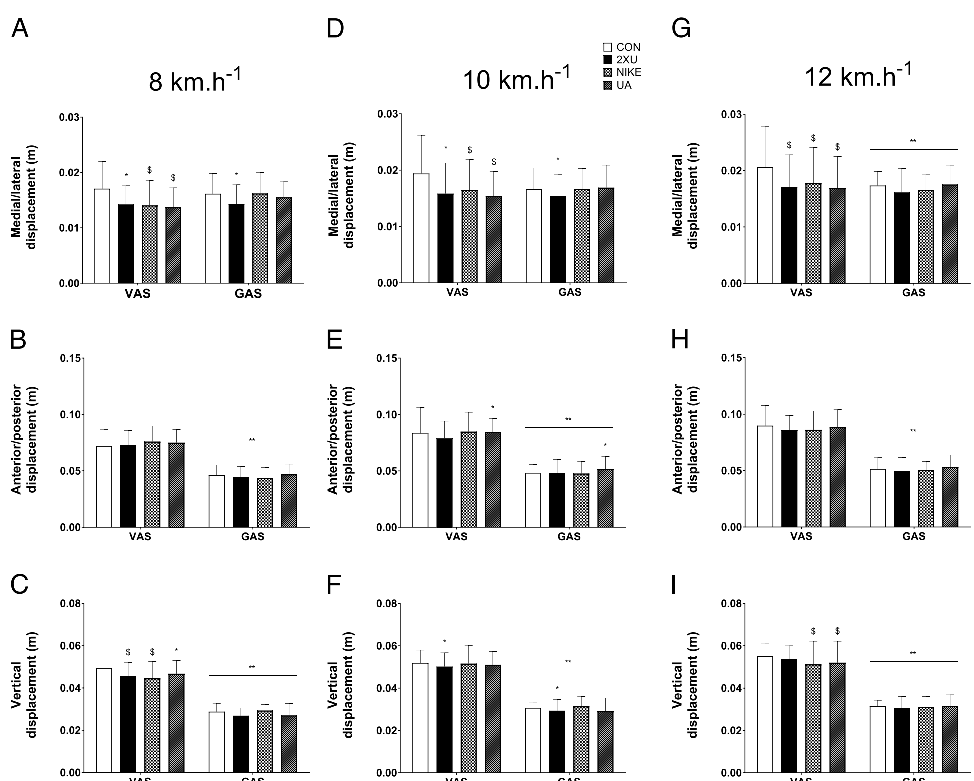


**FIGURE 2—Muscle displacement (m) during treadmill running (study 2) for the *vastii* (VAS) and *gastrocnemii* (GAS) muscle groups at 8 km·h$^{-1}$ (A–C), 10 km·h$^{-1}$ (D–F), and 12 km·h$^{-1}$ (G–I). Data are presented as mean ± SD in the medial–lateral, anterior–posterior axis, and vertical axes. $CON_2$, control. *Significant condition effect as compared with $CON_2$. **Significant muscle effect. $Significant interaction effect.**

