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Effects of compression garments on surface EMG and physiological responses during and after distance running

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Abstract

Background: The few previous studies that focused on the effects of compression garments (CG) on distance running performance have simultaneously measured electromyogram, physiological, and perceptual parameters. Therefore, this study investigated the effects of CG on muscle activation and median frequency during and after distance running, as well as blood-lactate concentration and rating of perceived exertion (RPE) during distance running.
Methods: Eight healthy male recreational runners were recruited to randomly perform two 40 min treadmill running trials, one with CG, and the other with control garment made of normal cloth. The RPE and the surface electromyography (EMG) of 5 lower extremity muscles including gluteus maximus (GM), rectus femoris (RF), semitendinosus (ST), tibialis anterior (TA), and gastrocnemius (GAS) were measured during the running trial. The blood-lactate levels before and after the running trial were measured.
Results: Wearing CG led to significant lower muscle activation ($p < 0.05$) in the GM (decreased 7.40%−14.31%), RF (decreased 4.39%−4.76%), and ST (decreased 3.42%−7.20%) muscles; moreover, significant higher median frequency ($p < 0.05$) in the GM (increased 5.57%) and ST (increased 10.58%) muscles. Wearing CG did not alter the RPE values or the blood-lactate levels ($p > 0.05$).
Conclusion: Wearing CG was associated with significantly lower muscle activation and higher median frequency in the running-related key muscles during distance running. This finding suggested that wearing CG may improve muscle function, which might enhance running performance and prevent muscle fatigue.

Keywords: Blood lactate; Compression garment; Fatigue; Muscle activation; Rate of perceived exertion; Running

1. Introduction

Compression garments (CG) have become quite popular and are widely used for distance running by both well-trained athletes and recreational runners. During distance running, runners must maintain a mechanical output while minimizing metabolic energy expenditure, resisting fatigue, and accelerating recovery.[1] It has been documented that runners who wear CG have improved post-exercise muscle function and recovery.[2,3] Previous studies focused on the effects of CG on measured post-running muscle function by examining runners' vertical jumping height[4,5] and also physiological recovery using reported blood lactate.[6,7] The improved scores in CG-wearers have been attributed to decreased oscillation of muscles[8] and enhanced venous hemodynamics.[9] Moreover, studies have shown that wearing CG while running improved runners' subjective ratings, such as rating of perceived exertion (RPE), as measured by the Borg scale.[5]

Despite the above documented benefits, the effects of CG on distance running performance still remain ambiguous. Some studies have indicated that compression stockings or sleeves on the lower legs have little or no beneficial effect on performance during and after distance running.[10,11] It remains unclear whether any change occurs in the local muscles of the lower extremities, as previous studies assessed muscle

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function after distance running using a comprehensive performance measure, specifically vertical jumping.[5,10] Such measurement does not give a detailed understanding of specific or sensitive changes in local muscles of the lower extremity. Thus, the question of whether wearing CG improves muscle function in the lower extremities during submaximal endurance running remains unanswered. To evaluate the efficacy of CG during and after distance running, this study combined muscular activation measures with physiological and perceptual assessments.

Muscular activity while running has been well documented using surface electromypgraphy (EMG).[12–14] In this technique, the average EMG amplitudes for a given period are used to quantify the level of muscle activation over the running time. While running, localized muscular fatigue induced by prolonged and sustained muscular activity may affect the ability to produce or maintain a certain force level. The median frequency (MDF) is a common parameter obtained from the power spectrum analysis of EMG signals, and shifts toward lower frequencies are taken as an index of muscle fatigue during muscle contractions.[10,15,16] Recently, EMG has been used to evaluate the effect of CG during calf-raising exercise,[17] 20 s runs,[18] and isometric and isokinetic knee extension tasks.[19] However, the effect of CG on EMG parameters during distance running has not yet been explored.

