Effects of Gradual-Elastic Compression Stockings on Running Economy, Kinematics, and Performance in Runners

Adrian Varela-Sanz,[1,2] Javier España,[1] Natasha Carr,[3] Daniel A. Boullosa,[4] and Jonathan Esteve-Lanao[1]

[1]*Exercise Physiology Laboratory, European University of Madrid, Madrid, Spain;* [2]*University of Coruña, La Coruña, Spain;* [3]*Arizona State University, Tempe, Arizona; and* [4]*Post Graduate Program for Physics, Catholic University of Brasília, Brasília, Brazil*

Abstract

Varela-Sanz, A, España, J, Carr, N, Boullosa, DA, and Esteve-Lanao, J. Effects of gradual-elastic compression stockings on running economy, kinematics and performance in runners. *J Strength Cond Res* 25(X): 000–000, 2011—We investigated the effect of gradual-elastic compression stockings (GCSs) on running economy (RE), kinematics, and performance in endurance runners. Sixteen endurance trained athletes (age: 34.73 ± 6.27 years; $\dot{V}O_2$max: 62.83 ± 9.03 ml·kg^{-1}·min^{-1}; 38 minutes in 10 km; 1 hour 24 minutes in half marathon) performed in random order 4 bouts of 6 minutes at a recent half-marathon pace on a treadmill to evaluate RE with or without GCSs. Subsequently, 12 athletes were divided into 2 equal groups matched by their $\dot{V}O_2$max, and they performed a time limit test (T_{lim}) on a treadmill at 105% of a recent 10-km pace with or without GCSs for evaluation of physiological responses and running kinematics. There were no significant differences in the RE test in all of the variables analyzed for the conditions, but a moderate reproducibility for some physiological responses was detected in the condition with GCSs. In the T_{lim}, the group that wore GCSs reached a lower % of maximum heart rate (HRmax) compared with the control group (96.00 ± 2.94 vs. 99.83 ± 0.40) ($p = 0.01$). Kinematics did not differ between conditions during the T_{lim} ($p > 0.05$). There were improvement trends for time to fatigue (337 vs. 387 seconds; $d = 0.32$) and a lower $\dot{V}O_2$peak (≈53 vs. 62 ml·kg^{-1}·min^{-1}; $d = 1.19$) that were detected with GCSs during the T_{lim}. These results indicate that GCSs reduce the % of HRmax reached during a test at competition pace. The lower reproducibility of the condition with GCSs perhaps suggests that athletes may possibly need an accommodation period for systematically experiencing the benefits of this garment, but this hypothesis should be further investigated.

Key Words time limit, fatigue, half marathon

Introduction

Over the past several years, the effectiveness of compression garment (CG) in relation to performance improvements in different sports has been a topic of great interest (1,2,5,6,8,9,14,16,24,34,37). Interestingly, most studies have not confirmed the suggested positive influence on physiological responses during exercise (1,2,5,6,16,34,37), and only a few studies have demonstrated a small benefit but with moderately trained subjects (8,9,14,24). Further, most of the studies have reported no significant effect regarding athletic running performance (1,2,5,37), with only some studies showing a small positive effect in noncompetitive conditions (8,24). Moreover, others reported a better recovery with the use of these garments (13,15,25) that could suggest their use for daily training sessions. Thus, taking into consideration all these previous studies, it is still unclear as to how these garments could specifically help well-trained runners at competitive velocities.

Recently, attention has been focused on gradual-elastic compression stockings (GCSs) (1,2,6,9,24). The GCSs are a type of CG that are tightest around the ankle and gradually become less tight as they extend just below the knee (26,32). Various studies have reported a negligible effect of this garment on physiological responses and perception of effort and performance (1,6,9,24), with only one study reporting a higher comfort of the GCSs with a lower grade of compression (12–15 mm Hg) when compared to GCSs with a higher grade of compression (23–32 mm Hg) (2). Furthermore, knee-length GCSs have been demonstrated to be more comfortable with less possibilities of wrinkling when compared to thigh-length GCSs (4). Subsequently, it may be interesting to further explore the influence of knee-length GCSs on performance because their\

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Address correspondence to Dr. Daniel Alexandre Boullosa, d_boullosa@yahoo.es.
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TABLE 1. Physical and performance characteristics of the subjects involved in the RE test by gender (mean ± *SD*).*†