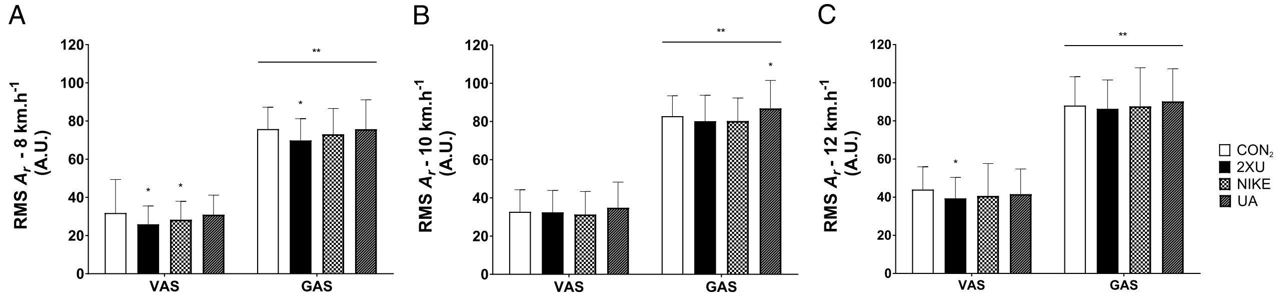


**FIGURE 3—Soft tissue vibrations for *vastii* (VAS) and *gastrocnemii* (GAS) muscle groups during treadmill running (study 2) at 8 km·h$^{-1}$ (A), 10 km·h$^{-1}$ (B), and 12 km·h$^{-1}$ (C). Data are presented as mean ± SD of the RMS $A_r$. CON$_2$, control. *Significant condition effect as compared with CON$_2$. **Significant muscle effect.**

Specifically, Nike ($P$ = 0.011) and UA ($P$ = 0.000) were more effective in reducing medial–lateral displacement in the VAS than the GAS muscles at 10 km·h$^{-1}$ as compared with CON$_2$. There were condition effects for muscle displacement at 10 km·h$^{-1}$ in the medial–lateral ($P$ = 0.000), anterior–posterior ($P$ = 0.012), and vertical ($P$ = 0.008) axes (Fig. 2D–F). As compared with CON$_2$, medial–lateral displacement at 10 km·h$^{-1}$ was significantly lower for 2XU in the VAS ($P$ = 0.000) and GAS ($P$ = 0.039). Anterior–posterior displacement at 10 km·h$^{-1}$ was significantly higher for UA in the VAS ($P$ = 0.039) and GAS ($P$ = 0.039) as compared with CON$_2$. In addition, vertical displacement at 10 km·h$^{-1}$ was significantly lower for 2XU in the VAS ($P$ = 0.036) and GAS ($P$ = 0.036) as compared with CON$_2$. There were muscle effects for muscle displacement at 10 km·h$^{-1}$ in the anterior–posterior ($P$ = 0.000) and vertical ($P$ = 0.000) axes, but not the medial–lateral axis ($P$ = 0.536). Specifically, muscle displacement at 10 km·h$^{-1}$ was significantly higher for VAS and compared with GAS in both anterior–posterior and vertical axes.

There were interaction effects for muscle displacement at 12 km·h$^{-1}$ in the medial–lateral ($P$ = 0.001) and vertical ($P$ = 0.037) axes, but not the anterior–posterior ($P$ = 0.581) axis. Specifically, 2XU ($P$ = 0.018), Nike ($P$ = 0.044), and UA ($P$ = 0.000) were more effective in reducing medial–lateral displacement in the VAS than the GAS muscles at 12 km·h$^{-1}$ as compared with CON$_2$. In the vertical axis, Nike ($P$ = 0.023) and UA ($P$ = 0.038) were more effective in reducing displacement in the VAS than the GAS muscles at 12 km·h$^{-1}$ as compared with CON$_2$. There was no condition effect for muscle displacement at 12 km·h$^{-1}$ in the anterior–posterior axis ($P$ = 0.093) (Fig. 2G–I). There were muscle effects for muscle displacement at 12 km·h$^{-1}$ in the medial–lateral ($P$ = 0.001), anterior–posterior ($P$ = 0.000), and vertical ($P$ = 0.000) axes. Specifically, muscle displacement at 12 km·h$^{-1}$ was significantly higher for VAS and compared with GAS in all axes.

