The Effects of Wearing Undersized Lower-Body Compression Garments on Endurance Running Performance

Ben J. Dascombe, Trent K. Hoare, Joshua A. Sear, Peter R. Reaburn, and Aaron T. Scanlan

**Purpose:** To examine whether wearing various size lower-body compression garments improves physiological and performance parameters related to endurance running in well-trained athletes. **Methods:** Eleven well-trained middle-distance runners and triathletes (age: 28.4 ± 10.0 y; height: 177.3 ± 4.7 cm; body mass: 72.6 ± 8.0 kg; VO2max: 59.0 ± 6.7 mL·kg⁻¹·min⁻¹) completed repeat progressive maximal tests (PMT) and time-to-exhaustion (TTE) tests at 90% VO2max wearing either manufacturer-recommended LBCG (rLBCG), undersized LBCG (uLBCG), or loose running shorts (CONT). During all exercise testing, several systemic and peripheral physiological measures were taken. **Results:** The results indicated similar effects of wearing rLBCG and uLBCG compared with the control. Across the PMT, wearing either LBCG resulted in significantly (P < .05) increased oxygen consumption, O2 pulse, and deoxyhemoglobin (HHb) and decreased running economy, oxyhemoglobin, and tissue oxygenation index (TOI) at low-intensity speeds (8–10 km·h⁻¹). At higher speeds (12–18 km·h⁻¹), wearing LBCG increased regional blood flow (nTHI) and HHb values, but significantly lowered heart rate and TOI. During the TTE, wearing either LBCG significantly (P < .05) increased HHb concentration, whereas wearing uLBCG also significantly (P < .05) increased nTHI. No improvement in endurance running performance was observed in either compression condition. **Conclusion:** The results suggest that wearing LBCG facilitated a small number of cardiorespiratory and peripheral physiological benefits that appeared mostly related to improvements in venous flow. However, these improvements appear trivial to athletes, as they did not correspond to any improvement in endurance running performance.

**Keywords:** aerobic, athletic training, exercise physiology, physical performance

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Compression garments (CG) have historically been used to treat circulatory illnesses such as venous thromboembolism and venous leg ulcers in a variety of populations. Lower body compression garments (LBCG) are typically worn from the foot to either the knee or thigh, producing a controlled graduated external pressure of between 20 and 50 mmHg at the ankle, decreasing proximally up the leg. Wearing LBCG has been shown to improve venous valve function and overall circulation within peripheral tissue. More recently, the wearing of hyper-compressive body-molded CG has been suggested to provide circulatory benefits for athletes during training and competition. While CG manufacturers claim that wearing CG improves muscular power, endurance, proprioception, thermoregulation, and recovery, there is limited supportive data. Interestingly, the recommended level of compression has been taken from clinical investigations, with no published data suggesting that it is sufficient to benefit athletic performance.

To date, several studies have demonstrated the benefits, or lack of, when wearing CG during endurance events. Originally, Chatard and colleagues investigated the effects of wearing LBCG on 12 cyclists during repeated 5 min high-intensity cycling bouts. Interestingly, the researchers reported a significant increase in subsequent performance when LBCG were worn during recovery. Chatard et al. hypothesized that wearing LBCG increases blood flow within the peripheral muscle, allowing for improved removal of metabolic wastes and subsequent cycling performance. More recent data from Scanlan et al. supported these findings, with a “likely” improvement in anaerobic threshold in a cycling cohort across an incremental exercise test. This may have been the result of an improved clearance rate of metabolic waste products. Interestingly, this study also reported that wearing LBCG did not improve endurance cycling performance despite changes in muscle oxygenation across a 1 h time trial.

