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Abstract

The effects of lower leg compression on cardiorespiratory responses and time to reach exhaustion are still contradictory in the literature. Therefore, the purpose of the study was to determine if lower leg graduated compression socks altered peak cardiorespiratory variables and time to exhaustion during incremental maximal exercise in young adults. Thirty-one healthy participants (weight: 72.1 ± 12.1 kg; height: 170.6 ± 10.2 cm; and body mass index: 24.7 ± 2.5 kg/m²) volunteered to perform a maximal Cardiopulmonary Exercise Test ($CPET_{max}$) on a treadmill. Participants visited the laboratory on two separate days to perform the $CPET_{max}$ test under two different conditions in a repeated measure and randomized design in a counterbalanced order: (1) wearing graduated compression socks (GCS), and (2) not wearing graduated compression socks (NGCS). Peak oxygen uptake ($\dot{V}O_{2peak}$), peak carbon dioxide output ($\dot{V}CO_{2peak}$), peak respiratory exchange ratio (RER_{peak}), peak breathing rate (BR_{peak}) and peak minute ventilation ($\dot{V}E_{peak}$) were collected via a metabolic cart system. Peak heart rate (HR_{peak}) was measured using a heart rate monitor. Peak systolic blood pressure (SBP_{peak}) and peak diastolic blood pressure (DBP_{peak}) were measured by auscultation technique. Exercise time to exhaustion (ETE) was determined by the time from beginning to the end of the exercise. None of the peak cardiorespiratory variables measured, nor the exercise time to exhaustion, showed statistically significant differences between NGCS and GCS. In conclusion, the study results support that lower leg graduated compression did not alter cardiorespiratory responses to incremental maximal exercise and time to reach exhaustion in young, healthy adults.

Keywords: graduated compression, maximal exercise, cardiovascular, respiratory, peak oxygen uptake

Introduction

The human body responds to external stressors with physiological changes throughout its systems. Questions remain surrounding the body's specific responses to different external stressors, particularly during exercise. Compression garments acting as an external stressor may induce physiological effects throughout the body during exercise within the cardiorespiratory system. However, whether lower leg graduated compression socks affect cardiorespiratory responses to exercise remains controversial. Currently, evidence does not clearly support the use of graduated compression in improving performance during maximal (Sperlich et al., 2011; Beliard et al., 2014) or submaximal exercise (Book et al., 2016); although some studies have shown evidence of compression improving time to exhaustion (Kemmler et al., 2009; Varela-Sanz et al., 2011) and exhibiting a trend towards beneficial effects for recovery (Rimaud et al. 2010; Armstrong et al., 2015; Chatard et al., 2004; Rivas et al., 2017).

Initially, compression garments were first developed for clinical use in treating symptoms associated with chronic venous diseases, leg edema, diabetes, peripheral artery disease, and deep vein thrombosis (Lim and Davies, 2014; Stanek, 2017; Rivas et al., 2017). More recently, there has been a transition in the compression market where these garments have gained popularity with a specific population of athletes, recreational athletes, and active, healthy individuals (Lim and Davies, 2014; Stanek, 2017). This gain in popularity can be attributed to the advertised benefits of compression socks for athletic purposes of enhancing performance and recovery time by (1) reducing venous pooling (Stanek, 2017; Rivas et al., 2017); (2) increasing venous return (Stanek, 2017; Rivas et al., 2017) to transport waste products removed from the exercising muscles; (3) increasing deep tissue oxygenation (Stanek, 2017; Rivas et al., 2017); (4) enhancing cardiac output (Rivas et al., 2017) and; (5) increasing blood flow to the exercising muscles due to reduced cardiac stress in response to improved venous return (Varela-Sanz et al., 2011).

Lower leg graduated compression socks exert their greatest pressure at the ankle and, subsequently, lower pressures when moving proximally along the calf muscle to the knee (Lim and Davies, 2014). The graduated ankle-to-knee pressure is thought to create a pressure gradient that promotes better circulation, reduce swelling, improve local blood flow (Lim and Davies, 2014), and improve blood flow back to the heart (improved venous return) during exercise (Jorn Bovenschen et al., 2013), all enhancing cardiac output. Additionally, this pressure gradient is thought to improve running economy and alleviate delayed-onset muscle soreness (DOMS) due to greater waste product removal, all with no detrimental effects on performance (Lim and Davies, 2014). Considering the compression mechanisms, hypothetically, graduated compression socks may improve peripheral circulation, which then improves cardiac output during exercise. MacRae et al. (2011) found an observable difference of a 5% increase in cardiac output with compression, indicating increased venous return under this condition. With enhanced cardiac output during exercise, it is speculated that measurable variables such as aerobic capacity, oxygen uptake, breathing rate, heart rate, and ventilation would then be improved. It is generally accepted that the minimum pressure required to influence cardiac output is approximately 17 mmHg (Lim and Davies, 2014). This minimum pressure results in decreased vein diameter, which in turn increases venous velocity and decreases pooling at the feet, as well as enhances blood return to the heart (Lim and Davies, 2014). Without adequate pressure, deep and/or superficial veins do not compress enough when wearing graduated compression socks (Lim and Davies, 2014; Vargo and Sanderson, 2014; Priego et al., 2015), and pressures less than approximately 17 mmHg would not be sufficient to mitigate strain on the cardiovascular system during exercise (MacRae et al., 2011).

Despite the supposed benefits of wearing graduated compression socks, current evidence does not clearly support the use of graduated compression in improving cardiorespiratory responses and performance during an incremental exercise on a treadmill (Jorn Bovenschen et al., 2013; Sperlich et al., 2010; Moehrle et al., 2007; Wahl et al., 2012), high intensity treadmill running (Ali et al., 2010), maximal aerobic speed (Priego et al., 2015) or cycle ergometer (Moehrle et al., 2007; Scanlan et al., 2008; Rimaud et al., 2010). Such claims that graduated compression socks improve athletic performance by altering cardiorespiratory responses to exercise may be more speculative than based on evidence; although, some studies have shown evidence of compression improving performance, as shown by lowering energy expenditure at a given speed (Bringard et al., 2006) or increasing the exercise time to reach exhaustion (Kemmler et al., 2009; Varela-Sanz et al., 2011; Chatard et al., 2004; Sear et al., 2010).

However, contradictory results associated with compression and time to exhaustion are noted throughout the literature. For example, Kemmler et al. (2009) show that compression increased exercise time to exhaustion. They speculated that the enhancement is due to greater oxygen transport capacity, thereby improving exercise performance. It is also speculated that increased compression by graduated compression socks improves muscle's biomechanical support and may increase mechanical efficiency, decreasing metabolic costs at given workloads, ultimately allowing performance enhancement, as shown by an increase in exercise time to exhaustion (Kemmler et al., 2009). Armstrong et al. (2015) showed a significant positive effect of compression with an increased time to exhaustion by 2.6% when using compression socks compared to placebo socks, speculating that decreases in muscle damage during exercise delay the onset of fatigue during testing. Varela-Sanz et al. (2011) found that time to exhaustion also increased with graduated compression socks; this may be due to changes in venous return with compression, decreasing cardiac stress. This mechanism may allow runners to exercise for a longer duration because of improved circulation. However, Rider et al. (2014) showed significant adverse effects on time to exhaustion due to the perception of added weight from the socks or negative perceptions of compression socks themselves. Other studies have shown no significant effects of compression socks on performance (Sperlich et al., 2010; Berry and MacMurray, 1987; Wahl et al., 2011).

The literature's contradictory results indicate that further research is required to determine and provide stronger evidence whether graduated compression socks promote the claimed physiological benefits in a healthy, active population. Applicable conclusions may be difficult to draw as there are studies that reveal physiological results that suggest performance improvement, as well as studies that show no performance improvement with lower leg compression. With a multitude of studies in the current literature supporting both claims, it is important that more conclusions be drawn from newly conducted studies in order to offer additional support for either claim. Even if newly conducted studies may not be considered novel, results from additional subjects and slightly differing protocols would give further insight into the effects of compression. Definite conclusions about the effects of lower leg compression should be interpreted with caution, considering the different experimental designs (i.e., exercise protocol, duration, intensity, variables measured, fitness level) and populations (i.e., professional athletes, recreational athletes, healthy young adults) (Mota et al., 2020).