**Soft tissue vibrations.** There were no interaction effects for RMS $A_r$ at 8 km·h$^{-1}$ ($P$ = 0.962), 10 km·h$^{-1}$ ($P$ = 0.268), or 12 km·h$^{-1}$ ($P$ = 0.423) (Fig. 3). There were condition effects for RMS $A_r$ at 8 km·h$^{-1}$ ($P$ = 0.000), 10 km·h$^{-1}$ ($P$ = 0.000), and 12 km·h$^{-1}$ ($P$ = 0.000). Specifically, RMS $A_r$ was significantly lower for 2XU in the VAS ($P$ = 0.000) and GAS ($P$ = 0.000) at 8 km·h$^{-1}$, significantly lower for Nike in the VAS ($P$ = 0.026) at 8 km·h$^{-1}$, significantly higher for UA in the GAS at 10 km·h$^{-1}$ ($P$ = 0.010), and significantly lower for 2XU in the VAS at 12 km·h$^{-1}$ ($P$ = 0.018). There were muscle effects for RMS $A_r$ at 8 km·h$^{-1}$ ($P$ = 0.00), 10 km·h$^{-1}$ ($P$ = 0.000), and 12 km·h$^{-1}$ ($P$ = 0.000). Specifically, RMS $A_r$ was significantly higher for GAS compared with VAS for all running speeds.

**Muscle activation.** There was an interaction effect for iEMG at 10 km·h$^{-1}$ ($P$ = 0.020), but not 8 km·h$^{-1}$ ($P$ = 0.556) or 12 km·h$^{-1}$ ($P$ = 0.056). Specifically, the reduction in GAS activation (as compared with VAS activation) was significantly lower for UA as compared with CON$_2$ (Fig. 4). There were condition effects for iEMG at 8 km·h$^{-1}$ ($P$ = 0.001), 10 km·h$^{-1}$ ($P$ = 0.000), and 12 km·h$^{-1}$ ($P$ = 0.000). Specifically, iEMG was significantly lower for 2XU ($P$ = 0.007, 0.000, and 0.000, respectively), Nike ($P$ = 0.000, 0.001, and 0.000, respectively), and UA ($P$ = 0.003, 0.000, and 0.000, respectively) as compared with CON$_2$. There were muscle effects

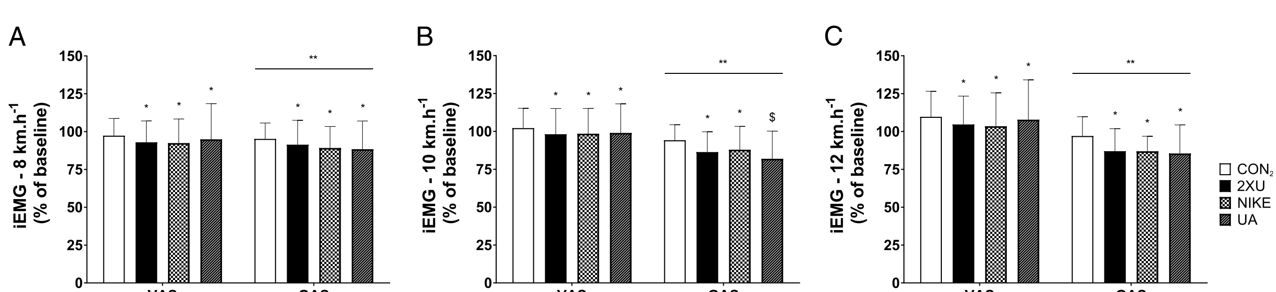


**FIGURE 4—Muscle activation of the *vastii* (VAS) and *gastrocnemii* (GAS) muscle groups during treadmill running (study 2) at 8 km·h$^{-1}$ (A), 10 km·h$^{-1}$ (B), and 12 km·h$^{-1}$ (C). iEMG is presented as a percent of baseline data recorded during the initial 60 s of CON2 and at a running speed of 8 km·h$^{-1}$ (average of 113 ± 5 EMG bursts). CON$_2$, control. *Significant condition effect as compared with CON$_2$. **Significant muscle effect. $ Significant interaction effect.**

for iEMG at 8 km·h$^{-1}$ ($P$ = 0.009), 10 km·h$^{-1}$ ($P$ = 0.000), and 12 km·h$^{-1}$ ($P$ = 0.000). Specifically, iEMG was significantly lower for GAS compared with VAS at all running speeds.