Variables	Men ($n = 13$)	Women ($n = 3$)
Age (y)	35.41 ± 6.61	32.00 ± 4.58
Weight (kg)	72.35 ± 9.34	51.06 ± 5.25
Height (m)	1.76 ± 0.05	1.62 ± 0.08
10-km Best (h:min:s)	0:37:55 ± 0:04:59	0:46:08 ± 0:05:11
Half marathon best (h:min:s)	1:23:59 ± 0:11:09	1:43:06 ± 0:16:13
$\dot{V}O_2max$ (ml·kg^{-1}·min^{-1})	64.48 ± 8.85	55.66 ± 6.80
HRmax (b·min^{-1})	184.69 ± 5.87	190.33 ± 1.15
Skinfolds (mm)	49.95 ± 15.02	57.00 ± 10.53

*RE = running economy.
†Age of the subjects in years; weight of the subjects in kilograms; height of the subjects in meters; 10-km best time of the subjects in hours, minutes, and seconds; half marathon best time of the subjects in hours, minutes, and seconds; maximum oxygen uptake of the subjects in milliliters per kilogram per minute ($\dot{V}O_2max$); maximum heart rate of the subjects in beats per minute (HRmax); sum of the skinfolds of the subjects in millimeters (skinfolds).

characteristics suggest that they are appropriate for daily use in runners.

Running economy (RE) could be defined as the energy required for a given submaximal running speed and is determined by measuring oxygen uptake ($\dot{V}O_2$) in steady-state conditions. The RE has been demonstrated to be a better predictor of performance than maximal oxygen uptake ($\dot{V}O_2max$) in athletes who have a similar $\dot{V}O_2max$ (20,22,36). In addition, a good RE would reduce the % of $\dot{V}O_2max$ required to maintain a given mechanical load, which would affect performance (28). From the wide number of intrinsic and extrinsic factors that have been demonstrated to influence RE (3,11,12,18,31,35,36,38), attire is one extrinsic factor that might modify it (11). In this regard, some authors (8) suggest that wearing compression tights influences RE but only at very low velocities. More recently, another study (24) has reported an enhanced aerobic capacity with GCSs from the observed higher velocities at different physiological thresholds. Although these previous studies consisted of incremental tests with stages of short duration (e.g., ≤3 minutes), it is well known that longer stages are required for proper RE measurements with steady-state conditions (11,12,19). Furthermore, because RE has been suggested to be related to running specific velocities (21), we have not found any study that reported the effect of wearing GCSs in RE at competitive velocities. Consequently, more information is still lacking with regard to the influence of GCSs on RE in steady-state conditions, and more importantly, at competitive velocities.

Interestingly, although the vast majority of studies have proposed an enhanced venous return as the main physiological mechanism promoted by compression stockings (CSs) (1,26,32), it is also suggested that there is a mechanical

TABLE 2. Physical and performance characteristics of the subjects involved in the T_{lim} by gender (mean ± *SD*).*

Variables	Men ($n = 10$)	Women ($n = 2$)
Age (y)	34.80 ± 7.13	34.00 ± 4.24
Weight (kg)	71.64 ± 8.56	49.60 ± 6.50
Height (m)	1.75 ± 0.48	1.60 ± 0.99
10-km Best (h:min:s)	0:37:14 ± 0:04:04	0:43:09 ± 0:00:25
Half marathon best (h:min:s)	1:22:38 ± 0:09:45	1:33:46 ± 0:02:16
$\dot{V}O_2max$ (ml·kg^{-1}·min^{-1})	65.87 ± 8.79	59.50 ± 2.12
HRmax (b·min^{-1})	184.18 ± 6.19	190.00 ± 1.41
Skinfolds (mm)	50.22 ± 15.45	52.00 ± 8.48

*Age of the subjects in years; weight of the subjects in kilograms; height of the subjects in meters; 10-km best time of the subjects in hours, minutes, and seconds; half marathon best time of the subjects in hours, minutes, and seconds; maximum oxygen uptake of the subjects in milliliters per kilogram per minute ($\dot{V}O_2max$); maximum heart rate of the subjects in beats per minute (HRmax); sum of the skinfolds of the subjects in millimeters (skinfolds).