More specific to the present study, Ali and colleagues reported a nonsignificant benefit in 10 km running performance through wearing LBCG in 14 healthy males when compared with loose athletic clothing. The investigators reported that 10 km time decreased nonsignificantly from 45 to 44.7 min between the control and LBCG conditions, respectively. This improvement in performance may have resulted from the improved energy cost of running that has also been reported to occur while wearing LBCG during endurance running. Chatard reported a significant increase (31 s) in the time taken to complete a 5 km circuit in 10 high-performance runners wearing LBCG compared with a control condition. This reduction in running performance was weakly related to a decreased stride length. A more recent study by Sperlich investigated whether the surface area of the compression was related to improvements in submaximal and maximal endurance running performance. The investigators reported no significant benefits in physiological responses or performance when wearing compressive socks (ankle to knee), LBCG (ankle to waist), or whole body CG (ankle to wrists). Taken together, the above results provide conflicting evidence as to whether wearing CG benefit endurance running performance.

At present, the effects of the proposed circulatory benefits that result from wearing CG remain unclear. The majority of research has not reported the level of garment compression or monitored peripheral circulation. Previous studies that have identified changes in endurance performance have offered alternative mechanisms to be responsible for their observations. It can be hypothesized the level
of compression applied by the recommended LBCG size may be insufficient to significantly enhance any physiological or performance responses. Therefore, the present study aims to determine the effectiveness of wearing an undersized LBCG on physiological and performance parameters relating to endurance running.

## Methods

### Participants

Eleven male athletes ([M ± SD] age: 28.4 ± 10.0 y; height: 177.3 ± 4.7 cm; body mass: 72.6 ± 8.0 kg; VO2max: 59.0 ± 6.7 mL·kg⁻¹·min⁻¹) volunteered to participate in the study. All participants were competitive runners who had recorded personal best times of below 12 min for a 3 km run within the last calendar year. All participants were informed of procedures and screened for medical contraindications before providing written consent. All research practices were approved by the CQUniversity Human Ethics Committee.

### Experimental Design

All participants performed repeat progressive maximal tests (PMT) and time to exhaustion (TTE) tests over three weeks in a randomized crossover design. Testing sessions were conducted at the same time of day to avoid circadian variances and were separated by a minimum of 48 h. Participants were instructed to maintain consistent training loads for the duration of the study. A 24 h food diary was recorded before the initial testing session, and participants were instructed to repeat this for all subsequent visits. All participants were instructed to abstain from alcohol, caffeine, and food for 3 h before testing. Throughout all testing, participants were given standardized verbal encouragement. All tests were completed within standardized laboratory conditions at 22 ± 2°C and <70% relative humidity. All exercise tests were performed on a Precor motorized treadmill (model C962; Precor Inc., Bothell, WA, USA).

### Compression Garments

The LBCG used in the present study were unisex full-length tights (Sport Skins Classic, Skins, Campbelltown, NSW) that were comprised of 76% Nylon and Meryl microfiber and 24% Roica Spandex. The LBCG ran from the superior aspect of the medial malleolus of the ankle to the area fractionally superior to the iliac crest. In this study, participants completed the exercise testing in regular LBCG (rLBCG) (sizing guidelines based on stature and body mass) and undersize LBCG (uLBCG) (one size smaller than rLBCG). The pressure gradients (shown in Figure 1) of each LBCG condition were measured using a Kikuhime pressure monitor (TT MediTrade, Sorø, Denmark). The control condition (CONT) consisted of wearing loose running shorts.

### Progressive Maximal Test

Initially, participants performed a PMT to assess the second lactate threshold (LT2) and maximal aerobic capacity (VO2max). Before each PMT, participants performed
a 5 min warm-up of running at 8 km·h⁻¹. The PMT commenced at 8 km·h⁻¹ and increased by 2 km·h⁻¹ in successive 3 min stages until VO₂max was attained. Each stage was separated by 1 min of recovery to allow for capillary blood sampling. Individuals’ LT₂ were calculated using the 4 mmol·L⁻¹ method in the ADAPT software (South Australian Sports Institute, Adelaide, Australia). At test completion, VO₂max was determined using commonly reported criteria and defined as the highest 30 s rolling average observed across the PMT. The PMT was randomly repeated in the rLBCG and uLBCG conditions to examine if LT₂ and VO₂max were significantly influenced by the different compression gradients of the LBCG.