Blood-lactate concentration, an indicator of muscle metabolites and recovery, has been widely used to investigate the effects of CG during running and post-running recovery.[6,20,21] Some studies indicated that running with CG reduced blood-lactate[6,22] by inducing greater blood flow. However, when CG were worn by well-trained athletes during high-intensity exercise, only small effects were observed in post-exercise lactate removal following a 400-m sprint,[20] a 40-min run,[10] and an endurance run.[23] Therefore, the effect of wearing CG on blood-lactate concentration during post-exercise recovery is unclear. Moreover, it is unknown whether wearing CG alters the level of lactate during distance running or post-running recovery.

Due to the inconsistent findings of previous studies combining EMG analysis with physiological and perceptual parameters, this study investigated the effects of wearing CG on muscle activation, MDF, blood-lactate concentration, and RPE during and after distance running in recreational runners. We have hypothesized that wearing CG would enhance the efficiency of muscle function but would not reduce perceived fatigue or alter the level of blood-lactate concentration after running.

2. Methods

2.1. Participants

Eight healthy male recreational runners (age 24.9 ± 2.3 years, height 170.0 ± 3.3 cm, weight 60.0 ± 7.1 kg; mean ± SD) participated in the study. The inclusion criteria were age of 20−35 years old with regular running habits (8−12 h/week). The exclusion criteria were history or complaints of any cardiovascular disease, lower limb trauma, and current use of medication. All of the participants were informed of the potential risks and gave informed written consent according to the protocol approved by the Institutional Review Board of the Antai Tian-Sheng Memorial Hospital Ethics Committee (14-037-A2).

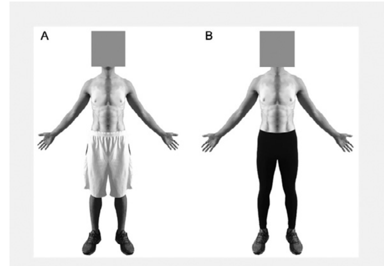

Fig. 1. The normal sports clothing (A) and the compression garment (B).

2.2. Garments

The CG, the full lower body garments from ankle to waist, were individually produced (74% polyamide and 26% Spandex) and fitted for each subject. A pressure sensor (Tekscan, Inc., South Boston, MA, USA) was used to assess the pressure of the CG for each subject and was placed between skin and the CG on the muscle belly of lateral gastrocnemius (GAS), rectus femoris (RF), and gluteus maximus (GM). The CG pressure was 32 ± 2 mmHg at shank, 22 ± 2 mmHg at thigh, and 16 ± 2 mmHg at hip. Normal sports clothing without any pressure was used in this study as the control garment (CON) (Fig. 1).

2.3. Measurement

Each participant's average maximal oxygen consumption (VO_{2max}) was measured with an incremental exercise test to exhaustion using the Bruce protocol with a metabolic system (Cortex METALYZER, Leipzig, Germany).[24] The VO_{2max} was 44.00 ± 3.41 mL/kg/min and the maximal heart rate was 188.98 ± 2.25 beats/min. Seven days after the VO_{2max} measurement, the study participants performed two 40-min treadmill running sessions wearing either the CG or CON. The tests used a randomized counterbalanced design and each session was separated by a 7-day recovery period to avoid any residual effect and fatigue. Each running trial began with a 10-min warm-up, consisting of 5-min of running on the treadmill at a speed corresponding to the individual's aerobic threshold followed by 5-min of lower extremity stretching. The participants then performed a 40-min treadmill run at a predicted oxygen uptake to estimate the velocity at 75%VO_{2max} and at a gradient of 1% to correct for the effect of air resistance.[25]

With an external trigger, the EMG signals and digital video data were synchronously collected for 1 min during the first (initial stage) and last (end stage) minute of the 40-min running trial. The EMG signals of the 5 lower extremity muscles, GM, RF, semitendinosus (ST), tibialis anterior (TA), and GAS, were measured using preamplified surface electrodes (Trigno Wireless EMG systems; Delsys, Boston, MA, USA) at a sampling rate of 2000 Hz. The skin was shaved and scrubbed with alcohol to reduce interelectrode resistance before the electrodes were placed according to the anatomic guide for the electromyographer.[26] The same research assistant was assigned to place the electrodes each time to ensure consistency. Video data were captured with a high-speed camera at a sampling rate of 300 Hz (EX-FH20; Casio Computer Co., Ltd., Shibuya, Japan), and were used to define the stance and swing phases per running cycle for analysis of EMG and MDF.