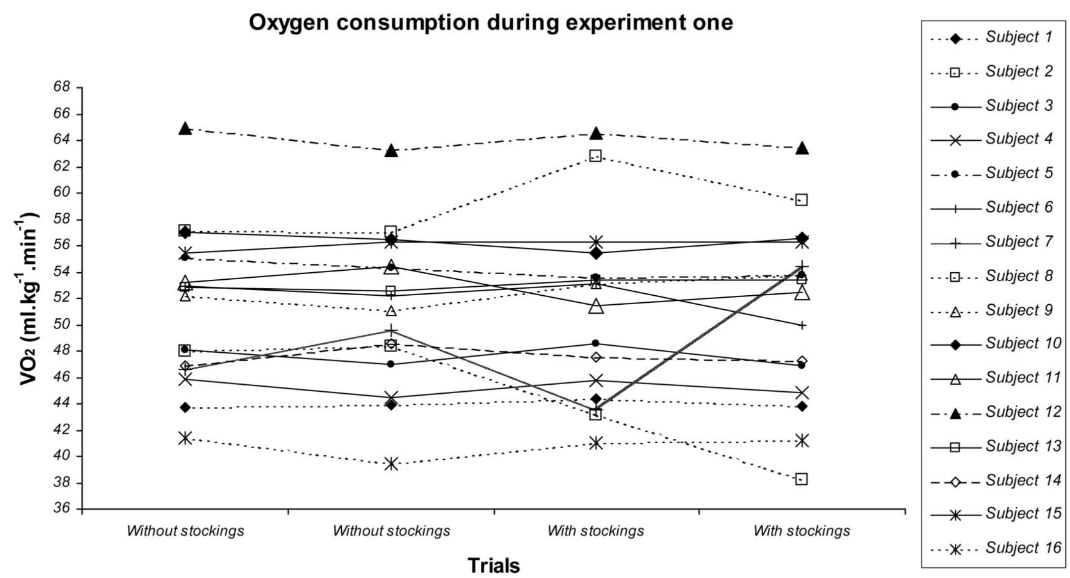

Figure 1. "Spaghetti graph" for oxygen consumption during the running economy (RE) test based on "wearing" or "not wearing" gradual-elastic compression stockings.

explanation because there is a lowered slow component when running with compressive garments (8). Based on previous findings (30), these authors (8) suggested that the reduced muscle oscillations promoted by compression may optimize the contraction direction of muscle fibers favoring, in this manner, mechanical efficiency. Moreover, athletes usually comment on their leg's feelings with a lower perception of strain in the calf when running with CSs. In this regard, given that the improvement on RE via greater mechanical efficiency could be reflected on changes in running kinematics (3,11,12,38), one may speculate the influence of GCSs on running kinematics, but to our knowledge, no study has addressed this question.

Therefore, the objective of this study was to assess the influence of beneath-knee GCSs on RE and performance at competitive velocities in a group of well-trained runners. It was hypothesized that GCSs could promote a better RE at a submaximal intensity that corresponded to the athletes'

Table 3. RE and RPE variables based on "wearing" or "not wearing" gradual-elastic compression stockings during the RE test (mean ± *SD*).*†

Variables	Trials without stockings ($N = 16$)	Trials with stockings ($N = 16$)	Best effect size *d*	ICC: Trials without stockings	ICC: Trials with stockings
HR ($b \cdot min^{-1}$)	171.06 ± 6.47	171.59 ± 7.47	0.19	0.81	0.81
[La^+] ($mmol \cdot L^{-1}$)	6.01 ± 2.28	6.47 ± 2.59	0.37	0.38	0.52
RPE (0–10)	6.72 ± 1.22	6.69 ± 0.96	0.13	0.68	0.31
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	51.25 ± 5.87	51.04 ± 6.71	0.05	0.97	0.75
% $\dot{V}O_2$max	82.31 ± 8.50	82.00 ± 9.55	0.07	0.97	0.74
% HRmax	92.06 ± 3.29	92.25 ± 3.60	1.36	0.80	0.75

*RE = running economy; ICC = intraclass correlation coefficient; HR = heart rate; HRmax = maximum heart rate; RPE = rating of perceived exertion.

†The HR of the subjects in beats per minute; blood lactate concentration of the subjects in millimoles per liter at the end of each 6-minute bout ([La+]); ratios of perceived exertion of the subjects in a scale from 0 to 10 at the end of each 6-minute bout (RPE); oxygen consumption of the subjects in milliliters per kilogram per minute ($\dot{V}O_2$); percentage of maximum oxygen uptake of the subjects (%$\dot{V}O_2$max); percentage of maximum heart rate of the subjects (%HRmax).

Table 4. RE and RPE variables based on "wearing" or "not wearing" gradual-elastic compression stockings during the T_{lim} (mean ± *SD*).*†

Variables	With stockings ($n = 6$)	Without stockings ($n = 6$)	Effect size *d*	*p* Value
Time to fatigue (s)	387.42 ± 129.33	337.16 ± 179.72	0.32	0.57
HRpeak (b·min^{-1})	180.00 ± 4.86	181.50 ± 6.15	0.27	0.63
[La$^+$] (mmol·L^{-1})	11.71 ± 2.76	10.08 ± 1.87	0.69	0.25
RPE (0–10)	9.71 ± 0.48	9.50 ± 0.83	0.31	0.72
$\dot{V}O_2$peak (ml·kg^{-1}·min^{-1})	53.62 ± 4.80	62.09 ± 8.81	1.19	0.09
Speed (km·h^{-1})	16.47 ± 2.14	16.66 ± 2.26	0.09	0.87
% $\dot{V}O_2$max	89.40 ± 6.69	93.83 ± 10.55	0.50	0.44
% HRmax	96.00 ± 2.94	99.83 ± 0.40	1.82	0.01‡
RE (ml·kg^{-1}·km^{-1})	198.80 ± 12.87	215.00 ± 21.84	0.90	0.16