Time to Exhaustion

On three separate occasions, each participant performed a TTE test to determine the effects of wearing LBCG on endurance running performance. The TTE consisted of the participant running at 90% of the velocity at VO₂max (vVO₂max) until volitional exhaustion. Standardized verbal encouragement was provided to all participants across the TTE. The performance time was stopped when the participant indicated volitional exhaustion by reaching for the treadmill handle.

Physiology Measures

Blood Lactate. Blood lactate concentration ([BLa⁻]) was determined from capillary blood samples taken from hyperemic fingertips. Samples were measured using an Accusport Lactate Analyzer (Boehringer Mannheim, Germany). Before testing, the Accusport was calibrated using a lactate control solution (Boehringer Mannheim, Germany). Capillary blood samples were taken after every stage across the PMT, and before and immediately after TTE.
Heart Rate. Heart rate (HR) was continually monitored using a Polar s610i HR monitor (Polar Electro, Oy, Kempele, Finland) at 5 s intervals. Following testing, HR data was downloaded to a personal computer for analysis (Polar Precision Performance Software v4.0, Polar Electro).

Expired Gas Analysis. Breath-by-breath analysis of expired gas was continually performed during all exercise testing using a TrueOne 2400 Metabolic Measurement System (Parvomedics, Utah, USA). Participants wore a mouthpiece with a saliva trap and nose clip during all respiratory gas testing (Parvomedics). Ventilation was measured through a heated screen pneumotach and pressure transducer (model 3813; Hans Rudolf, Inc. Kansas City, MO, USA) with a flow range of 0–800 L·min⁻¹. Before each test, the pneumotach was calibrated with a 3 L syringe (Hans Rudolph, Inc.) at five different flow rates and the analyzers calibrated with gases of known concentrations (reference: 21.0 ± 0.2% O₂; calibration: 12.1 ± 0.2% O₂, 5.05 ± 0.1% CO₂) according to the manufacturer’s instructions. The average data from the last 2 min of each PMT stage and the peak values observed during the TTE in each condition were used for statistical analysis.

Near-Infrared Spectroscopy. Muscle oxygenation of the vastus lateralis muscle (VL) was continually monitored using the NIRO-200 near-infrared spectroscopy (NIRS) system (Hamamatsu Photonics, Hamamatsu City, Japan). Before the NIRS assembly was applied to the VL, the application area was shaved to remove excess hair. The optodes were placed in an optically dense plastic holder to ensure that they maintained a fixed distance of 4 cm apart. The assembly was then covered with specially made clear double-sided tape (Hamamatsu Photonics) to prevent sweat and oils from disturbing the sensitivity of the optodes. The probe was positioned 14 cm superior to the border of the patella on the right leg and placed over the belly of the VL. The optode assembly was then secured to the skin with strapping tape allowing free movement of the leg yet restricting the NIRS assembly from large movement artifacts, and loss of incidental and NIRS-transmitted light. Minimal compressive forces were applied to the thigh during the application of the apparatus. Changes in oxyhemoglobin (HbO₂) and deoxyhemoglobin (HHb) were monitored using four laser diodes that pulsed light at specific wavelengths (775, 810, 850, and 910 nm) into the working muscle. Using the principle of spatial resolved spectroscopy, described in depth elsewhere, tissue oxygenation index (TOI = ΔHbtotal/ΔHbO₂) and tissue hemoglobin index (nTHi = HHb + HbO₂) measurements are also calculated. The NIRS signal was recorded at a sampling frequency of 1 Hz. Data was later exported to a personal computer for analysis.