Furthermore, in a systematic review, Mota et al., 2020, reported that some studies showed that graduated compression socks induced benefits; however, the underlying mechanisms to explain these benefits are unclear. These studies only suggest possible mechanisms or perceived effects of using graduated compression socks lacking physiological measurements and biological markers to support their conclusions. In order to draw applicable conclusions in favor or not of utilizing graduated compression, it is necessary to reveal the physiological mechanisms involved, in addition to determining if such claims of performance improvement can be supported by evidence.

Therefore, the purpose of this study was to determine if lower leg compression applied by graduated compression socks would affect peak cardiorespiratory variables as well as exercise time to exhaustion during a maximal cardiopulmonary exercise test ($CPET_{max}$). It was hypothesized that (1) peak oxygen consumption ($\dot{V}O_2$), peak carbon dioxide output ($\dot{V}CO_2$), peak respiratory exchange ratio (RER_{peak}), peak minute ventilation ($\dot{V}E_{peak}$), peak breathing rate (BR_{peak}), peak heart rate (HR_{peak}), peak systolic blood pressure (SBP_{peak}), and peak diastolic pressure (DBP_{peak}) would be similar between non-graduated compression socks (NGCS) and graduated compression socks (GCS) based on previous studies (Rivas et al. 2017; Sperlich et al. 2010; Wahl et al. 2012; Bringard et al. 2006; Rimaud et al. 2010; Rider et al. 2014), and (2) that exercise time to exhaustion (ETE) would be longer with GCS due to improvements in cardiovascular and respiratory system efficiency. Cardiorespiratory efficiency would improve with increased venous return due to compression socks promoting blood flow back up from the feet and lower legs to the heart. With increased blood flow, the heart would pump out more blood with each beat allowing increased oxygen delivery via the blood to the working muscles with greater energy production by oxidative phosphorylation.

Methodology

Participants

Thirty-one healthy, young adults (16 males and 15 females; age: 20.37 ± 1.54 years; weight: 72.11 ± 12.12 kg; height: 170.60 ± 10.16 cm; and body mass index: 24.65 ± 2.49 kg/m2) volunteered to participate in the current study. Participants in this study were from Franklin Pierce University's student population (Rindge, New Hampshire). The inclusion criteria required participants to be healthy, young males and females, not overweight or obese, non-smokers, and not pregnant. They were excluded from this study if they had severe asthma or any cardiorespiratory complications, any injuries or orthopedic issues, and were taking any medications that interfere with cardiorespiratory responses. Individuals were instructed to refrain from consuming alcohol, drugs, and caffeine for 12 to 24 hours prior to their scheduled testing time and avoid heavy meals approximately 3 hours prior to testing. Additionally, participants were asked to refrain from engaging in intense physical activity 24 hours before testing.

Participants provided consent after reading an information letter and receiving a detailed overview of the experimental procedures and potential risks by signing a written informed consent document. They had the opportunity to ask questions and raise concerns regarding the protocol and made aware of their right to withdraw from the study at any time without prejudice. The study was reviewed and approved by the Franklin Pierce University Institutional Research Board (IRB), and it was conducted according to the Declaration of Helsinki ethical principles. Participants were given a standardized health status form and a physical activity readiness questionnaire (PAR-Q) to be filled out prior to pre-test procedures. At least two National Institute of Health/New Hampshire-Idea Network of Biomedical Research Excellence (NIH/NH-INBRE) certified research assistants were present for the entire duration of any test.

Experimental Design

The experiment was randomized, counterbalanced, and consisted of repeated measures with two conditions to determine if lower leg passive external compression would alter peak variables and time to exhaustion during the $CPET_{max}$ on an automated treadmill. Participants visited the laboratory on two separate occasions: one occasion for testing with non-graduated compression socks (NGCS) and the other occasion for testing with the use of graduated compression socks (GCS). A coin flip randomly assigned the testing conditions for each initial

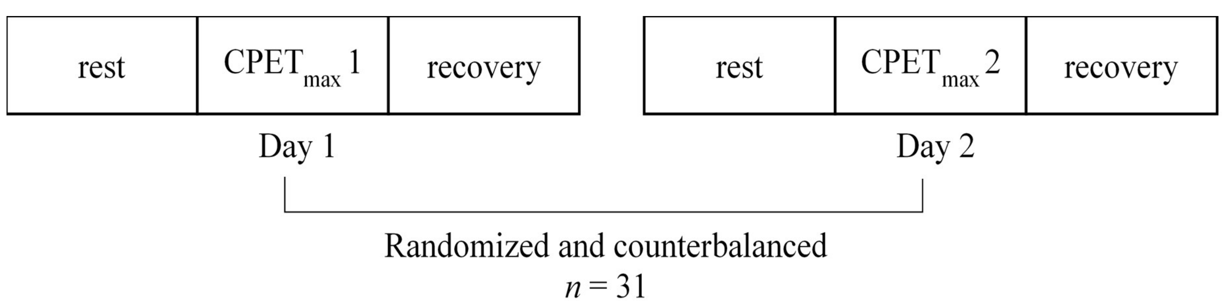

Figure 1. Schematic illustration of the two lab visits: (1) maximal cardiopulmonary exercise tests ($CPET_{max}$) in Day 1 and Day 2 not wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS). Experimental conditions were randomized and counterbalanced (n = 31). n = number of participants.

test, followed by the participant completing the opposite condition another day (Figure 1). In order to minimize the circadian cycle effects, both tests were performed around the same time of the day. Participants were given a minimum 48-hour period between each $CPET_{max}$ to avoid any carry-over effect between the two. In the current study, a total of sixty-two (62) $CPET_{max}$ tests were performed (31 participants x 2 experimental conditions).

After arrival to the Cardiovascular & Respiratory Research laboratory and prior to the experimental protocol execution, participants' ankle (24.87 ± 2.98 cm), calf (37.52 ± 3.23 cm) and knee circumferences (35.92 ± 2.56 cm) were measured by a cloth, non-distensible fabric tape. The calf circumference was measured at the widest point and used to determine the appropriate sock size based on sex as per the manufacturer's recommended sizing method (see Table 1). Ankle circumference was measured around its widest point around the lateral malleolus. Knee circumference was measured just below the patella at the head of the fibula. CEP Progressive Men's and Women's Run Socks 2.0 (Holabird Sports, Baltimore, MD, USA) were used in this study. The manufacturer reports that this sock's model main features are as follows: encircles your muscles more than 300 times in graduated compression, exceptional airflow, seamless toe closure for maximum comfort, anatomically padded cushioning, anti-blister, anti-hotspot, smooth, 85% polyamide (Nylon) and 15% elastane (Lycra), lifetime 6 months (150-200 wears; https://www.cepcompression.com/products/womens-compression-run-socks-2-0). The supplied 20-30 mmHg graduated compression is classified as medium, class 2, with operational pressure difference from ankle-to-knee approximately 10 mmHg as reported by the manufacturer.

Table 1. Sock size chart provided by the manufacturer

Size	Calf circumference (inches)	Calf circumference (cm)
2	9.5-12	25-31
3	12.5-15	32-38
4	15.5-17.5	39-44
5	18-20	45-50

For GCS experimental condition, an accommodation period of at least 10 minutes was used to allow acclimation of the lower leg to the additional applied pressure (Downie et al., 2007; Mosti, 2002). For NGCS condition, conventional ankle-length socks were used by the participants. It was assumed that these socks did not influence lower leg circulation because the approximately 17 mmHg minimum pressure would not have been exerted in this condition. After this period of time, each participant was fitted with a heart rate strap over their skin positioned near to the xiphoid process of the chest to allow heart rate measurements via a heart rate sensor. Participants were also fitted with cushioning masks to their faces for the measurement of ventilatory variables. They were instructed to step on the treadmill and familiarized according to the required speed determined by the protocol (4 mph at 0% inclination). Experimental procedures were performed with temperature and humidity relatively constant (21.26 ± 1.04 °C; 29.0 ± 0.06%, respectively) and a barometric pressure of 732.03 ± 5.95 mmHg.