*RE = running economy; HR = heart rate.
†Time limit to fatigue of the subjects at a pace of 105% of a recent 10-km run in seconds (time to fatigue); peak heart rate of the subjects achieved in beats per minute (HRpeak); blood lactate concentration of the subjects in millimoles per liter at the end of the test ([La+]); ratios of perceived exertion of the subjects in a scale from 0 to 10 at the end of the test (RPE); peak oxygen consumption of the subjects achieved in milliliters per kilogram per minute ($\dot{V}O_2$peak); speed of the subjects during the test in kilometers per hour (speed); percentage of maximum oxygen uptake of the subjects (%$\dot{V}O_2$max); percentage of maximum heart rate of the subjects (%HRmax); running economy of the subjects measured in milliliters per kilogram per kilometer (RE).
‡Significant differences at $p < 0.05$.

best half-marathon pace. It was also hypothesized that there would be a positive influence of GCSs on running kinematics, physiological responses, and performance in a time limit test at 105% of their best 10 km.

Methods

Experimental Approach to the Problem

In experiment 1, we used a randomized repeated-measures design to determine the effects of wearing beneath-knee GCSs on RE in well-trained runners. Athletes acted as their own controls. Running economy was evaluated at the pace of their recent best time in a half marathon. Participants performed in random order 4 bouts of 6 minutes with a rest of 2 minutes between them either with or without the use of GCSs.

A randomized non–crossover design was used in a second experiment to determine the effects of wearing beneath-knee GCSs on physiological responses, running kinematics, and performance in a time limit test at 105% of the best time in a recent 10-km run. In this second experiment, we divided the sample into 2 groups ($n = 6$) with athletes matched by their $\dot{V}O_2$max.

Subjects

Before conducting the tests, all participants were informed of the risks such tests would entail. Written consent was obtained from each subject according to the guidelines of the

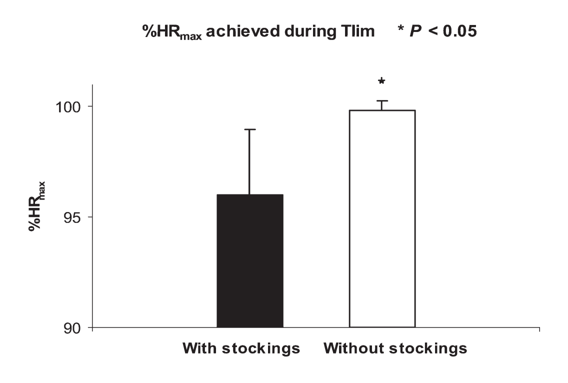

Figure 2. Percent of maximum heart rate reached during the time limit running test based on "wearing" or "not wearing" gradual-elastic compression stockings.

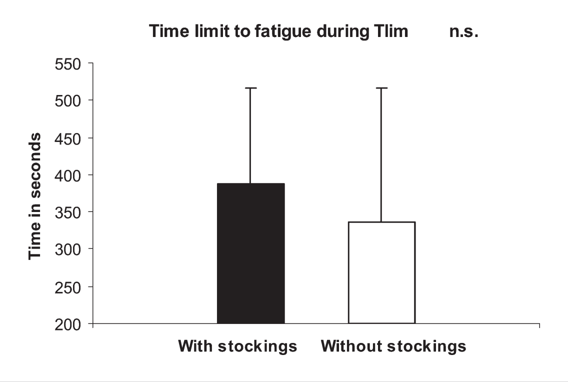

Figure 3. Time limit in seconds based on "wearing" or "not wearing" gradual-elastic compression stockings during the time limit running test.