Statistical Analysis

Means and standard deviations (M ± SD) were calculated for all descriptive, physiological, and performance measures. In order to reduce the likelihood of a Type I error, a Greenhouse-Geisser adjustment was completed to ensure the sphericity of all measures. A 3 (condition) × 6 (time) repeated measure analysis of variance (RMANOVA) was used to determine any significant effects between the treatment conditions or across time in the performance and physiological variables. A one-factor analysis of variance (ANOVA) was used to determine whether there was a significant main effect of any of the three treatment conditions for the performance and physiological variables throughout the TTE. Least significant difference (LSD)
post hoc comparisons were used to identify the individual significant differences within and between groups. All statistical analyses were performed using Statistical Package for Social Sciences software (SPSS Inc., Chicago, Illinois, USA). Statistical significance was set at $P < .05$.

Results

Progressive Maximal Test

The physiological data from the PMT in each condition is presented in Table 1. No main effect of LBCG condition was reported for any cardiorespiratory or peripheral circulatory measures across the PMT.

No significant difference was observed in physiological predictors of endurance running performance, including LT2 or maximum aerobic capacity (Table 2). With respect to the cardiorespiratory measures (Table 1), a weak and inconsistent effect of LBCG was evident over the increasing running velocities. Heart rate was significantly higher in the CONT condition compared with both LBCG conditions at moderate-intensity running speeds (12–16 km·h⁻¹). Similarly, VO₂ was observed to be significantly increased in both the uLBCG and rLBCG conditions at 8 km·h⁻¹ compared with the no LBCG condition. Consequently, O₂ pulse was significantly increased and running economy was decreased in the uLBCG and rLBCG conditions compared with the CONT condition at lower running velocities (8 km·h⁻¹). No further significant effects of LBCG condition were observed in any cardiorespiratory measures at running velocities greater than 12 km·h⁻¹.

A number of significant effects of LBCG condition were observed in the NIRS measures taken from the VL across the PMT. Firstly, HbO₂ was significantly elevated in the uLBCG condition compared with both rLBCG and CONT conditions at 8 km·h⁻¹. Furthermore, a significant effect of LBCG was demonstrated in regards to the LBCG on HHb concentration within the VL. As such, the HHb concentration in the VL was significantly higher wearing the rLBCG compared with the CONT condition across the entire PMT. The uLBCG demonstrated a similar effect to the CONT condition, though it failed to reach significance (see Figure 2). An LSD post hoc comparison showed that HHb concentration in the rLBCG was significantly higher than the CONT condition at 10 and 16 km·h⁻¹, as well as the uLBCG condition at 16 km·h⁻¹.

Wearing uLBCG produced a significantly higher TOI at 8 km·h⁻¹ than both the rLBCG and CONT conditions. Interestingly, the CONT condition TOI at 8 km·h⁻¹ was significantly higher than that in the rLBCG condition. The TOI in the uLBCG continued to be significantly higher than the CONT condition at 10 km·h⁻¹; however, this finding was reversed at both 16 km·h⁻¹ and 18 km·h⁻¹, as the TOI in the uLBCG was significantly lower than that in the CONT condition. Lastly, while the uLBCG demonstrated no significant effect on nTHI across the PMT, wearing the rLBCG significant increased nTHI at both 8 km·h⁻¹ and 18 km·h⁻¹ when compared with the CONT condition.