Three running cycles during the first and last minutes of the 40 min running trials were abstracted. Each running cycle began with one foot strike and ended with the same foot strike, which marked the beginning of the stance phase. The swing phase started when the foot was no longer in contact with the ground. The phases of each cycle were manually defined using commercialized video motion analysis software (Dartfish, Atlanta, GA, USA). EMGworks Version 4 analysis software (Delsys)[27] was used to analyze EMG data for all the trials. After the removal of the baseline offset (bias), the raw EMG data were rectified and bandpass filtered (20−450 Hz) using a dual-pass, fourth-order Butterworth filter (EMGworks, Delsys).[28] The linear envelope was then treated using the root-mean-square method (window length: 0.050 s; window overlap: 0.045 s) to obtain the EMG amplitude. Finally, the average EMG amplitude of each muscle was calculated. The average EMG amplitude of the muscle activation was normalized by dividing by the maximal voluntary isometric contraction (MVIC) of each muscle; this value was collected when the target muscle performed its MVIC for 3 s while manual resistance was applied following standard manual muscle testing position.[29] In all the MVIC positions, subjects were instructed to contract the target muscle “as hard as possible”. EMGworks software was also used to calculate MDF of each muscle using a moving window (window length: 0.064 s; window overlap: 0.032 s). The data within each window were treated first by fast Fourier transform, after which the power spectrum density and the magnitude were determined. Then the MDF was calculated by determining the frequency that divided the power spectrum density into 2 areas containing the same amount of power. The MDF shifting toward lower frequency is an index of muscle fatigue.[16,30] Thus, the MDFs of the power spectrum density were calculated during the stance and swing phases.[31]

Blood-lactate concentration was assessed at 6 measured time points using the Biosen C-Line kit (EKF diagnostic GmbH, Magdeburg, Germany). After cleaning with a sterile alcohol swab, a finger prick capillary puncture was performed and approximately 10 μL of sampled whole blood was aspirated into an EKF Diagnostics glucose and lactate analyzer. Two measurement time points were obtained before the running trial: on arrival at the laboratory (Pre) and after standardized warm-up (AWU). Four measurement time points were obtained after the running trial: immediately after (post-0 min), 5 min after (post-5 min), 15 min after (post-15 min), and 30 min after (post-30 min). Moreover, during the 40 min running trial, their RPE was assessed using Borg 6−20 scale[32] at the beginning (0 min) and every 10 min (10 min, 20 min, 30 min, and 40 min).

2.4. Statistical analysis

To analyze the EMG and MDF variables of each muscle during the stance and swing phases, paired comparisons between 2 garment conditions (CG and CON) and between 2 time points (the initial and end stages of running) were performed using Wilcoxon signed-rank test. For the blood-lactate and RPE variables, the Wilcoxon signed-rank test was also performed to compare the garment conditions at each time point. The significant level was set at $\alpha = 0.05$. SPSS Version 19.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analysis.

3. Results

The muscle activations, as shown in Table 1, were significantly smaller in CG condition than in CON condition for GM and ST at both stages during stance phase and for RF at both stages during swing phase. At the end of the running trial,

Table 1
Average muscle activation for each muscle during the stance and swing phases at the initial and end stages (mean ± SD).