Experimental Protocol

Resting Measurements. After all instrumentation, participants' height and weight as well as resting heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), respiratory exchange ratio (RER), minute ventilation ($\dot{V}E$), and breathing rate (BR) were measured and recorded to determine baseline values. If participants had SBP values higher than 140 mmHg or DBP higher than 100 mmHg or both combined (140/100 mmHg), the test was not performed. None of the participants showed blood pressure values higher than the cut-off criteria before the beginning of testing.

Maximal Cardiopulmonary Exercise Testing. After resting measurements, participants performed a $CPET_{max}$ adapted from Vanhoy (2012). This protocol differed based on sex, with both initially starting with baseline measurements as participants stood on the treadmill edges. The female test protocol included a 3-minute warm-up at 4 mph, followed by an increase to 5 mph over the next minute, 6 mph over the next minute and one last increase of speed to 7 mph for the rest of the test with 0% incline. After reaching 7 mph, the treadmill was inclined by a 2% grade every minute until exhaustion. The male test protocol included the same 3-minute warm-up at 4 mph followed by an increase to 6 mph over the next minute, 7 mph over the next minute, and lastly increasing to 8 mph for the rest of the test with 0% incline. After reaching 8 mph, the treadmill was inclined by a 2%

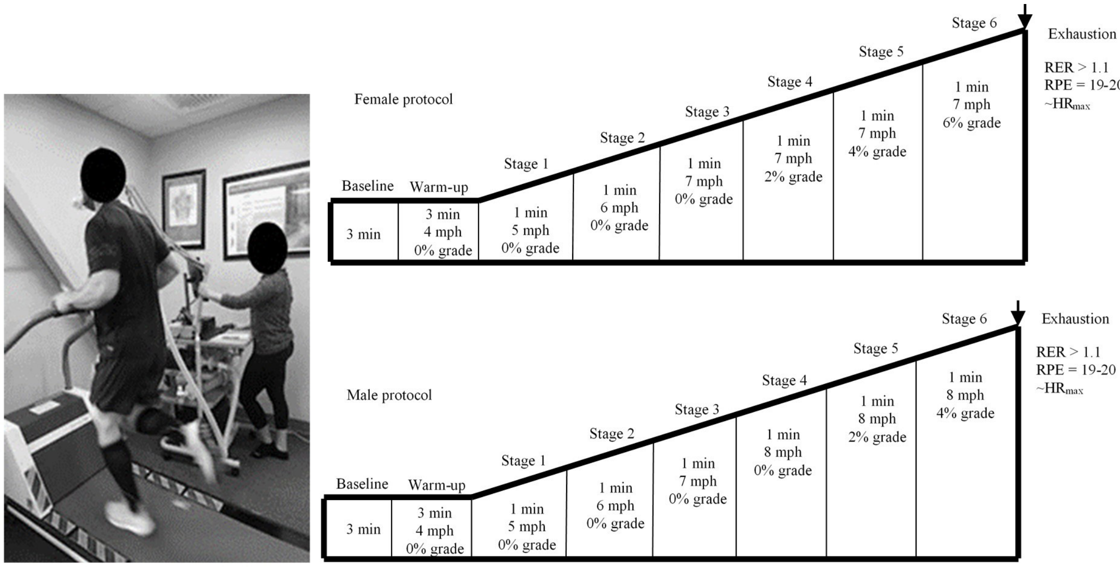

Figure 2. Female and male incremental cardiopulmonary exercise test ($CPET_{max}$) adapted from Vanhoy (2012).

grade every minute until exhaustion (Figure 2). For both females and males, a recovery time of approximately 15 minutes was administered to allow a return to baseline values in both conditions (NGCS and GCS). Participants were required to reach at least 8 minutes for their total test, including the warm-up time. Criteria to determine if individuals reached maximum effort included the following: (1) respiratory exchange ratio (RER) greater than 1.1, (2) rating of perceived exertion (RPE) between 19-20, and (3) heart rate close to maximal value based on the formula HR_{max} = 220 - age.

The computer screen on the metabolic cart remained turned away from the participant during the duration of the test to avoid any anticipatory responses and effect on participants' responses to the experimental protocol. They were given the option to press an emergency stop button on the treadmill at any point throughout the test and were strongly recommended to signal to the researcher when they needed to stop, as there was a control on the computer to stop the treadmill. Upon stopping, participants were immediately sat in a chair within range of the heart rate transmitter and remained seated with the mask on until the end of the recovery time (15 minutes). Heart rate and ventilatory variables were continuously monitored as well as systolic and diastolic blood pressure recorded every 3 minutes during the 15-minute recovery. After completing the $CPET_{max}$, researchers asked follow-up questions about how individuals felt and their experience throughout the test. All these procedures were performed to ensure participants' safety under both testing conditions.

Data Acquisition

The $CPET_{max}$ was performed on a treadmill (Q-Stress, TM55, Mortara Instrument Inc., Milwaukee, WI, USA) that had less than a second delay when responding to the computer in terms of speed and inclination changes. Compression socks (CEP Progressive + Compression Run Socks 2.0, Holabird Sports, Baltimore, MD, USA) were fitted according to the manufacturer's specifications as previously described. The compression socks were advertised to (1) increase venous blood flow, or the return of blood, with waste products removed from the exercising muscles to recirculate; (2) activate the arterial system increasing the amount of oxygen and nutrient rich blood supplied to the muscles, as a result of increased blood flow, giving muscles more energy and more oxygen to perform efficiently; and (3) decrease swelling in the lower extremities to increase kinetic and physiological performance (https://www.youtube.com/watch?v=8NTt17-RFEY). The air humidity (%), barometric pressure (in mmHg), and temperature (in Celsius) were monitored by the Vantage Vue Console (Davis Instruments, Hayward, CA, USA) in order to properly calibrate the Parvomedic Metabolic Measurement System (TrueOne 2400, Metabolic Measurement System, Parvo Medics, Murray, UT, USA).

$\dot{V}O_2$, $\dot{V}CO_2$, RER, $\dot{V}E$, and BR were measured breath-by-breath by a computerized metabolic Cart (TrueOne 2400, Metabolic Measurement System, Parvo Medics, Murray, UT, USA). Oxygen and carbon dioxide exchange were collected from a silicone rubber face mask (7450 Series Silicone V2™ Oro-Nasal Mask, Hans-Rudolph Inc. Shawnee, KS, USA) connected to a two-way Non-Rebreathing Valve (2700 Series, Body Style Saliva, Hans Rudolph Inc., Shawnee, KS, USA). The exhaled gas travelled through a corrugated flexible plastic hose (3.2 cm diameter) into a linear pneumotachometer mixing chamber (3813 Series, 0-800 L/min, Hans Rudolph, Shawnee, KS, USA) and then transferred to an analyzer module. The analyzer module measured and analyzed O_2 and CO_2 percentage of expired air. The mixed chamber uses a paramagnetic oxygen analyzer (range 0-10%, accuracy: 0.1%, response 200 ms) and an infrared, single beam, single wave-length carbon dioxide analyzer (range 0-15%, accuracy: 0.1%, response 100 ms).

Prior to each $CPET_{max}$, the metabolic measurement system was calibrated according to the manufacturer's recommendations by two methods: (1) flow meter calibration and (2) gas calibration. The flowmeter calibration used a 3 L Syringe (Series 5530, Hans Rudolph Inc., Shawnee, KS, USA) with a wave stroke calibration at different flow rates for each stroke (five flow rates). After this procedure, a screen pop-up showed the results of the calibration. Flowmeter calibration under 1% difference was considered acceptable; otherwise, a new calibration was performed to ensure data quality. The gas calibration used a room air auto-calibration routine and a two-point gas calibration with a single gas tank and a medical-grade mixture of compressed air (Calibration Gas Mixture, Airgas USA LLC, Radnor, PA, USA). The gas analyzers were calibrated in two ways: (1) room air that consisted of approximately 20.94% of O_2 and 0.04% of CO_2, and (2) the mixture of compressed gas that consisted of 16% O_2 and 4% CO_2. For each calibration, updated environmental parameters (humidity, temperature and barometric pressure) were used to get the best calibration possible to ensure data quality control.