Time to Exhaustion

The mean performance and physiological measures from the TTE are shown in Tables 1 and 2, respectively. A one-factor ANOVA revealed no main effect of
<table>
<thead>
<tr>
<th>Speed (km·h⁻¹)</th>
<th>Condition</th>
<th>HR (b·min⁻¹)</th>
<th>VO₂ (mL·kg⁻¹·min⁻¹)</th>
<th>O₂ Pulse (mL O₂·kg⁻¹·b⁻¹·min⁻¹)</th>
<th>RE (mL O₂·kg⁻¹·m⁻¹)</th>
<th>[BLa⁻] (mmol·L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>CONT</td>
<td>119 ± 16</td>
<td>23.9 ± 3.4</td>
<td>0.20 ± 0.04</td>
<td>0.18 ± 0.03</td>
<td>1.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>rLBCG</td>
<td>114 ± 15</td>
<td>26.0 ± 2.6*</td>
<td>0.23 ± 0.04*</td>
<td>0.20 ± 0.02*</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>117 ± 10</td>
<td>26.5 ± 2.8*</td>
<td>0.23 ± 0.02*</td>
<td>0.20 ± 0.02*</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>10</td>
<td>CONT</td>
<td>132 ± 13</td>
<td>31.4 ± 3.5</td>
<td>0.24 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>rLBCG</td>
<td>131 ± 13</td>
<td>32.0 ± 2.6</td>
<td>0.25 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>1.9 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>131 ± 15</td>
<td>31.9 ± 2.7</td>
<td>0.25 ± 0.03</td>
<td>0.19 ± 0.02</td>
<td>1.9 ± 0.4</td>
</tr>
<tr>
<td>12</td>
<td>CONT</td>
<td>145 ± 13</td>
<td>37.4 ± 3.5</td>
<td>0.26 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>2.2 ± 0.5</td>
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<tr>
<td></td>
<td>rLBCG</td>
<td>142 ± 13*</td>
<td>37.7 ± 2.6</td>
<td>0.27 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>2.1 ± 0.5</td>
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<tr>
<td></td>
<td>uLBCG</td>
<td>143 ± 13</td>
<td>38.1 ± 3.0</td>
<td>0.27 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>2.2 ± 0.5</td>
</tr>
<tr>
<td>14</td>
<td>CONT</td>
<td>157 ± 14</td>
<td>43.5 ± 3.6</td>
<td>0.28 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>2.8 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>rLBCG</td>
<td>155 ± 13</td>
<td>43.3 ± 3.5</td>
<td>0.28 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>2.8 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>155 ± 13</td>
<td>44.1 ± 2.8</td>
<td>0.29 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>2.7 ± 0.9</td>
</tr>
<tr>
<td>16</td>
<td>CONT</td>
<td>169 ± 13</td>
<td>49.8 ± 3.5</td>
<td>0.30 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>4.0 ± 0.9</td>
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<tr>
<td></td>
<td>rLBCG</td>
<td>167 ± 12</td>
<td>50.7 ± 3.0</td>
<td>0.30 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>4.1 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>166 ± 12*</td>
<td>49.7 ± 2.9</td>
<td>0.30 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>3.8 ± 1.0</td>
</tr>
<tr>
<td>18</td>
<td>CONT</td>
<td>175 ± 20</td>
<td>54.7 ± 4.0</td>
<td>0.32 ± 0.03</td>
<td>0.18 ± 0.01</td>
<td>6.4 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>rLBCG</td>
<td>177 ± 10</td>
<td>55.6 ± 2.9</td>
<td>0.31 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>6.3 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>178 ± 9</td>
<td>55.7 ± 3.5</td>
<td>0.31 ± 0.02</td>
<td>0.19 ± 0.01</td>
<td>6.2 ± 2.1</td>
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<tr>
<td>TTE</td>
<td>CONT</td>
<td>181 ± 14</td>
<td>52.0 ± 9.6</td>
<td>0.30 ± 0.05</td>
<td>0.18 ± 0.03</td>
<td>11.6 ± 2.2</td>
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<tr>
<td></td>
<td>rLBCG</td>
<td>181 ± 12</td>
<td>54.0 ± 6.6</td>
<td>0.32 ± 0.03</td>
<td>0.18 ± 0.02</td>
<td>10.6 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>uLBCG</td>
<td>182 ± 12</td>
<td>53.8 ± 5.7</td>
<td>0.32 ± 0.02</td>
<td>0.18 ± 0.02</td>
<td>10.5 ± 3.1</td>
</tr>
</tbody>
</table>