Table 5. Running technique kinematics variables based on "wearing" or "not wearing" gradual-elastic compression stockings during the T_{lim} (mean ± *SD*).*

Variables	With stockings ($n = 6$)	Without stockings ($n = 6$)	Effect size *d*	*p* Value
First third contact time (s)	0.21 ± 0.02	0.22 ± 0.01	0.63	0.84
First third flight time (s)	0.10 ± 0.01	0.09 ± 0.01	1	0.62
First third height (cm)	1.35 ± 0.40	1.23 ± 0.47	0.11	0.65
First third power ($W \cdot kg^{-1}$)	3.76 ± 0.90	3.50 ± 0.97	0.28	0.63
First third frequency ($steps \cdot s^{-1}$)	3.11 ± 0.15	3.12 ± 0.09	0.08	0.81
First third length (cm)	152.79 ± 9.72	142.31 ± 20.37	0.65	0.28
Third third contact time (s)	0.22 ± 0.02	0.22 ± 0.02	0	0.92
Third third flight time (s)	0.09 ± 0.01	0.09 ± 0.01	0	0.79
Third third height (cm)	1.17 ± 0.32	1.12 ± 0.35	0.15	0.79
Third third power ($W \cdot kg^{-1}$)	3.38 ± 0.71	3.26 ± 0.78	0.16	0.79
Third third frequency ($steps \cdot s^{-1}$)	3.12 ± 0.14	3.14 ± 0.08	0.17	0.79
Third third length (cm)	152.32 ± 10.33	141.58 ± 18.23	0.72	0.23

*Contact time on the first third of the T_{lim} in seconds (first third contact time); flight time on the first third of the T_{lim} in seconds (first third flight time); height on the first third of the T_{lim} in centimeters (first third height); power on the first third of the T_{lim} in Watios per kilogram (first third power); steps frequency on the first third of the T_{lim} in steps per second (first third frequency); steps length on the first third of the T_{lim} in centimeters (first third length); Contact time on the last part of the T_{lim} in seconds (third third contact time); flight time on the last part of the T_{lim} in seconds (third third flight time); height on the last part of the T_{lim} in centimeters (third third height); power on the last part of the T_{lim} in Watios per kilogram (third third power); steps frequency on the last part of the T_{lim} in steps per second (third third frequency); steps length on the last part of the T_{lim} in centimeters (third third length).

institutional ethics committee (European University of Madrid, Spain). The study was approved by the university ethics committee and was in accordance with the Declaration of Helsinki for Human Research. Our sample consisted of 16 experienced runners (13 men: 35 ± 7 years and 3 women: 32 ± 5 years). All of them were well-trained endurance runners (38 minutes in 10 km, 1 hour 24 minutes in half marathon). The athletes reported a mean of 5.6 ± 3.4 years of running practice at the time of the study, with a weekly training load of 5.1 ± 1 sessions (≈52.1 ± 13.9 $km \cdot wk^{-1}$). Tables 1 and 2 show the physical and performance characteristics of the sample involved in both experiments.

Procedures

Each of the subjects participating in the study came to our laboratory (≈600-m altitude) on 2 occasions between the time span of 2 weeks in June (i.e., summer season). Participants were instructed not to perform any exhausting activity, not to drink any beverages with caffeine, and to ingest a high carbohydrate meal the day before the tests. The tests were conducted with a constant temperature and humidity (ca. 24° C and 60%, respectively). All the participants were always tested in the same time of the day. They were asked to hydrate ad libitum before and after the tests only with water. All subjects ran in their usual running shoes and competition attire.

Day 1. Determination of maximum oxygen uptake ($\dot{V}O_2max$) and maximum heart rate: A ramp incremental test was conducted on a treadmill (Technogym Run Race 1400 HC, Gambettola, Italy) at a gradient of 1% to correct for the air resistance effect (18,23,33) for the determination of $\dot{V}O_2max$. After a submaximal individualized warm-up, the test began at a speed of 11 $km \cdot h^{-1}$, with an increase in speed at 0.5 $km \cdot h^{-1}$ every 30 seconds until exhaustion. The athletes were reinforced by the researchers to do their best. During the test, gas exchange was measured continuously through an automated breath-by-breath system, (*V*max 29C, Sensormedics, Yorba Linda, CA, USA), which was calibrated before performing each exercise according to the manufacturer's instructions. The volume calibration was performed at different flow rates with a 3-L calibration syringe allowing an error ≤3%. The calibration of gas analyzers was performed automatically by the system, using the reference values of environmental gases and cylinders (16% O_2, 4% CO_2). The following variables were measured: $\dot{V}O_2$, pulmonary ventilation (VE), ventilatory equivalent for oxygen ($VE \cdot \dot{V}O_2^{-1}$) and carbon dioxide ($VE \cdot VCO_2^{-1}$), and end-tidal pressure of oxygen and carbon dioxide ($PETO_2$ and $PETCO_2$, respectively). The $\dot{V}O_2max$ was assumed as the highest $\dot{V}O_2$ value achieved during a continuous period of 1 minute during the test. Finally, compliance was required with 2 of the following criteria to determine $\dot{V}O_2max$: a plateau in the values of $\dot{V}O_2$ despite an increase in velocity, an RQ ≥ 1.15, or a peak HR >95% of maximum heart rate (HRmax) predicted by age (17). Heart rate was measured continuously ($b \cdot min^{-1}$) during the test using an HR monitor (Polar Electro OY, 90440, Kempele, Finland).