Phase, muscle, and times	CG (%)	CON (%)	Mean difference (%)†	p†
Stance				
GM				
Initial	9.81 ± 5.59	17.22 ± 9.86	−7.40 ± 6.51	0.017#
End	9.10 ± 7.64	23.41 ± 19.57	−14.31 ± 22.62	0.036#
RF				
Initial	12.88 ± 6.98	17.66 ± 7.78	−4.78 ± 8.76	0.208
End	13.83 ± 9.84	25.21 ± 16.04	−11.38 ± 15.81	0.161
ST				
Initial	10.26 ± 6.97	17.50 ± 11.50	−7.20 ± 4.83	0.012#
End	9.46 ± 7.22	12.88 ± 7.12	−3.42 ± 4.60	0.049#
TA				
Initial	41.35 ± 30.07	38.96 ± 24.85	2.39 ± 25.09	0.484
End	27.37 ± 13.51*	30.40 ± 21.78*	−3.03 ± 14.09	0.575
GAS				
Initial	90.77 ± 29.32	81.18 ± 16.92	9.59 ± 26.67	0.889
End	72.97 ± 18.15	80.92 ± 15.23	−7.96 ± 16.71	0.263
Swing				
GM				
Initial	8.55 ± 3.37	11.90 ± 6.93	−3.36 ± 8.43	0.327
End	5.47 ± 2.15	20.61 ± 17.16	−15.14 ± 18.15	0.063
RF				
Initial	7.66 ± 2.95	12.04 ± 2.34	−4.39 ± 3.06	0.018#
End	6.74 ± 4.29	11.51 ± 3.29	−4.76 ± 2.91	0.018#
ST				
Initial	15.62 ± 5.01	19.51 ± 7.75	−3.98 ± 11.09	0.401
End	14.76 ± 4.24	22.80 ± 13.19	−8.04 ± 15.22	0.123
TA				
Initial	51.20 ± 58.50	22.99 ± 7.04	28.21 ± 58.71	0.069
End	30.18 ± 25.01	20.25 ± 7.92	9.93 ± 26.17	0.575
GAS				
Initial	12.06 ± 3.42	10.37 ± 5.30	1.69 ± 2.84	0.123
End	9.77 ± 4.04	8.26 ± 3.60	1.51 ± 3.00	0.575

* Significant difference between time points.
# Significant difference between conditions.
† The difference between CG and CON (CG values minus CON values).
Abbreviations: CG = compressive garment; CON = normal control garment; GAS = gastrocnemius; GM = gluteus maximus; RF = rectus femoris; ST = semitendinosus; TA = tibialis anterior.

the muscle activation of TA significantly decreased during stance phase in 2 conditions (CG: $p = 0.018$, mean difference = −13.98% ± 18.82%; CON: $p = 0.018$, mean difference = −8.56% ± 10.46%).

As shown in Table 2, regarding the MDF, CG exerted significant effects on ST at the end stage during stance phase and on GM at the initial stage during swing phase; the MDF values were both greater in CG condition than that in CON condition. At the end of the running trial, the MDF of TA significantly increased during stance phase in both conditions (CG: $p = 0.018$, mean difference = 13.00% ± 10.93%; CON: $p = 0.012$, mean difference = 13.23% ± 10.15%).

No difference in blood-lactate concentration was observed between CG and CON conditions at any measurement time points (Table 3). The blood-lactate concentration increased after the 40-min running trial in both CG and CON conditions. Furthermore, the RPE in both conditions significantly increased after the 40-min running trial. Additionally, no differences were observed between the CON and CG conditions at the beginning (0 min), and after 10 min, 20 min, 30 min, and 40 min of running (Table 4).

Table 2
Median frequency during the stance and swing phases at the initial and end running stages (mean ± SD).