*Significantly (P < 0.05) different from CONT.
Table 2  Mean (± SD) performance measures from the progressive maximal and time-to-exhaustion tests in the three compression conditions

<table>
<thead>
<tr>
<th>Measure</th>
<th>CONT</th>
<th>rLBCG</th>
<th>uLBCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed at LT2 (km·h⁻¹)</td>
<td>16.0 ± 1.6</td>
<td>15.9 ± 1.8</td>
<td>16.3 ± 1.7</td>
</tr>
<tr>
<td>HR at LT2 (b·min⁻¹)</td>
<td>171 ± 15</td>
<td>168 ± 12</td>
<td>171 ± 12</td>
</tr>
<tr>
<td>VO₂ at LT2 (mL·min⁻¹·kg⁻¹)</td>
<td>51.1 ± 5.7</td>
<td>51.4 ± 6.9</td>
<td>52.3 ± 5.5</td>
</tr>
<tr>
<td>HRmax (b·min⁻¹)</td>
<td>187 ± 13</td>
<td>187 ± 12</td>
<td>187 ± 12</td>
</tr>
<tr>
<td>VO₂max (mL·min⁻¹·kg⁻¹)</td>
<td>59.0 ± 6.7</td>
<td>60.6 ± 6.6</td>
<td>59.9 ± 6.3</td>
</tr>
<tr>
<td>Speed at 90% VO₂max (km·h⁻¹)</td>
<td>17.8 ± 1.3</td>
<td>17.8 ± 1.3</td>
<td>17.8 ± 1.3</td>
</tr>
<tr>
<td>Time to Exhaustion (s)</td>
<td>435.5 ± 269.7</td>
<td>431.1 ± 238.5</td>
<td>454.2 ± 240.1</td>
</tr>
<tr>
<td>Post TTE [BLa⁺] (mmol·L⁻¹)</td>
<td>11.6 ± 2.2</td>
<td>10.6 ± 2.0</td>
<td>10.3 ± 3.1</td>
</tr>
</tbody>
</table>

compression for any peak physiological or performance variable across the TTE. However, LSD post hoc comparison revealed wearing the rLBCG and uLBCG resulted in a significantly higher HHb concentration within the VL when compared with the CONT condition. The uLBCG condition also demonstrated a significant increase in nTHI during the TTE, when compared with both the rLBCG and control conditions. Figure 3 provides an example of an individual response in these measures across the three LBCG conditions.

Discussion

The purpose of the present study was to investigate the effects of wearing uLBCG on physiological or performance parameters related to endurance running. The study demonstrated no significant effects of wearing uLBCG on any of the measured physiological or performance parameters. However, the data suggests that at slower running velocities (approx. 8–10 km·h⁻¹), both LBCG conditions significantly increased muscle blood flow and O₂ utilization and O₂ pulse compared with the CONT condition. During the faster running velocities (>12 km·h⁻¹), both LBCG conditions significantly increased the HHb concentration within the VL, which coincided with a decrease in HR and TOI. This is suggestive of an improvement in venous flow and cardiac return. However, no performance improvements were observed between the LBCG conditions. The HHb concentration was significantly higher in both the LBCG conditions. Overall, the limited physiological changes and absence of performance benefits while wearing the uLBCG compared with the rLBCG and CONT conditions suggest that increasing the compression gradient of LBCG did not benefit endurance running performance.

Progressive Maximal Test

The present data demonstrated no significant effects of wearing LBCG on the selected physiological predictors of performance (ie, LT₂ and VO₂max) across the PMT (see Table 2). This supports similar data on well-trained cyclists.⁹ Previous
Figure 2 — Representation of the variations in the changes in muscle oxygenation parameters across the progressive maximal test. * uLBCG significantly ($P < .05$) different from CONT; $^5$ CONT significantly ($P < .05$) different to rLBCG; $^#$ rLBCG significantly ($P < .05$) different from uLBCG.
data has reported that VO₂max and LT2 are strongly correlated to endurance running performance. The lack of significant improvement in these measures across the LBCG conditions strengthens the absence of improvements in running performance reported in the current study.