Day 2. Before conducting the tests, participants put on the GCSs (*Medilast Sport*, Lleida, Spain) with degressive pressure (15–22 mm Hg at the ankle; 88% Polyamid; 12% Elasthane)

Table 6. Interaction between running technique kinematics variables during the T_{lim} (mean ± *SD*).

Variables for interaction	*p* Value for factor time	*p* Value for factor condition	*p* Value for interaction
Contact time	0.02*	0.90	0.77
Flight time	0.05*	0.75	0.63
Height	0.06	0.75	0.68
Power	0.05*	0.75	0.64
Frequency	0.61	0.82	0.96
Length	0.54	0.32	0.83

*Significant differences at $p < 0.05$.

from the ankle to the calf area, which was always completed under the supervision of an investigator. The elastic CS's length was below the knee (just below the kneecap). Thereafter, a supervised warm-up was performed, which consisted of active tension stretches followed by 15 minutes at the speed of 60% of their maximum aerobic speed (MAS, minimum speed to reach $\dot{V}O_2max$) along with some calisthenics.

Running Economy Test–Experiment 1

In a randomized order, participants performed 4 consecutive trials of 6 minutes at a recent half-marathon pace (average speed of 14.8 ± 2.2 $km\cdot h^{-1}$) with or without GCSs on the treadmill at a gradient of 1% to correct for the air resistance effect (18,23,33). The HR measurements were carried out using an HR monitor (Polar Electro OY, 90440), and $\dot{V}O_2$ measurements were taken through an automated breath-by-breath system (*V*max 29C, Sensormedics) throughout the test, which was calibrated as previously described. A standardized resting time of 2 minutes between trials was employed.

At the end of each 6 minute-bout, [La$^+$] was determined through a portable lactate analyzer (Lactate Pro Arkray Inc., Amstelveen, Netherlands), which analyzed a small blood sample obtained by pricking the tip of a finger with a lancet. rating of perceived exertion (RPE) was collected at the end of each 6-minute bout, in which the runner assessed his/ her perception of effort through the 10 points Borǵs scale (7).

Time Limit Running Test (T_{lim})–Experiment 2

Twelve of the 16 runners (Table 2) were divided into 2 identical groups matched for their $\dot{V}O_2max$ (64.7 vs. 66.2 $ml\cdot kg^{-1}\cdot min^{-1}$). These groups completed another test but with one group using GCS ($n = 6$) and the other ($n = 6$) using their habitual running socks. This test consisted of running as long as possible on a treadmill at a gradient of 1% and at a speed of 105% of the athlete's recent 10-km time (average speed of 17 ± 2 $km\cdot h^{-1}$) until exhaustion. This velocity was significantly lower ($p = 0.000$) than their MAS (17.9 $km\cdot h^{-1}$) recorded during the competitions period. The athletes were positively reinforced by the researchers to run as long as possible. The following variables were measured: HR (using an HR monitor) (Polar Electro OY, 90440) and $\dot{V}O_2$ through an automated breath-by-breath system (Vmax 29C, Sensormedics), and both variables were measured throughout the test. Also, the equipment was calibrated, as indicated above, before each of the tests. In addition, [La$^+$] and RPE were measured at the end of the test as previously described.

Kinematics Running Technique Analyses

Two laser cells (OptoJump, Microgate, Bolazano Italy) were placed on both sides of the treadmill to record the contact time, flight time, height, power generated, frequency, and stride length of the athletes during the T_{lim}. The speed at which the test would be conducted for each runner was programmed; thus, the software of the system could perform the calculation of the variables mentioned above. The analysis included the first and the last parts of the T_{lim} test and the difference between these time intervals for the evaluation of fatigue throughout the test.

Statistical Analyses

The data were analyzed using SPSS 15.0 for Windows. The results are presented as mean values ± *SD*. The Kolmogorov–Smirnov–Lilliefors variant test was conducted to check the normal distribution of the variables. An analysis of variance (ANOVA) repeated-measures test was conducted to determine differences in RE variables in relation to the use or nonuse of GCSs during the RE tests, whereas the Friedman nonparametric test was performed for analysis of differences in the RPE. Intraclass correlation coefficient (ICC) was used to check the reproducibility of variables between attempts. The unpaired 2-sample *t*-test was performed to check differences between means in all variables during the T_{lim}. The nonparametric *U* Mann–Whitney test was performed to assess differences in RPE during the T_{lim}. A repeated-measures ANOVA with 2 factors (factor time and factor condition) was conducted to evaluate kinematic variables during the T_{lim}. Cohen's *d* was also calculated for assessing the effect size. Thresholds for effects were as follows: 0.20 "small," 0.50 "medium," and 0.80 "large" (10). The statistical significance was set at 0.05 with a confidence level of 95%.