Height and weight were measured with a mechanical beam scale and a height rod (402KL, Health o Meter Professional, McCook, IL, USA) following the American College of Sports Medicine standard procedures (American College of Sports Medicine, 2014). Heart rate was measured by a heart rate sensor transmitter (H1, Polar Electric Inc., Lake Success, NY, USA) and recorded into a computerized metabolic card via a specific software (TrueOne 2400, Metabolic Measurement System, Parvo Medics, Murray, UT, USA). The sensor was connected to a heart rate monitor via 5 kHz transmission signal to continuously record heart rate with the elastic band strapped around the inferior of the participants' sternum at the xiphoid process. Arterial systolic and diastolic blood pressures were measured by auscultation technique using a stethoscope (Lumiscope, GF Health Products, Inc., Atlanta, GA, USA) and an HCS Adjustable Clock Aneroid Sphygmomanometer (Dyad Medical Sourcing, LLC, Bannockburn, IL, USA) following the American College of Sports Medicine standard procedures (American College of Sports Medicine, 2014). Briefly, the stethoscope was placed on the cubital fossa (of either arm) over the brachial artery and the blood pressure cuff was placed around the same arm. The systolic blood pressure was measured during the contraction phase of the cardiac cycle (systole) and diastolic blood pressure during the relaxation phase (diastole) at baseline, immediately after $CPET_{max}$ test completion, and every three minutes during 15 minutes to ensure that participant arterial blood pressure returned to baseline values. RPE was recorded at the end of testing using the Borg rate of perceived exertion from the 6-20 scale.

Data Analysis

Peak oxygen uptake ($\dot{V}O_{2peak}$), peak carbon dioxide output ($\dot{V}CO_{2peak}$), peak respiratory exchange ratio (RER_{peak}), peak minute ventilation ($\dot{V}E_{peak}$), peak breathing rate (BR_{peak}), and peak heart rate (HR_{peak}) data from the metabolic cart were exported to an excel file and then ensemble-averaged over the last 15 seconds of the final stage, generating a single peak dataset per participant for each condition (NGCS and GCS). Peak systolic blood pressure (SBP_{peak}) and peak diastolic pressure (DBP_{peak}) measured immediately after $CPET_{max}$ termination were averaged, generating a single peak dataset per participant per condition (NGCS and GCS). The exercise time to exhaustion representing the duration from the beginning of testing to the point where individuals could no longer continue running on the treadmill due to fatigue was averaged in a single dataset for NGCS and GCS conditions per participant. All the variables were compared between the NGCS and GCS.

Statistical Analysis

Data were presented as means ± standard deviation (SD). The Shapiro-Wilk test analyzed the normal distribution of the data and equal variance. If the data passed the normal distribution and the equal variance tests ($p > 0.05$), a Paired T-Test was used to identify any statistically significant differences between the experimental conditions. However, if the data failed to pass the normal distribution and the equal variance tests ($p < 0.05$), the Wilcoxon Signed Rank Test was used to identify such differences. The significance level was set at $p < 0.05$. All analyses were conducted using Sigma Plot software version 12.5 (Systac Software, Inc., San Jose, CA, USA).

Results

Peak $\dot{V}O_2$, BR, and HR did not pass normal distribution test as shown by the Shapiro-Wilk test ($p < 0.05$). The Wilcoxon Signed-Rank test for these variables showed no statistically significant differences between non-graduated compression socks (NGCS) and graduated compression socks (GCS) with a two-tailed p-value > 0.05 (Table 2). Peak $\dot{V}O_2$, RER, $\dot{V}E$, SBP and DBP passed the normal and equal variance distribution test (Shapiro-Wilk test, $p > 0.05$). These variables were not different statistically between NGCS and GCS, as shown by the two-tailed Paired T-test ($p > 0.05$) (Table 2).

Table 2. Peak variables comparison between non-graduated compression socks (NGCS) and graduated compression socks (GCS).

	NGCS	**GCS**	**P value (two-tailed)**	**95% CI**
$\dot{V}O2_{peak}$ (mL/kg/min)	45.72 ± 6.37	44.90 ± 7.28	0.651	-0.82-2.46
$\dot{V}CO2_{peak}$(mL/kg/min)	51.87 ± 7.33	50.64 ± 9.75	0.269	-1.00-3.46
RER_{peak}	1.13 ± 0.07	1.12 ± 0.08	0.547	-0.02-0.03
$\dot{V}E_{peak}$ (L/min)	114.81 ± 24.54	110.83 ± 29.48	0.156	-1.61-9.59
BR_{peak} (breaths/min)	51.38 ± 6.99	50.08 ± 8.76	0.241	-1.20-3.81
HR_{peak} (bpm)	193.12 ± 7.80	190.57 ± 10.50	0.136	0.08-5.01
SBP_{peak} (mmHg)	174.97 ± 15.63	171.19 ± 14.97	0.250	-2.80-10.35
DBP_{peak} (mmHg)	91.87 ± 10.65	94.42 ± 9.84	0.280	-7.27-2.18

Wilcoxon Signed-Rank Test. Significance level $p < 0.05$. Confidence Interval (CI).

Figure 3 displays the distribution and dispersion data (box plot) of the exercise time to exhaustion (ETE) comparison between NGCS and GCS during the $CPET_{max}$. There were no statistically significant differences between NGCS (8:98 ± 0:93 min) and GCS (9:03 ± 1:02 min), as demonstrated by the Wilcoxon Signed-Rank test (Z-value = 1.019; p = 0.313).

$\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, $\dot{V}E_{peak}$, HR_{peak} increased as exercise intensity increased until participants reached voluntary exhaustion, and the test was terminated. There were no statistically significant differences for all the variables between NGCS and GCS (Table 2; Figure 4B; Figure 5B; Figure 6B; and Figure 7B).

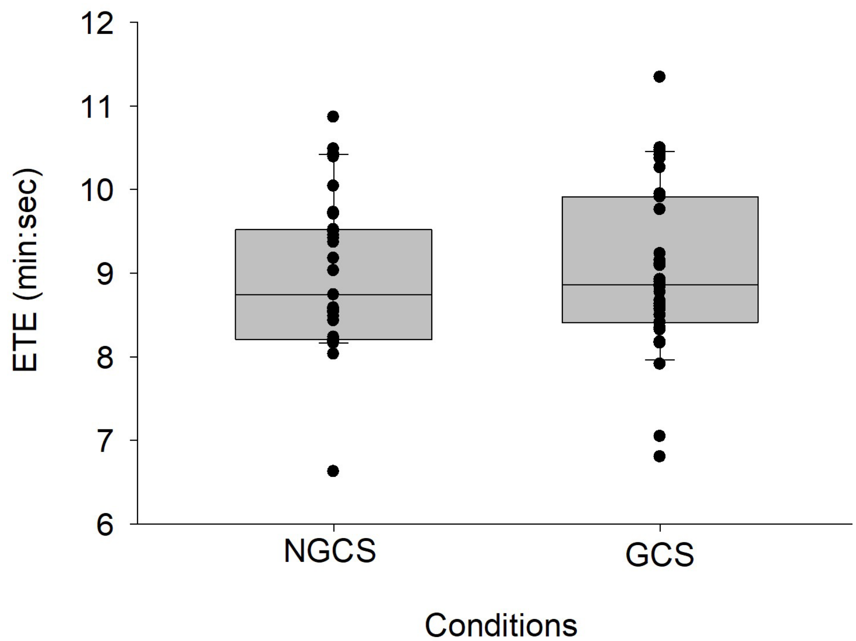

Figure 3. Box Plot of the responses during the maximal cardiopulmonary exercise test ($CPET_{max}$) for exercise time to exhaustion (ETE) while not wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS) (*n* = 31). *n* = number of participants.

Figure 4A displays second-by-second $\dot{V}O_2$ response and figure 4B displays the distribution and dispersion (box plot) of the $\dot{V}O_{2peak}$ response during the $CPET_{max}$ protocol comparing NGCS and GCS experimental conditions.