**Running economy.** There were no interaction ($P$ = 1.000) or condition ($P$ = 0.965) effects for oxygen consumption during treadmill running (Fig. 5). There was a main effect of running speed for oxygen consumption ($P$ = 0.000). Specifically, oxygen consumption was significantly higher at 10 km·h$^{-1}$ ($P$ = 0.006) and 12 km·h$^{-1}$ ($P$ = 0.000) as compared with 8 km·h$^{-1}$.

## DISCUSSION

The main finding of this study was that compression tights worn during submaximal treadmill running reduced markers of muscle displacement and soft tissue vibrations (as measured by 3D motion capture) in the lower limb. These reductions were reported during running speeds varying from 8 to 15 km·h$^{-1}$ and were prominent in both the knee extensor and the ankle plantarflexor musculature. Compression-induced reductions in muscle displacement also corresponded to a reduction in muscle activation. However, despite previous hypotheses that compression-induced reductions in muscle movement may improve running economy (13), we observed no effect of compression on running economy.

This study provides the novel observation that lower limb compression tights reduce the displacement of lower limb musculature during submaximal treadmill running. In study 1, compression tights reduced (3.1 mm, ~23%) thigh musculature displacement in the vertical axis when running at 12 km·h$^{-1}$, consistent with the reduction (3.2 mm, ~50%) reported in the thigh with compression shorts during landing from a vertical jump (10). In study 2, similar reductions (up to 4.7 mm, ~10%) of thigh musculature displacement in the vertical axis were seen for the VAS, which were observed for all compression conditions. Although not evident in study 1, displacement in the medial–lateral axis was significantly reduced for the VAS (up to 4.0 mm, ~20%) in study 2, which was evident for all compression conditions and at all running speeds. Potential explanations for the discordant findings between studies 1 and 2 in medial–lateral thigh musculature displacement

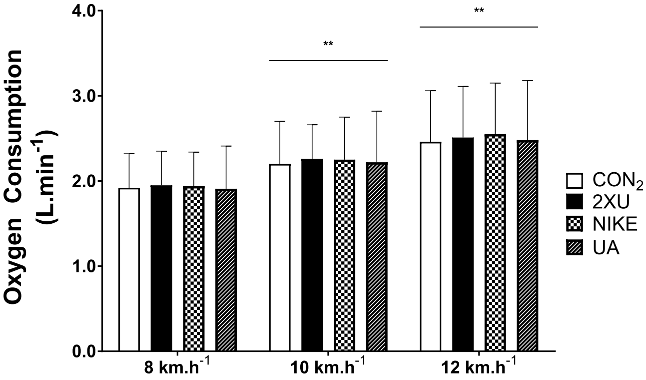


**FIGURE 5—Oxygen consumption (L·min$^{-1}$) during treadmill running (study 2). CON$_2$, control. Data are presented as mean ± SD. **Significant time effect as compared with 8 km·h$^{-1}$.**

include the placement of the markers (i.e., on the midline of the femur vs the VL/VM muscle bellies) and/or running speed (i.e., muscle displacement may be larger when running at slower speeds) used in the studies. As discussed previously (10,11), the physiological and biomechanical relevance of reductions in muscle displacement during dynamic movements (e.g., jumping or running) is currently unknown but commonly implicated in enhancing neurotransmission and sarcomere mechanics at the molecular level (29). In turn, improvement in muscle mechanics may also improve contraction efficiency, reduce energy loss, and reduce muscle fatigue, all of which are advantageous for exercise modalities requiring frequent and repetitive submaximal muscle contractions (e.g., running).