Phase, muscle, and times	CG	CON	Mean difference†	p†
Stance				
GM				
Initial	44.08 ± 14.62	42.12 ± 15.11	1.97 ± 20.67	0.674
End	51.64 ± 13.69	44.66 ± 24.57	6.98 ± 27.61	0.208
RF				
Initial	61.33 ± 10.37	54.63 ± 9.06	6.69 ± 12.14	0.208
End	64.54 ± 16.64	54.33 ± 14.40	10.21 ± 25.71	0.327
ST				
Initial	78.18 ± 12.75	72.41 ± 14.61	5.77 ± 14.12	0.208
End	83.49 ± 14.97	72.91 ± 19.45	10.58 ± 11.80	0.049#
TA				
Initial	69.63 ± 16.75	69.06 ± 18.80	0.57 ± 21.31	1.000
End	82.63 ± 17.18*	82.29 ± 15.13*	0.31 ± 14.46	0.779
GAS				
Initial	117.43 ± 22.99	124.44 ± 20.09	−7.01 ± 15.84	0.263
End	126.63 ± 19.14	119.87 ± 19.05	6.77 ± 20.47	0.208
Swing				
GM				
Initial	57.15 ± 7.52	51.48 ± 8.91	5.57 ± 6.61	0.036#
End	60.26 ± 7.27	46.72 ± 14.69	13.54 ± 20.61	0.161
RF				
Initial	65.42 ± 11.00	59.60 ± 4.80	5.81 ± 14.29	0.208
End	62.54 ± 17.02	53.85 ± 9.22	8.69 ± 23.97	0.575
ST				
Initial	82.13 ± 10.90	75.97 ± 7.19	6.15 ± 14.55	0.401
End	74.78 ± 9.19	75.33 ± 8.35	−0.55 ± 7.62	1.000
TA				
Initial	86.85 ± 15.80	85.93 ± 14.18	0.92 ± 14.29	0.575
End	92.26 ± 14.73	82.44 ± 14.35	9.82 ± 15.59	0.123
GAS				
Initial	74.70 ± 12.16	64.15 ± 14.20	10.56 ± 13.73	0.123
End	74.01 ± 13.39	65.16 ± 4.91	8.85 ± 17.52	0.208

* Significant difference between time points.
\# Significant difference between conditions.
† Mean difference means the difference between CG and CON (CG values minus CON values).
Abbreviations: CG = compressive garment; CON = normal control garment; GAS = gastrocnemius; GM = gluteus maximus; RF = rectus femoris; ST = semitendinosus; TA = tibialis anterior.

Table 3
Lactic acid accumulation and clearance before and after running (mean ± SD).

	CG (mmol/L)	CON (mmol/L)	p†
Pre	2.30 ± 0.55	1.88 ± 0.54	0.50
AWU	2.33 ± 1.07	2.39 ± 0.69	0.48
Post-0	6.82 ± 3.60*	8.38 ± 3.51*	0.21
Post-5	7.24 ± 2.56	7.69 ± 3.34	0.58
Post-15	4.91 ± 2.76	4.93 ± 1.58	0.58
Post-30	2.87 ± 0.71	2.82 ± 0.78	0.78

* Significant difference between Pre and Post-0 time points within group.
† p value means the difference between CG and CON.
Abbreviations: AWU = after warm-up; CG = compressive garment; CON = normal control garment; Post-0 = after the end of running; Post-5 = 5 min post-running; Post-15 = 15 min post-running; Post-30 = 30 min post-running; Pre = before any warm-up or any exercise.

4. Discussion

This study is the first to simultaneously measure EMG and physiological and psychological parameters to investigate the effects of CG on distance running. It examined muscular activation, MDF, blood-lactate concentration, and RPE. The major results revealed reduced muscle activation and increased MDF of certain running-related key muscles as GM, ST, and RF in CG condition, which indicated CG effects on muscle function during distance running, although wearing CG did not improve the blood-lactate concentration and RPE during distance running.

Previous studies evaluated the effects of CG on muscle function by vertical jumping after endurance running.[5,10] Instead, this study used EMG signals to directly measure muscle activation and MDF, and thus to examine specific changes in the running-related muscles during endurance running. Under CG condition, smaller average muscle activation of GM and ST during stance phase and RF during swing phase at the 1-min initial and the 40-min final running phase was found, suggesting that CG reduces the demand for muscle activation in the GM, ST, and RF during the 40-min run. Although no previous study has directly monitored EMG signals during long-distance running while wearing CG, one study did

Table 4
RPE at the beginning (0 min), 10 min, 20 min, 30 min, and 40 min of running (mean ± SD).