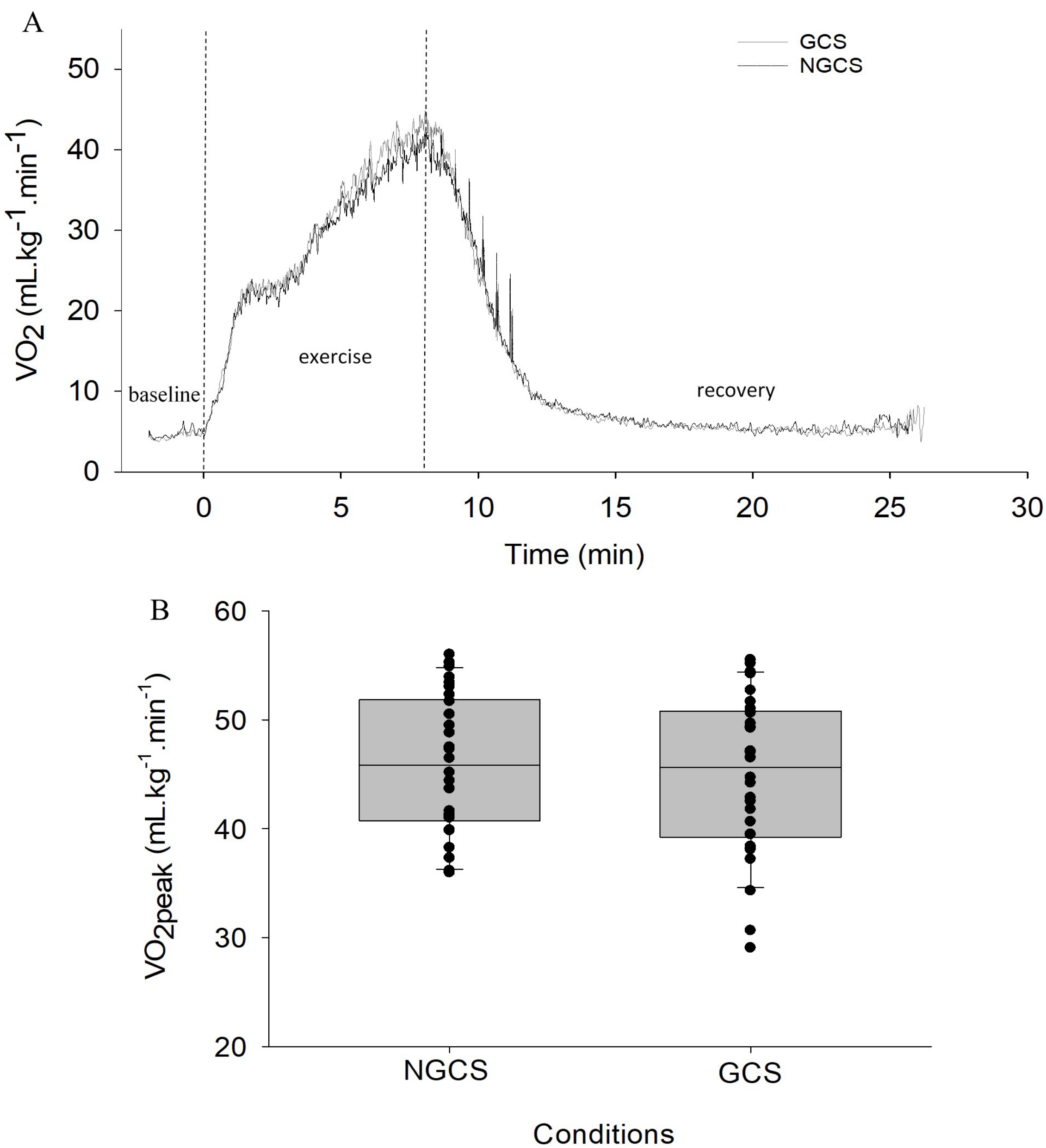

Figure 4. (A) Second-by-second oxygen uptake ($\dot{V}O_2$) response during cardiopulmonary exercise test ($CPET_{max}$); (B) Blox plot of the peak oxygen uptake ($\dot{V}O_{2peak}$) response while not wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS). Dashed lines indicate transition from rest to exercise and exercise to recovery (*n* = 31). *n* = number of participants.

Figure 5A displays second-by-second $\dot{V}CO_2$ response and figure 5B displays the distribution and dispersion (box plot) of the $\dot{V}CO_{2peak}$ response during the $CPET_{max}$ protocol comparing NGCS and GCS experimental conditions.

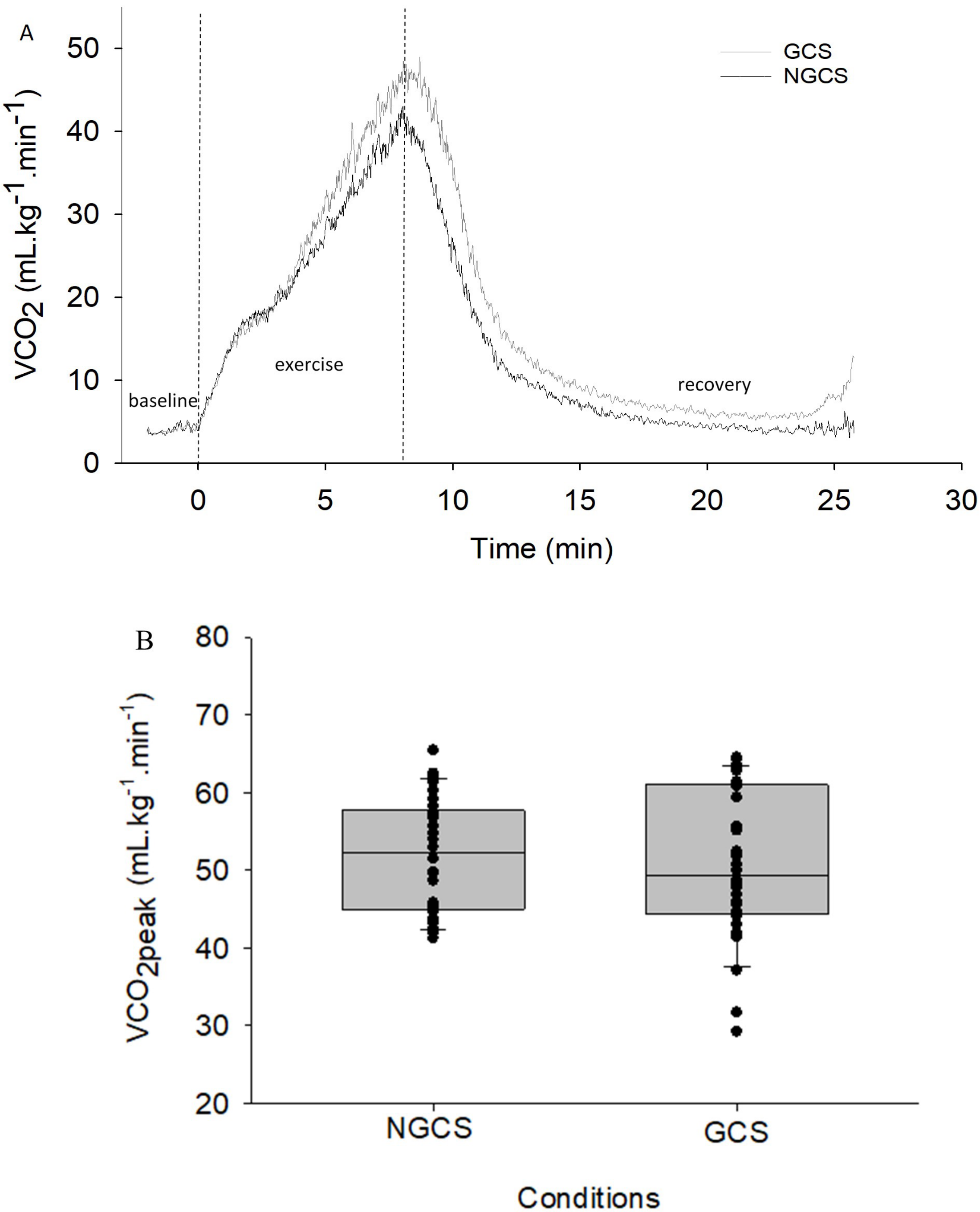

Figure 5. (A) Second-by-second carbon dioxide output ($\dot{V}CO_2$) response during cardiopulmonary exercise test ($CPET_{max}$); (B) Blox plot of the peak carbon dioxide output ($\dot{V}CO_{2peak}$) responses while no wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS). Dashed lines indicate transition from rest to exercise and exercise to recovery (*n* = 31). *n* = number of participants.