However, a number of significant physiological changes were observed during the PMT in the LBCG conditions with few differences observed between the two LBCG conditions. Of interest, the significant decrease in HR observed in both LBCG conditions during moderate-intensity running (12–16 km·h⁻¹) may be the result of an increase in venous return and subsequent stroke volume, via the Frank-Starling mechanism. This finding supports previous research that has reported a nonsignificant trend for HR to be lower during a 10 km run when wearing LBCG. In support of the hypothesis of improved venous function and return, the HHb concentration within the VL was significantly increased in the rLBCG condition across several speeds (approx. 10–16 km·h⁻¹).

Wearing both the uLBCG and rLBCG appeared to significantly increase VO₂ and O₂ pulse and as well as decrease RE at 8 km·h⁻¹ in the present study. These results contrast those presented by Bringard and colleagues who reported that wearing LBCG significantly lowered the VO₂ required and improved the metabolic efficiency during submaximal running (ie, 12 km·h⁻¹). The current finding is suggestive of an increased VO₂ requirement at lower running velocities to overcome the increased resistance to movement that wearing LBCG may cause. Past data has suggested that
wearing LBCG produces significant resistance to shorten stride length, which would increase the required metabolic cost. Future research might attempt to determine if wearing LBCG changes running kinematics and the required energetic requirements.

The present study is one of a small number of investigations to report on the effects of LBCG on measures of peripheral muscle circulation during high-intensity endurance running. While no consistent effect of wearing uLBCG was observed in the peripheral circulatory measures of the present study, a significant increase in nTHI was reported when wearing rLBCG compared with the CONT condition. Interestingly, the uLBCG demonstrated a similar response to the rLBCG over the PMT, though the difference to the CONT condition did not reach significance. These observations strengthen the argument of enhanced circulation when wearing LBCG, without delineating between the rLBCG and uLBCG conditions. The trends observed in the individual responses of HbO2 and HHb concentrations within the VL (Figure 2) strongly support the idea that the improvements in nTHI may be the result of increases in venous flow. Possible mechanisms by which LBCG may allow for improved venous function during exercise can be drawn from clinical research, as wearing LBCG may stimulate venous enhancing mechanisms such as enhanced valvular cusp function or decreased venous cross-sectional area, which result in increased venous blood flow velocities and decreased venous stasis. Therefore, the high HHb concentrations reported in the present study suggests that wearing LBCG facilitated an improved return of venous blood through peripheral muscles.

The present results demonstrated a significant decrease in TOI at 16 (53.7 ± 6.9%) and 18 km·h−1 (50.9 ± 8.4%) in the uLBCG compared with the CONT (55.4 ± 6.3%; 53.0 ± 6.6%) condition, respectively. However, the inferred improved capacity for O2 utilization within the muscle during high-intensity running did not related to an improvement in endurance running performance as determined from the TTE test. Similar changes in TOI have been reported as a result of training and tapering in endurance cyclists across a 20 km time trial. However, despite the lower TOI in the two LBCG conditions during the higher running velocities, this did not correspond to an improvement in endurance running performance as determined by the TTE. These findings also refute the presence of a dose effect of lower-body compression to improved physiological parameters to improve endurance running performance.

**Time to Exhaustion**

The present study demonstrated that wearing either uLBCG or rLBCG did not improve endurance running performance, which supports recently previously published data and suggested that increasingly tight LBCG offer no further performance benefits. Furthermore, no improvements in correlates of endurance performance such as muscle deoxygenation, RE, and VO2max were facilitated by wearing either the uLBCG or rLBCG. These findings supported the data taken from the PMT, which suggested that wearing LBCG caused limited physiological benefits at higher running velocities. Despite this, wearing LBCG significantly influenced a number of peripheral circulatory measures within the VL throughout the duration of the TTE, similar to the PMT. Overall, no performance benefits were reported through increasing the level of graduated compression applied over the lower limbs.