Results

No significant differences were detected for any of the RE and RPE variables analyzed in both conditions during the RE tests ($p > 0.05$) (see Figure 1 and Table 3). Moreover, the reproducibility of the trials for the stocking's condition, shown by the ICC, was modest. The RPE and RE variables analyzed in both conditions during the T_{lim} tests are shown in Table 4. Only significant differences in %HRmax during the test were detected, with this percentage being lower in the group wearing GCSs ($p = 0.01$; $d = 1.82$) (Figure 2).

No significant differences were found between groups during the T_{lim} in any of the other RE variables analyzed, but there was a trend of approximately 13% in time to fatigue performance with GCS ($d = 0.32$; 337 vs. 387 seconds) (Figure 3). Further, $\dot{V}O_2$peak tended to be lower when subjects wore GCSs during the T_{lim} (≈53 vs. 62 ml·kg^{-1}·min^{-1}), but the difference was not statistically significant ($p = 0.09$; $d = 1.19$). Regarding the kinematics variables analyzed, there were no differences between wearing and not wearing GCSs, nor were there differences in interactions between the time and condition factors during the T_{lim} ($p > 0.05$ for all variables). However, a significant effect of time was detected for contact time ($p = 0.02$), flight time, and power variables ($p = 0.05$) for both groups (Tables 5 and 6).

Discussion

The main finding of this study was that wearing GCSs lowered the %HRmax reached during a time limit running test at a competitive velocity, which corresponded to 105% of the best time in a 10-km run. Furthermore, T_{lim} tended to be greater (337 vs. 387 seconds; $p = 0.57$; $d = 0.32$), and $\dot{V}O_2$peak tended to be lower (≈ 53 vs. 62 ml·kg^{-1}·min^{-1}; $p = 0.09$; $d = 1.19$) when using GCSs. No other differences between conditions were found.

Our findings are different from those reported in the literature (1,24,37). The study of Ali et al. (1) reported similar running times (44.7 vs. 45 minutes) and a lower but nonsignificant ($p = 0.12$) mean HR in the stocking condition after 2 pace-controlled 10-km trials in the field. However, we decided to perform a time limit test in the laboratory at a slightly higher intensity (i.e., 105% of the athletes' best time in 10 km) for the achievement of a true maximum effort at a similar competitive intensity. Thus, it may be suggested that the runners of our study experienced a significantly higher relative intensity, which was close but significantly ($p = 0.000$) lower than their MAS. Furthermore, the mean $\dot{V}O_2$peak recorded on this trial was lower and statistically different from the $\dot{V}O_2$max recorded during the incremental test (≈59 vs. 65 ml·kg^{-1}·min^{-1}, respectively, $p = 0.01$). Another difference with this previous study (1) refers to the runner's level because the sample of our study had a higher $\dot{V}O_2$max (≈65 vs. 55 ml·kg^{-1}·min^{-1}) and competitive level. In this regard, a recent study (37), that evaluated a group of well-trained athletes (i.e., runners and triathletes) at submaximal (i.e., 70% $\dot{V}O_2$max) and maximal (i.e., T_{lim} at MAS) tests with different compressive garments (socks, tights, and whole-body compression) did not find any difference among conditions for any variable studied. Consequently, based on current and previous studies (1,37), it may be suggested that our protocol could be more specific with a better correspondence with running performance, which possibly allowed the finding of this lower %HRmax while running with GCSs. Moreover, it may also be suggested that the level of our athletes may be interacting with the intensity selected for the current results, but this hypothesis should be addressed in further studies.

Although the ability of the heart to change stroke volume in response to changes in venous return is called the Frank–Starling mechanism (29), it may be suggested that the lower cardiac stress experienced by runners in the GCS condition could be a consequence of an enhanced circulatory flow. In this regard, some authors (1) employed HR as a measure of venous return, assuming that an improvement in venous return would improve the end-diastolic volume and, subsequently, stroke volume, enabling a lower cardiac response to maintain a similar cardiac output. Because we did not study any of these parameters, further studies should focus on cardiac responses concurrently with running intensity because this could influence stroke volume (27) and therefore the Frank–Starling mechanism. In other words, one may suggest that the effectiveness of the GCSs may be dependent on individualized running velocities.