Figure 6A displays second-by-second V̇E response and figure 6B displays the distribution and dispersion (box plot) of the $\dot{V}E_{peak}$ response during the $CPET_{max}$ protocol comparing NGCS and GCS experimental conditions.

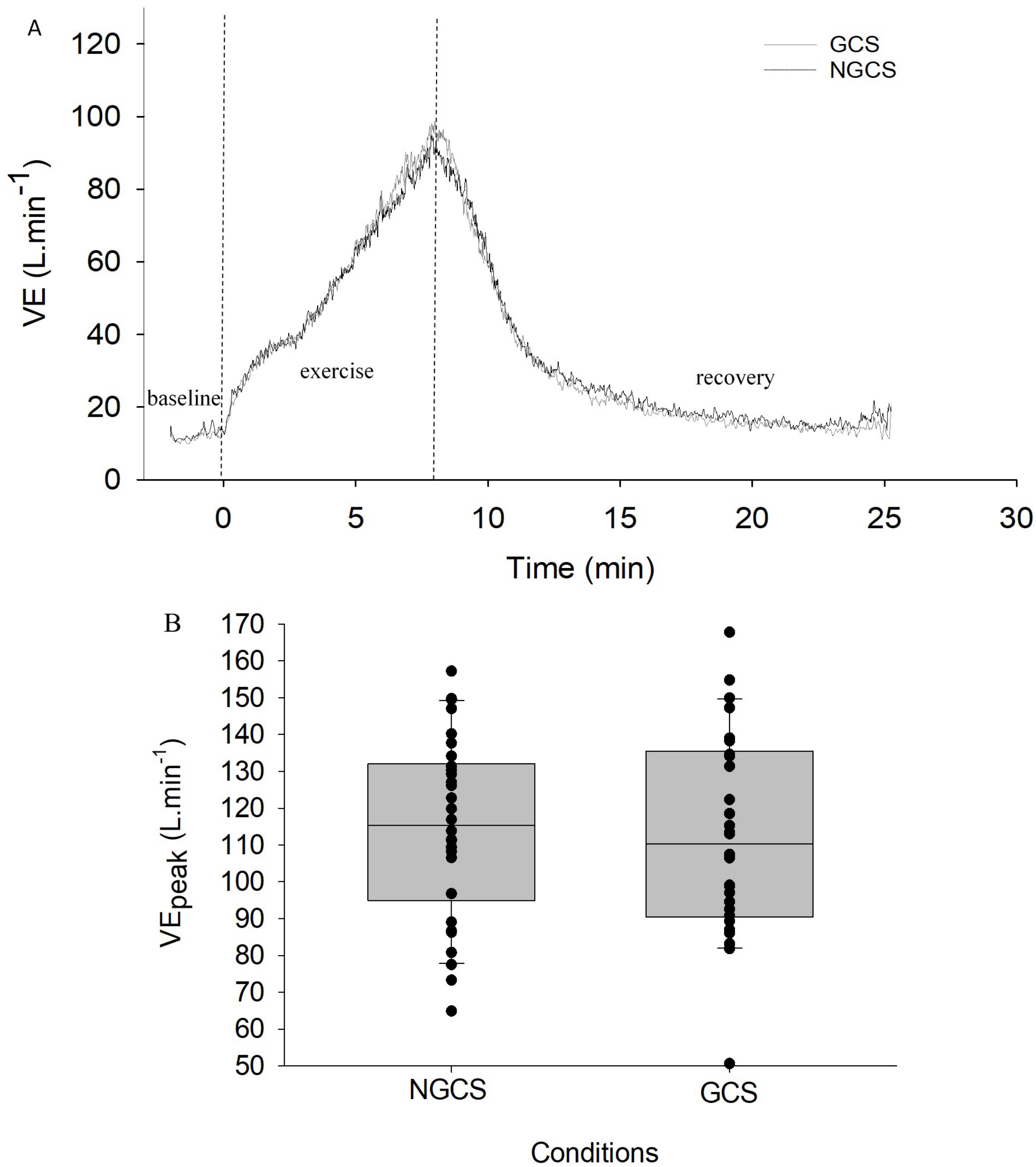

Figure 6. (A) Second-by-second minute-ventilation (V̇E) response during cardiopulmonary exercise test ($CPET_{max}$); (B) Blox plot of the peak minute-ventilation ($\dot{V}CO_{2peak}$) responses while no wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS). Dashed lines indicate transition from rest to exercise and exercise to recovery (n = 31). n = number of participants.

Figure 7A displays second-by-second HR response, and figure 7B displays the distribution and dispersion (box plot) of the HR_{peak} response during the $CPET_{max}$ protocol comparing NGCS and GCS experimental conditions.

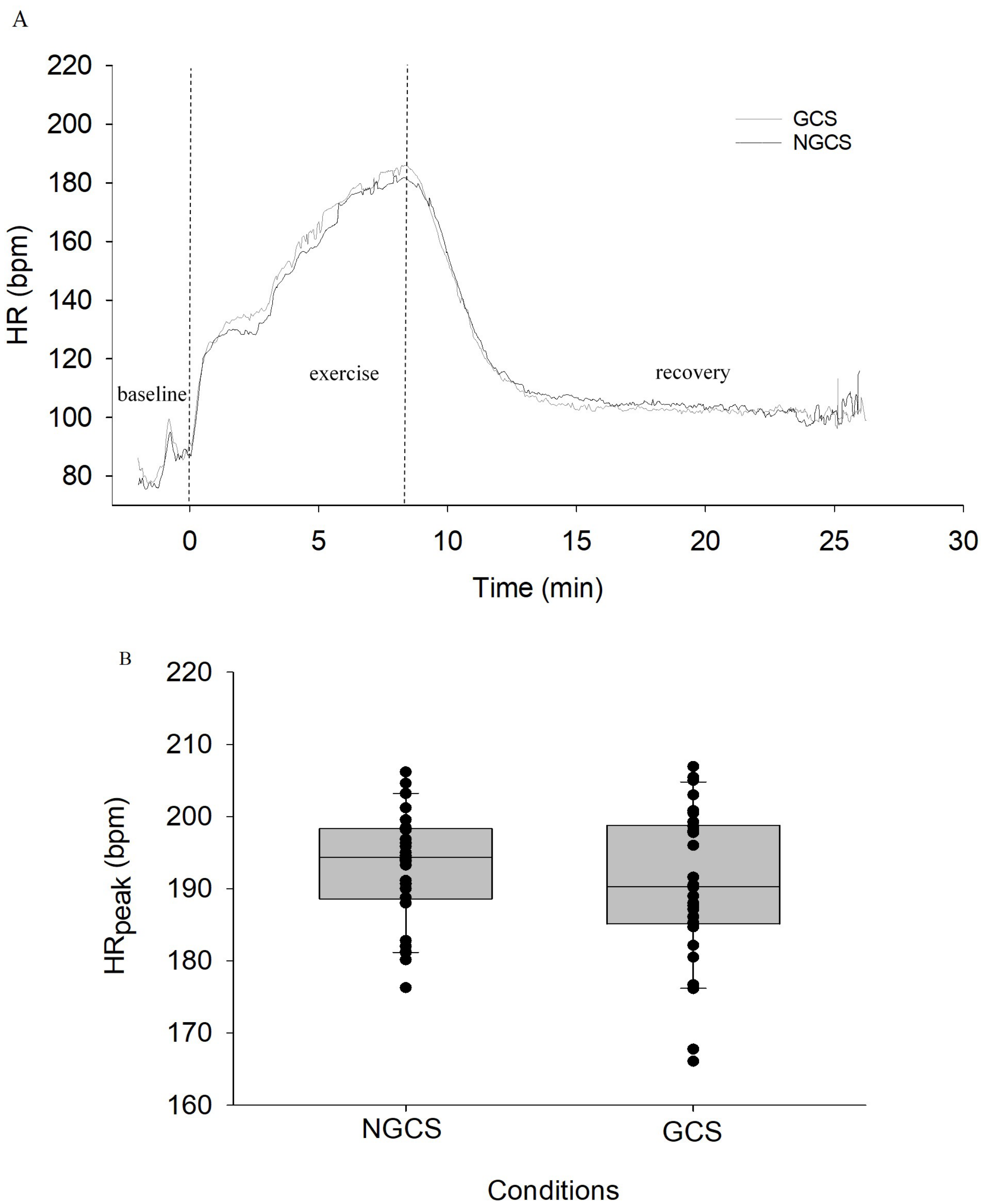

Figure 7. (A) Second-by-second heart rate (HR) response during cardiopulmonary exercise test ($CPET_{max}$); (B) Blox plot of the peak heart rate (HR_{peak}) responses while no wearing graduated compression socks (NGCS) and wearing graduated compression socks (GCS). Dashed lines indicate transition from rest to exercise and exercise to recovery (n = 31). n = number of participants.