This is the first study to investigate the effects of compression garments on calf musculature displacement during running. Calf musculature plays a crucial role during running, namely, the transfer of force production from the main locomotive muscles (quadriceps and hamstrings) as well as the storage of elastic energy from foot contact and provide the greatest contribution toward forward propulsion (23). Plantarflexion velocity is also associated with improved running economy (30), in turn implicating a reduction in calf muscle movement as potentially advantageous for running performance. In study 1, compression reduced calf displacement in the medial–lateral axis at 12 km·h$^{-1}$ (1.3 mm, ~13%) and in the anterior–posterior axis at both speeds (up to 1.9 mm, ~20%). In study 2, 2XU were the only garments to reduce GAS displacement, which was evident in the medial–lateral (1.8 mm, ~11%) and vertical (up to 1.1 mm, ~4%) axes. By contrast, the other conditions either had no effect (Nike) or increased (UA) GAS displacement during submaximal running, thereby supporting the notion that greater external pressure reduces muscle displacement. However, study 2 also provided the novel observation that compression garments are more effective in reducing VAS displacement during treadmill running as compared with GAS displacement (medial–lateral and vertical axes; Fig. 2), despite the noticeably larger pressure applied to the GAS region. A likely explanation for this is the anatomical differences between VAS and GAS muscle masses. Given the elastic nature of muscle and surrounding soft tissues, the capacity for soft tissue displacement following heel strike is likely larger for bigger soft tissue masses (i.e., VAS as compared with GAS). As such, compression is likely to have a greater damping effect on the VAS muscles, as confirmed by the muscle and interaction effects reported in Figure 2.

A novel component of this study was to investigate the effects of three different lower limb compression garments on soft tissue vibrations during treadmill running. When comparing garments, the 2XU garments were most effective in reducing soft tissue vibrations, which were reported for the VAS (8 and 12 km·h$^{-1}$) and GAS (12 km·h$^{-1}$) muscles. These reductions are consistent with previous observations that compression garments reduce anterior–posterior muscle velocity during landing from maximal jumps (10,11), indicative of compression-induced muscle damping. Reductions in soft tissue vibrations have been implicated in reducing the energetics of running (31) and vibration-induced muscle (32) and/or nerve (33) injuries, which in turn implicate 2XU garments as a novel method to improve running efficiency and reduce the risk of running-related injury. In comparison, the Nike garments reduced vibrations in the VAS (8 $km \cdot h^{-1}$) only, whereas the UA garments increased vibrations in the GAS (10 $km \cdot h^{-1}$). Considering the pressure measurements around the VAS (landmark E) and the GAS (landmark C) muscles were similar between all garments, the observed differences in soft tissue vibrations between garments were independent to the degree of compression applied. However, the degree of compression applied to the limb may vary between passive rest (i.e., current study) and during running (i.e., when the Vicon data was collected). As such, the observed discrepancies in soft tissue vibrations during running could be explained by the garment's capacity to maintain pressure during dynamic movements (i.e., running). Future research investigating the degree of pressure applied from garments in "real time" during exercise is thus warranted. As expected, we also made the observation that vibrations were significantly larger in the GAS, as compared with the VAS, following heel strike. Considering VAS soft tissue mass is considerably higher than GAS soft tissue mass (1), as well as the comparable ground reaction force applied to both muscle groups, Newton's second law of motion dictates the amplitude of soft tissue acceleration to be larger in the GAS. Taken together, and consistent with previous research during downhill running (17), the current study observed that wearing compression garments might constitute a mechanical strategy to increase damping of soft tissue vibrations during running, thereby reducing the body's reliance on muscle tuning.