	CG	CON	p†
0 min	6.33 ± 0.52	6.33 ± 0.52	1.00
10 min	8.33 ± 2.58	7.83 ± 1.94	0.78
20 min	10.50 ± 2.59	10.17 ± 2.04	0.50
30 min	12.33 ± 2.73	12.17 ± 1.47	0.86
40 min	13.83 ± 3.43*	13.83 ± 2.14*	0.95

* Significant difference between 0 min and 40 min time points within group.
† p value means the difference between CG and CON.
Abbreviations: CG = compressive garment; CON = normal control garment; RPE = rating of perceived exertion.

observe lower limb muscle activation in the RF and GAS during a short run when CG was worn.[18] Another study found that wearing CG significantly decreased muscle activation during the MVIC performance and isokinetic knee extension.[19] The reduction in muscle activation while wearing CG may be due to the reduction of muscle oscillation,[8] which decreases the recruitment of muscles to maintain joint stability. Most importantly, it has been reported that CG help to delay the onset of fatigue and to maintain muscle function,[17,19] which may be associated with the enhancement of running performance and a reduced risk of running-related injuries. RF plays a major role in hip flexion and GM and ST, which help to extend the hip in the first half of stance phase and the second half of swing phase, are crucial for producing forward propulsion. A previous study showed that the elasticity of CG can enhance running performance by providing additional force in hip flexion and extension.[8] Moreover, ST also decelerates the momentum of the swing limb as the knee extends during the late swing phase, which has important eccentric and concentric functions. The tight fit and elastic nature of CG may assist the hamstrings in limiting knee extension at the terminal swing phase, a period that is particularly risky for hamstring injuries. Thus, the enhancement of support and compressive pressure brought about by wearing CG appear to increase the efficiency of muscle contraction.

It is well-known that a shift in MDF toward lower frequencies is an index of muscle fatigue.[16,30] In our study, the MDFs did not decrease in any muscle, with or without CG, during the 40-min running trials with constant 75%VO_{2max}. This indicated that there was no fatigue during the high-intensity running. This result is consistent with the study of Ali et al.,[10] in which a 40-min treadmill running test was also performed among runners with 75%−85%VO_{2max} and found that compression stockings did not affect muscle fatigue measured by vertical jumping height after running. Although according to the current testing protocol, the subjects were not in fatigue condition, interpretations of the CG effect on muscle fatigue were limited. The current study determined that wearing CG induced higher MDF in ST during stance phase and in GM during swing phase; the participants who wore CG also maintained higher MDF between the 1-min and 40-min running phases. Fu et al.[19] also used nonfatigue protocol and reported that the mean power frequency of the knee extensor under CG condition was significantly higher than the control condition during isokinetic muscle contractions at 60°/s. They suggested that local CG increase muscle efficiency, which might reduce muscle fatigue. The shift in MDF toward higher frequencies may be due to increment in the conduction velocity of muscle fibers.[33] Thus, higher MDF in CG condition of this study indicated greater muscle efficiency in GM and ST, and possibly greater resistance to fatigue during endurance running. This is in agreement with previous studies on other nonfatigue testing protocol. After fatigue-induced exercise, Miyamoto et al.[17] discovered that wearing compression stockings could relieve leg muscle fatigue with less decline in mean power frequency.

The possible mechanisms for the enhancement of muscle function or recovery using CG are still unclear. These positive effects on muscle function may commonly be explained by the effect of CG on improved proprioception, increased venous flow velocity, and decreased muscle oscillation, which have been reported previously.[7,34] Recently, some studies focused on the influence of transversal muscle loads on muscle function by experimentation and simulation. Their findings indicated that transversal loads or pressures induced by external compression had negative effect on muscle force production and gearing,[35,36] especially on explosive muscle performance, due to the change of muscle architecture.[36] On the other hand, this transversally compressed muscle may be a benefit to repetitive and dynamic locomotion, such as running. The transversal loads can lead to more positive work of the contractile component of muscle.[37] Moreover, passive restoring and recoil of muscle elastic elements, which are induced by transversal loads, may decrease metabolic energy expenditure.[38,39] These reactions may be another mechanism to improve muscle efficacy during distance running in the present study. However, it remains unclear how much transversal loads or pressures induced by CG can result in the alternation of muscle structure and negatively or positively influence muscle function. Accordingly, further research is still required to investigate the effect of transversal loads or pressures on muscle function and sport performance.