Regarding running kinematics, there were no differences between conditions for each moment or for interactions between the time and condition factors. This may signify that all kinematic parameters studied showed the same pattern with GCSs as in the control condition. Moreover, there was a significant effect of time for contact time, flight time, and power variables for both groups. This increment of contact times during the last part of the T_{lim} on both conditions suggests that the runners experienced fatigue similarly, confirming their maximum effort. Previously, a mechanical origin was suggested for the higher RE with GCSs because the improvement of RE via greater mechanical efficiency could be expected with changes in running kinematics (3,11,12,38). The absence of effect of GCSs on kinematics in our study does not remove this possibility because the variables studied could not be sensitive enough for measuring this effect. Consequently, further studies are needed for testing this hypothesis with other approaches (e.g., electromyography) that help to study this possible mechanism more precisely.

Contrary to our hypotheses, wearing GCS did not improve RE at a best recent half-marathon pace (≈14.8 km·h^{-1}). The RE is the variable used to measure the relationship between speed and energy cost, in terms of $\dot{V}O_2$. For its determination, several bouts of medium duration (6–10 minutes) are employed because subjects tend to reach a steady-state $\dot{V}O_2$ over 3 minutes (19). Hence, the values are taken from that time until the end of the set time. Previously (8), it was suggested that the energy cost was lower only at a very low intensity (≈12 km·h^{-1}) wearing compressive and elastic tights, but the duration of the stages in an incremental test was of only 3 minutes. Interestingly, the slow component of $\dot{V}O_2$ decreased a 26% (compared to elastic tights) and 36% (compared to conventional shorts) when wearing compression tights during a 15-minute running test at 80% of $\dot{V}O_2$max (≈13.8 km·h^{-1}), which was also a very low velocity. More recently (2), the oxygen uptake at a run of 40 minutes at 80% of $\dot{V}O_2$max did not differ between conditions when studying a group of well-trained athletes, suggesting that RE was not higher with compressive stockings. On the other hand, in a recent study (24), a positive effect of wearing GCSs during an incremental treadmill test up to a voluntary exhaustion was found, using stages of 5 minutes, but with a slope of 0%. This cohort of authors detected an improvement in time under load and total work developed wearing GCSs during the test, but $\dot{V}O_2$max did not differ between conditions. Nevertheless, in our study, $\dot{V}O_2$peak during the T_{lim} tended to be lower for the GCS condition (≈53 vs. 62 ml·kg^{-1}·min^{-1}; $p = 0.09$). Therefore, it seems that the effect of GCSs on physiological responses could be questioned at low–medium velocities and at the MAS, whereas the current study reflects some positive effects in a velocity near but lower to the MAS.

Interestingly, the $\dot{V}O_2$ during bouts with GCSs demonstrated a lower reproducibility (i.e., ICC) when compared with the very high values found in the control condition (0.75 vs. 0.97). This finding may be important, signifying instability on the metabolic rate while wearing GCSs for the first time. In this regard, it may be speculated that this is a consequence of a lower adaptation of the cardiovascular system that requires a longer period of familiarization. Therefore, it may be hypothesized that some sessions are needed for a consistent response of the cardiovascular system, chronologically experiencing the benefits of GCSs. Further studies are needed for the assessment of cardiovascular responses with GCSs in a longitudinal design.

In conclusion, it was demonstrated that GCSs reduce the % of HRmax reached during a time limit test at competition pace near but lower than MAS (i.e., 105% best 10-km run), also showing a tendency to improve endurance time to fatigue and $\dot{V}O_2$peak with these garments. Moreover, neither RE nor kinematics have demonstrated any difference between conditions at a half-marathon pace or at 105% of the best 10-km run, respectively. The lower reproducibility of the condition with GCSs may suggest that athletes may possibly need an accommodation period for systematically experiencing the benefits of this garment, but this hypothesis should be further investigated in a longitudinal study.

Practical Applications

From these results, we suggest that a decrease in cardiac stress at a competitive velocity near but lower to MAS (i.e., 105% best 10-km run) with the use of gradual CSs may be expected. Also, the reported tendencies to a lower $\dot{V}O_2$peak and higher endurance time at this velocity suggest that this garment could be more effective at this exercise intensity and not at lower (e.g., half-marathon pace) or higher intensity (e.g., MAS). This consideration should not be excluded because current success in running competitions depends upon the exhibition of very small improvements.

Moreover, taking into consideration previous studies that reported a higher comfort of the GCSs and the positive influence of compressive garment on recovery, let us suggest the appropriateness of these garments for daily use, especially if we consider the current finding on the lower reproducibility of the physiological responses with GCSs that may signify that athletes could need an accommodation period for systematically experiencing their benefits.

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