Discussion

In the present study of the effects of lower leg passive external compression on peak cardiovascular, ventilatory, and performance variables during a maximal cardiopulmonary exercise test in healthy young adults, we have demonstrated the lack of positive effects on cardiorespiratory responses and exercise time to exhaustion when wearing graduated compression socks. Consistent with our first hypothesis, peak oxygen uptake, peak carbon dioxide output, peak respiratory exchange rate, peak ventilation, peak breathing rate, peak heart rate, peak systolic blood pressure, and peak diastolic blood pressure were not different between wearing non-graduated compression socks and wearing graduated compression socks. Our results are supported by previous studies investigating maximal exercise (Sperlich, 2010; Moehrle, 2007; Wahl, 2011; Rivas et al., 2017; Bringard et al., 2006; Rimaud et al., 2010; Rider et al., 2014). Our results do not support allegations that lower leg graduated compression socks would improve venous return, ultimately enhancing cardiac output, increasing blood flow and oxygen delivery to the exercising muscles, increasing oxygen uptake, breathing rate, heart rate, and ventilation, all leading to better performance in healthy, young active adults. Contradicting our second hypothesis, exercise time to exhaustion was not different between wearing non-graduated compression socks and wearing graduated compression socks. These results are in agreement with previous studies using maximal treadmill exercise (Wahl et al., 2011; Sperlich et al., 2010), but conflicting with other investigations that showed improved time to exhaustion (Kemmler et al., 2009; Varela-Sanz et al., 2011; Armstrong et al., 2015).

Peak Cardiorespiratory Responses to Incremental Maximal Cardiopulmonary Test

Previous investigations have shown conflicting results about the effects of graduated compression socks on cardiorespiratory variables and performance, in which some studies showed positive effects on performance measured by time to exhaustion (Kemmler et al., 2009; Varela-Sanz et al., 2011; Armstrong et al., 2015), ventilation (Rivas et al., 2017), $\dot{V}O_2$ (Reed et al., 2016), and energy costs throughout exercise (Bringard et al., 2006). Some studies have also shown no effect at all (Wahl et al., 2011). Our results that graduated compression socks did not show any significant effect on oxygen uptake are similar to the results reported by Rider et al. (2014) as well as the heart rate results reported by Rider et al. (2014) and Priego et al. (2015) and the respiratory exchange ratio results reported by Rider et al. (2014) during a ramped treadmill test until exhaustion. Furthermore, our results showed that specific variables such as carbon dioxide output, peak breathing rate (similar to Rivas et al., 2017), peak ventilation (similar to Bringard et al., 2006), peak systolic and diastolic blood pressure (similar to Rimaud et al., 2010) were not statistically different between experimental conditions (Table 2).

The lack of positive effects on peak cardiorespiratory responses when wearing graduated compression socks was anticipated, as evidence does not clearly support the notion that peak cardiorespiratory variables would improve with lower leg passive external compression. For example, to further increase peak oxygen consumption, it would be required that venous return enhances cardiac output while increasing blood flow and oxygen delivery to the exercising muscles. Independently of using graduated or non-graduated compression socks, an increase in cardiac output is limited during maximal exercise by heart rate and stroke volume. In turn, blood pressure is limited by both cardiac output and peripheral resistance. Our data showed no differences in peak heart rate and peak oxygen consumption during maximal exercise testing between both experimental conditions (Table 2). Therefore, oxygen pulse (the ratio between $\dot{V}O_{2peak}$ and HR_{peak}) as a surrogate measurement of stroke volume is similar between experimental conditions, meaning no differences in cardiac output.

Additionally, peak systolic, peak diastolic, and consequently peak mean arterial pressure were similar between experimental conditions. As described above, cardiac output is limited by heart rate and stroke volume, meaning that the only way to further increase blood pressure is by increasing peripheral resistance via vasoconstriction. This then limits blood flow and oxygen delivery to the exercising muscles. Allowing for a greater $\dot{V}O_{2peak}$ would require an increase in oxygen delivery by a local increase in blood flow via vasodilation of local vessels and/or increased perfusion pressure (Villar and Hughson, 2013). However, perfusion pressure is not altered by maximal exercise (Calbet, 2012). During maximal exercise, there is limited ability of the vessels to dilate because they have reached maximal capacity. Massive dilation at very high intensities would promote a sudden drop in blood pressure resulting in reduced blood flow to the brain. However, in the current study, maximal dilation is probably reached and blood flow cannot further increase, in turn limiting oxygen delivery and oxygen uptake by the exercising muscles. This may explain why we did not find any differences in $\dot{V}O_2$ when comparing the use of graduated compression socks and non-graduated compression socks during maximal exercise.

Other reasons may explain why peak cardiorespiratory variables did not show any statistically significant differences wearing graduated compression socks in the current study. The ankle to knee pressure applied is essential to create a pressure gradient great enough to enhance venous return. It seems that the minimal pressure required to influence cardiac output is approximately 17 mmHg (Lim and Davies, 2014; MacRae et al., 2011). It is speculated that this pressure would reduce the diameter of the veins by altering venous velocity, pooling, and improving venous return while enhancing cardiac output (Lim and Davies, 2014; MacRae et al., 2011). If insufficient pressure is applied from ankle-to-knee, the deep and/or superficial veins would not compress enough (Lim and Davies, 2014, Vargo and Sanderson, 2014, Priego et al., 2015) to promote improvements in local blood flow and oxygen delivery. It is also speculated that lower leg compression may create a localized pressure on the calf muscle supporting and stimulating calf muscle pumping to ultimately improve venous return during exercise (Jorn Bovenschen et al., 2013). Despite logical physiological assumptions as to how graduated compression would impact the cardiorespiratory and exercise time to exhaustion, the lack of effects on peak cardiorespiratory variables in the present study does not support these previous statements. The speculation that local external passive compression improves peripheral circulation and cardiac output during exercise while consequently improving oxygen uptake, breathing rate, heart rate, and ventilation is unlikely.

It is known that local and central hemodynamics can be influenced by applied pressure (Book et al., 2016). However, there is also a possibility that the external pressure applied in a small local region was not enough to improve venous return to ultimately affect the cardiovascular and respiratory responses. The applied compression might be too localized to produce any effect on cardiac output due to the distance between the local application of the compression and the heart (Priego et al., 2015). Despite meticulous control of applied pressure and following the manufacturer instructions in the experimental conditions, Book et al. (2016) reported that there were deviations and variations of applied pressures. Graduated compression socks did not consistently produce the same pressure gradient from ankle-to-knee, from one application to the next, and the local pressure varied during exercise (Book et al., 2016). The authors reported no significant impact on central and peripheral hemodynamics and recommended caution in studies of compression garments and incorporation of pressure measurements to determine the specific pressures and gradients applied (Book et al., 2016).

The participants' leg geometry may explain the deviations, variations, and inconsistency of the applied pressure by the graduated compression socks. Applied pressure can vary according to leg geometry, application of the socks, and sock stretching (Book et al., 2016). There is a possibility that participants' leg geometry would alter the ankle-to-knee applied pressure distribution, which may cause different results explaining why participants could show positive, negative, or no effects. The present study and previous investigations (Book et al., 2016; Rivas et al., 2017; Rider et al., 2014) did provide evidence to support the idea that graduated compression socks were not effective for healthy, active young adults. This is not surprising since this population has functional vessels with no venous, cardiovascular and respiratory deficiencies that would compromise the normal responses during exercise. It is possible that higher pressure may be required to significantly reduce cardiovascular strain in a specific population of healthy individuals (MacRae et al., 2011). Wahl et al. (2011) reported no statistically significant differences in cardiorespiratory variables at any compression ranging from 0 to 40 mmHg. Vasculature diameter, blood velocity or blood flow in healthy young population did not show any significant changes during submaximal exercise (Book et al., 2016). These results align with our findings of no significant changes in peak $\dot{V}O_2$ wearing graduated compression socks since there is a very close relationship between blood flow, oxygen delivery, and $\dot{V}O_2$ responses (Sundberg and Kaijser, 1992; Sperlich et al., 2013).