Our results support the hypotheses that wearing CG does not improve lactate clearance after a 40-min submaximal running session. Excessive workload may result in lactate production in the blood faster than its removal.[25] It is postulated that the blood-lactate clearance mechanism is enhanced by the external mechanical pressure provided with CG. However, our study did not find any significant effect of CG on lactate clearance. Lactate concentration might be a factor in MDF shift.[40] Consistent with previous studies in which the run-to-exhaustion protocol was not adopted,[10,41] we also identified no significant changes in blood-lactate levels after nonexhaustive high-intensity running when the participants wore CG. Different testing protocols, however, may lead to different results. The run-to-exhaustion graded protocol used in Rider's study[42] could improve recovery by lowering blood-lactate levels after exercise. It has been suggested that there is no simple relationship between MDF shift and lactate concentration.[43] The finding of this study indicated that wearing CG led to higher MDFs but no changes in lactate levels, which suggested that MDF could be used to evaluate the effect of CG in future studies.

RPE may not be a sensitive index of the CG effect during distance running, as indicated by the nonsignificant findings in our RPE score. CG had no significant effect on RPE during running, indicating that the perceptual demands of our participants were similar in both conditions. This finding contradicted our hypothesis that the participants would successfully perceive a positive effect of CG. This hypothesis was based on the positive effect of CG on RPE during 400-m sprints[20] and a 15-min running session.[5] However, our results of RPE were consistent with some previous studies, which suggests that wearing CG may not affect psychological fatigue during or after runs of 40 min[10] or 10 km.[4] In other words, the duration and distance of the running protocol may affect the results of perceptual fatigue.

The current study had several limitations. First, regardless of the effort to assess the pressure between the skin and CG on the muscle belly, there is a limitation that the real pressure when the muscle is working during running was not available. Second, unlike other methods such as those that involved dynamometers, which are commonly used to measure maximal muscle contractions, the inherent limitations of using the EMG for measuring maximal muscle contractions should be noted, whereas for a running protocol, the EMG remained a feasible measurement. Third, the CG used in the current study covered hip and knee joints but not the ankle joint, and the findings indicated that the changes of the EMG parameter were mainly identified in GM, ST, and RF but not in TA and GAS. The evidence of the CG effect in the current study may encourage the use of CG around the ankle joint, which may thus influence TA and GAS. Fourth, generalizations on the significant effect of the MDF should be limited to nonfatigue exercise protocols. The benefit of using the MDF as an index to examine the effect of CG during fatigue protocol should be investigated in future studies. Maintaining high activation may help to increase running performance in certain disciplines such as sprinting, whereas lower activation is favorable for conserving energy for other disciplines, such as long-distance running.[44] The effect of CG in maintaining high activation and thus enhancing sprinting performance was not included in the current study scope and merits further analysis. The muscle activation was significantly lower for CG than for GM; however, no differences in MDF were observed between CG and CON for the same muscle group. This inconsistency may be due to the fact that EMG amplitude is a parameter in the time domain that represents the level of activation, whereas the MDF is a parameter that is obtained from the frequency domain that has often been used to quantify fatigue. The possible dependence of the 2 parameters from time and frequency domains warrants further study to clarify the mechanisms that contribute to the 2 EMG parameters.

5. Conclusion

This study was the first to combine the analysis of EMG signals with physiological and psychological parameters to examine the CG effect on EMG variables, blood-lactate levels and RPE after distance running. During a 40-min running session, participants wearing CG had lower muscle activation in GM, ST, and RF muscles and higher MDF in GM and ST muscles, despite no additional benefit to lactate clearance or RPE. CG are recommended for distance running because they improve muscle function in key running-related muscles. These findings suggest that the increment in lower limb compression pressure may effectively increase muscle efficiency and this might be beneficial for preventing muscle fatigue during distance running.

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Authors' contributions

WCH and CL designed research and drafted the manuscript; LWT, FCC, and LCW collected all data; WWY and YJL analyzed the data and performed the statistical analysis. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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