For all running speeds, compression garments reduced iEMG activity in the VAS and GAS muscles. These findings are consistent with previous observations that compression reduces lower limb muscle activation during maximal voluntary contractions (34) and drop jumps (35), more specifically during running (18,19). Associated with the reduction in soft tissue vibrations, in particularly for the *vastii*, the reduction in muscle activation may indicate reduced muscle tuning. Indeed, the *vastii* musculature are highly active during the heel strike phase of the running gait cycle and are the largest contributor to braking forces (48). However, as the *gastrocnemii* are highly active during the toe-off phase of the running gait cycle and are the greatest contributors to forward propulsion (23), reduced iEMG of these muscles may indicate that the spatiotemporal recruitment of *gastrocnemii* motor units is lower for a given propulsive force during submaximal running with compression garments. It is possible that the potential proprioceptive changes reported with compression garments (36) alter motor unit firing patterns and/or the motor control strategy during submaximal running. These effects of compression on muscle activation are likely to be greater for muscles around the shank rather than the thigh, evidenced by the greater reduction in GAS iEMG and likely due to the higher garment pressure measurement. Another potential mechanism that may explain reduced muscle activation for a given running speed is the effect of compression on patella and calcaneal tendon stiffness. Although this requires further investigation, potential changes in motor unit discharge frequency with compression garments (34) could influence mechanical loading rate through the tendons and neuromuscular efficiency (37,38).

A potential implication of the observed reduction in muscle activation is an improvement in running economy. Increased muscle activity of the lower limbs has been reported as a potential mechanism behind increasing oxygen consumption and is thus seen as detrimental to running economy (20). For example, decreases in the ratio of eccentric–concentric activity of the knee extensors (i.e., increased activity during propulsion/concentric phase) have been associated with higher energetics cost of running and reduced running economy (21,22), thus implicating compression-induced reductions in muscle activity as a means to improve running economy. In addition, the gastrocnemius and the soleus are the greatest contributors to forward propulsion during running (23), and the observed reductions in activity of these muscle may therefore imply a greater neuromuscular efficiency during this phase of running (19). In support of previous suggestions (18), these results implicate compression garments as a novel method to reduce energy cost during running, thereby potentially postponing muscle fatigue and improving running economy.

Contrary to our hypothesis, compression-induced reductions in muscle vibrations and activation had no effect on markers of running economy. Previous studies investigating the effects of different compression garments on the energetics of running are mixed, with compression being reported to reduce (13), have no effect (39,40), and even increase (41) oxygen consumption/energy cost during submaximal treadmill running. Although a recent review by Engel et al. (42) reported that compression garments have a small positive effect to improve running economy (mean Hedges $g = 0.21 \pm 0.38$, range = 0.00–0.88), the current study supports the majority of research to date suggesting a limited effect (39–41). A potential explanation for the discordant effects of compression on running economy (i.e., submaximal oxygen consumption) between the current study and that of Bringard et al. (13) is the duration of submaximal running stages used. Considering that steady-state $\dot{V}O_2$ tends to be achieved after 3 min of exercise at a constant pace (43), the 3-min durations used in the current study may have been too short to observe any measurable effect during exercise (13). In addition, energy demand is typically underestimated with treadmill running as compared with traditional overground running (44), which may limit the applicability of results from the current study. Metabolic measures aside, compression-induced alterations in muscle vibrations may have influenced running kinematics (e.g., ground contact time, step frequency, step length, and swing time) and/or leg stiffness. Considering running kinematics (45) have been implicated in altering mechanical efficiency and/or running economy, these measures may represent a more sensitive means to investigate potential compression-induced changes in running economy.

Consistent with our hypothesis, this study shows that lower limb compression garments are effective in reducing muscle displacement, soft tissue vibrations, and muscle activation during submaximal treadmill running in recreationally active men. Despite the observation that these reductions did not influence running economy, these findings may have implications for reducing the risk of lower extremity injuries and neuromuscular dysfunction associated with repetitive impact forces. These include both orthopedic (e.g., iliotibial band syndrome, Achilles tendinopathy, and muscle strains) and neuromuscular (e.g., reduced motor unit firing rates/nerve conduction velocity, increased pain sensations, and attenuated sensory perception) injuries. The benefits of compression in reducing muscle movement and activation during running observed in the current study can also be translated to many other sports, particularly sports involving high-velocity movements (e.g., sprinting) or collisions (e.g., football).

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