Of particular interest, the current data observed a significant increase in HHb concentration during the TTE in both the LBCG conditions. This result suggests a
greater venous flow through the peripheral working muscles during high-intensity exercise. This may allow improved clearance of metabolic waste products. Past research has supported the hypothesis that wearing LBCG improves clearance of markers of anaerobic metabolism following exercise.17 Concomitantly, nTHI was significantly increased in the uLBCG condition throughout the TTE compared with the CONT condition with the rLBCG demonstrating a similar nonsignificant trend. Taken together, these observations also support the suggestion that wearing LBCG facilitates an improvement in total blood flow through the working muscles although this was largely reflected through an improvement in venous flow. External compression has been suggested to increase the myogenic response resulting from an increase in transmural pressure as well as an increased release of vasodilatory substances initiated from sustained venous shear stress.5,25 Therefore, the current participants demonstrated an improvement in blood flow through peripheral muscles that was somewhat related to the level of compression applied.

However, the magnitude of this improved venous flow through peripheral muscles appears trivial for athletes and coaches, as it did not improve TTE performance. This would suggest that any improvement in the clearance of waste products is insufficient to negate the development of fatigue. However, the data presented may have helped to identify and support the responsible mechanisms that relate to the postexercise recovery improvements associated with wearing LBCG.17 This proposed mechanism supports the findings of Chatard et al.16 which demonstrated that wearing LBCG improved performance in subsequent exercise bouts. Future research might quantify whether this improvement in venous function is continued to be present following exercise and if it is related to improvements in muscle recovery.

**Practical Applications**

The main purpose of the present study was to investigate the effect of wearing uLBCG on physiological or performance parameters in endurance runners when compared with rLBCG or loose running shorts. The current data demonstrate that wearing LBCG facilitated improvements in several physiological responses, but these appear unrelated to high-intensity running performance. As such, uLBCG no not appear to provide any ergogenic benefits through applying an increased level of compression over the working muscle.

It was noted that wearing either LBCG condition resulted in an improved venous flow through the VL during exercise. This observation strengthens the suggestion that wearing CG improves postexercise recovery. Further research should determine whether this improved venous flow is responsible for improving recovery across intermittent training modalities through facilitating faster removal of metabolic waste products to nonactive muscles.

While no performance and few physiological effects were reported in the present study, the results are subject to several limitations. Firstly, the use of a treadmill can potentially change the normal running kinematics and the subsequent energetic requirements of high-intensity endurance running.26 Secondly, the use of a TTE as a measure of performance restricts the use of pacing strategies likely to be related to race performance.27 Thirdly, the interpretation of the NIRS variables is localized to the VL and might not be valid for other lower-body muscles.28 This is further confounded by the graduated compression of the LBCG, which would place the lower limbs under increasing levels of compression. Finally, previous
research has reported that wearing LBCG may slightly reduce heat loss capacity (approx. 1–1.5°C),\textsuperscript{29} which in turn may alter peripheral blood flow responses due to thermoregulatory-related vasodilation.\textsuperscript{30} Past studies have also observed that the NIRS signal is elevated when both local muscle and whole body temperatures are passively elevated to high levels.\textsuperscript{29} However, the proportion of blood flow to the working muscles for O\textsubscript{2} transport, waste removal, and heat transfer remains unknown, with strong evidence demonstrating a reduced heat loss capacity through wearing LBCG requiring further investigation.

**Conclusion**

The present data demonstrated no significant effect of wearing uLBCG or rLBCG on endurance running performance. However, wearing either of the LBCG demonstrated significant changes in measures of peripheral blood flow. The potential implications of these benefits require further investigation. Thus, wearing LBCG offered no performance benefits for endurance running athletes regardless of a considerable increase in compression.

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