Exercise Time to Exhaustion

Literature results related to time to exhaustion are also controversial. Some previous studies reported positive effects of compression in improving performance (Kemmler et al., 2009; Varela-Sanz et al., 2011), whereas others reported detrimental effects (Rider et al., 2014) or no effects (Sperlich et al., 2011; Berry and McMurray, 1987). The current study results are in accordance with investigations that showed no changes in time to reach exhaustion during an incremental test to exhaustion (Sperlich, et al. 2010; Wahl et al., 2011), which was contrary to our original hypothesis. Our rationale was that graduated compression socks would improve cardiorespiratory efficiency at submaximal intensities within an incremental test, thereby postponing the onset of muscular fatigue. However, this rationale was not supported by our results (Table 2 and Figure 3).

Previous investigations that reported no significant effects of compression on time to exhaustion argue that the applied pressure by compression socks was not enough to influence blood flow possibly because sporting compression specifically only applies mild pressure resulting in the lack of effect on cardiovascular response (MacRae et al., 2011). However, if applied pressure by compression reaches levels superior to 37 mmHg, blood flow is impeded due to a mechanical hindrance where the cross-sections of superficial and deep veins are significantly reduced (Sperlich et al., 2013; MacRae et al., 2011). Sundberg and Kaijser (1992) found that as local external pressure increases, blood flow is hindered, reducing venous oxygen saturation. Additionally, Sperlich et al. (2010) reported no difference in oxygen uptake with compression, limiting possible performance improvement. Wahl et al. (2011) stated that red blood cells are very sensitive to external changes in the environment, altering their ability to move through capillaries (also known as erythrocyte deformability). This erythrocyte deformability may limit oxygen delivery via red blood cells to the exercising muscles.

To explain their results, the previous investigations that reported improvements in performance measured by time to exhaustion when wearing graduated compression socks have suggested that leg muscle blood flow should be enhanced (Varela-Sanz et al., 2011) and that aerobic energy costs should decrease throughout submaximal intensities of a test (Bringard et al., 2006). It is speculated that mechanical efficiency to support the muscle should increase (Kemmler et al., 2009), and muscle damage should decrease to improve performance (Armstrong et al., 2015). However, our results do not support performance improvement as indicated by similar exercise time to reach exhaustion between wearing graduated compression and not wearing graduated compression for incremental exercise to exhaustion. Our data do not provide evidence to support assumptions of improved venous return, blood flow, and O_2 delivery to the exercising muscles as well as suggesting no changes in cardiorespiratory efficiency during incremental exercise in young, healthy adults. Therefore, the reduction of energy costs during submaximal intensities of a test seems unlikely according to our results.

Limitations

In the current study, we did not control the applied pressure exerted by the graduated compression socks. We recognized that controlling for the applied pressure and magnitude is important. The garment manufacturer reported an operating pressure range of 20-30 mmHg from ankle to knee (10 mmHg difference). In a previous study, Book et al. (2016) reported that despite their efforts, they were unable to consistently control the movement of graduated compression socks during constant workload submaximal plantar flexion exercise, which may alter the pressure distribution of the graduated compression socks (Book et al., 2016). Therefore, it will be even more challenging to measure and control the applied pressure gradient during an incremental exercise test to exhaustion. We took great care to follow manufacturers' instructions on how to wear the socks to minimize such influences, but changes in applied pressure gradient and day to day variability need to be considered when studying compression garments (Book et al., 2016). We did our best to consistently repeat the same procedures every visit (2 times for each participant) to reduce such variability. According to the graduated compression sock manufacturer, after 150-200 uses, the compression socks most likely lose their elasticity, not providing the same pressure gradient to the participant's lower extremity. We used new socks after a few uses to avoid the effects of wearing on sock elasticity. It is very unlikely that just a few uses would be sufficient to produce fabric loss of elasticity to influence our results. Despite all careful preparation, we cannot rule out the influence of applied pressure on our results.

Physical fitness status and food intake may affect test outcomes, as well. Our sample included healthy young active adults, which may decrease the variability related to different levels of physical fitness. All participants were classified as having "good" cardiorespiratory fitness based on their $\dot{V}O_{2max}$ values obtained in the Maximal Cardiopulmonary Exercise Test (Kaminsky et al., 2015). We did not control for food intake before testing, but we strongly recommended that participants refrain from consuming alcohol, drugs, and caffeine for 12 to 24 hours prior to testing, heavy meals approximately 3 hours prior to testing, and not engage in intense physical activity 24 hours prior to their test as previously described.

Practical Applications

Based on the average results from the current study, the use of lower leg compression is not recommended for performance improvement in young and healthy individuals, specifically collegiate athletes. However, average results need to be analyzed with caution. For example, approximately 18 of 31 individuals showed an increase in peak variables; thus, approximately 55% of the sample from this study benefited from using compression socks. Another approximately 13 participants had no advantage in using them, as shown by a lack of improvement or even a decrease in these variables. When considering individual results for exercise time to exhaustion specifically (ETE), the current study showed that 16 individuals exhibited some degree of increase (52%), and 15 participants showed no change or a decrease in ETE (48%). This data showed that there was individual variability when graduated compression was applied in the lower legs.

In a performance environment where even the smallest improvements matter, those who showed a positive effect using graduated compression socks could have an advantage during competitions; however, the opposite is also true. Therefore, it is necessary to perform assessments to identify whether a person responds positively (responders) or negatively (non-responders) to graduated compression socks before adopting them as a performance enhancement aid.

Conclusions

In conclusion, the purported benefits of lower leg graduated compression socks related to improved venous return, increased blood flow, increased oxygen delivery to the exercising muscle tissue were not supported by our findings, as evidenced by a lack of statistically significant differences in peak cardiorespiratory variables and exercise time to exhaustion. The lack of performance improvement between conditions suggests no changes in cardiorespiratory efficiency in a young, healthy population during a maximal cardiopulmonary exercise test using lower leg graduated compression socks.

Future Research

We do not know if there are cardiorespiratory benefits under submaximal intensities because this was not the focus of the current study. In the future, we can analyze similar variables in the submaximal intensity domain to test for differences between wearing non-graduated compression socks and wearing graduated compression socks. This would offer a new type of incremental exercise test using a submaximal testing protocol.

Current studies focus majorly on performance improvements resulting from the use of compression. However, studies have shown the use of lower leg compression for reducing muscle fatigue and perceived muscle soreness after exercise (Motta et al., 2020). Future research should move beyond measuring only performance indicators during exercise and focus on the after-effects during recovery. Improving muscle soreness during recovery is relevant to those who perform multiple workouts with short recovery periods. For example, athletes on strict practices and competition schedules may benefit from compression for recovery purposes rather than performance improvements. Additionally, it would be relevant to add to the literature and explore lower leg compression results, among other exercise activities, such as cycling, high-intensity interval training (HIIT), and during game-play settings.

The meta-analysis done by Mota et al. (2020) showed that studies reported performance improvements with compression on the individual level (Mota et al., 2020). This suggests that the use of compression most likely has an individualized effect differing between users. Considering the concept of bio-individuality and individual variability, future research could explore lower leg external pressure effects based on individual responses to compression garments in professional sports, recreational sports, and/or clinical settings.

Finally, the lack of performance improvements in a young, healthy population may be due to physical fitness ability. Active individuals who utilize performance garments may not see significant performance increases because of their established fitness level. However, when studying the effects of compression on an older or less healthy or fit population (i.e., sedentary, chronic diseases, overweight and obese), it may pose different results.

Disclosure Statement

The authors report no conflict of interest associated with this manuscript.

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