J. Exerc. Sci. 28 : 1–10, 2018

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Effect of compression stocking on venous compliance at rest and circulatory responses to cycling exercise

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Abstract

The purpose of this study was to clarify whether calf and forearm venous compliance was increased by wearing graduated compression stockings (GCS), and whether changed venous compliance with GCS influenced the circulatory responses to submaximal cycling exercise. In ten young healthy subjects (7 men, 3 women; mean age 20.9 ± 0.9 [SD] years), calf and forearm venous volume with or without GCS was measured by venous occlusion plethysmography in subjects in the supine position during inflating a venous collecting cuff placed around the thigh and upper arm to 60 mmHg for 8 min and then decreasing cuff pressure to 0 mmHg at a rate of 1 mmHg/s. Calf and forearm venous compliance was calculated as the numerical derivative of the cuff pressure and venous volume curve. In addition, venous capacitance and maximal venous outflow was also determined from the changes in venous volume during inflation and deflation of cuff pressure. In main experiments, subjects performed cycling exercise at 30% and 60% of heart rate reserve (HRR) for 5 min and then had a recovery period of 5 min. Cycling exercise was carried out while wearing either GCS or no stockings (Control: CON) on separate days. Wearing GCS caused increases in venous compliance, venous capacitance, and maximal venous outflow in the calf, but did not change these venous properties in the forearm. Circulatory responses (HR and blood pressure) to cycling exercise at both intensities did not differ between CON and GCS. These results suggest that wearing GCS had a significant increase in the venous calf compliance but not in the arm compliance, and that the increased calf compliance during wearing GCS had no significant influence on the circulatory responses during cycling exercise in healthy young people.

Key words: Cuff deflation protocol, Venous capacitance, Venous outflow

Introduction

Veins have high compliance and contain approximately 70% of the total blood volume at rest (*Greenfield and Patterson* 1956, *Morris et al.* 1974). When physiological stress occurs such as during exercise and exposure to heat,

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the venous system must adjust to this new state, and usually does so through a change in venous compliance (*Rothe* 1983), which causes a shift of blood from the venous system to the heart and may contribute to maintenance of central blood volume and blood pressure. It is reported that aging and physical inactivity can induce the stiff of veins as well as arteries (*Hernandez et al.* 2004, *Monahan et al.* 2001, *Olsen and Lanne* 1998, *Tsutsui et al.* 2002, *Young et al.* 2006). Because decreased venous compliance might facilitate the shift of blood from the peripheral circulation to the heart and could secondarily induce elevation of blood pressure, vein stiffness is thought to contribute to the pathogenesis of hypertension (*Olsen and Lanne* 1998, *Safar and London* 1987). Indeed, decreased venous compliance has been observed in animal models of hypertension (*Fink et al.* 2000, *Xu et al.* 2007) and in hypertensive humans (*London et al.* 1987, *Takeshita et al.*1979). Thus, in considering the prevention of lifestyle-related diseases, it is important to maintain high venous compliance or improve decreased venous compliance.

Traditionally, the graduated compression stocking (GCS) have been used for the management of venous disorders such as venous thrombosis and varicose veins (*Agu et al.* 2004, *Ibegbuna et al.* 2003). However, recently, it has been reported that GCS could also increase the calf venous compliance at resting condition in healthy young subjects (*Hayata et al.* 2006). In addition, GCS has been used in various sports events for the purpose of improving exercise performance and recovery period after exercise, because GCS may help the skeletal muscle pump (*Kraemer et al.* 2000) and may increase deep venous velocity and/or decrease blood pooling in the calf veins (*Sigel et al.* 1975). Indeed, it was reported that running economy was improved for athletes wearing GCS (*Bringard et al.* 2006), and that the decrease in concentration of blood lactate during recovery period after exercise was greater in GCS than non-GCS (*Chatard et al.* 2004). On the other hand, some studies showed that the effect of GCS on circulatory responses was a little under sever conditions such as the prolonged exercise (*Fujii et al.* 2017) and orthostatic stress (*Lucas et al.* 2012, *Morrison et al.* 2014) in hot environment. However, since the application of positive pressure to the lower limbs during dynamic exercise at the light intensity in upright position has been shown to increase venous return and/or reduce venous pooling, enhancing cardiac output and mean arterial blood pressure (*Nishiyasu et al.* 1998), it is expected that the wearing GCS influence the circulatory responses to the short-term cycling exercise at the light-to-moderate intensity.

Thus, the purposes of this study were 1) to investigate the effect of wearing GCS on calf venous compliance at resting condition and 2) to clarify the circulatory responses to the light-to-moderate cycling exercise during wearing GCS.

Methods

Subjects

Participants were 10 healthy volunteers (7 men, 3 women) who were instructed not to consume caffeine for 24 h or food for 2 h before each experiment. Mean age, height, and weight was 20.9 ± 0.9 (SD) years, 167.2 ± 7.8 cm, and 61.4 ± 7.6 kg, respectively. Female subjects participated in this study in the follicular phase of the menstrual cycle (3-10 days after the onset of menstruation). The purpose, procedures, and risks of the study were explained to the subjects, and informed consent was obtained. This study was approved by the Human Ethics Committee of the Toyo University and was conducted in accordance with the Declaration of Helsinki.

Experimental design

Subjects visited our laboratory three times. In first day, the incremental cycling test was carried out in order to determine the exercise intensity that was used in the main experiments. In addition, venous compliance was also assessed in order to confirm whether wearing GCS increased calf venous compliance at resting condition. And in second and third days, the main experiment consisted of two trials performed on separate days in a counterbalanced manner (with an interval of at least 2 days) where participants undertook a cycling exercise while wearing either GCS or no stockings (Control: CON). We used commercially available GCS that induce a graduated pressure of 18 mmHg and 14 mmHg at the ankle and the calf, respectively (Ansilk-Pro J; ALCARE Co., Ltd., Tokyo, Japan) (Picture 1).

Picture 1 We used commercially available graduated compression stockings (GCS) was used in the present study.

Incremental cycling test

To determine the exercise intensity that was used in the main experiment, heart rate (HR) was measured using a heart rate monitor (Polar F11, Polar, kempele, Finland) during a submaximal incremental cycling test. Subjects were asked to pedal on a semi-reclining cycle ergometer (cordless bike V67Ri, Senoh, Chiba, Japan) at a constant frequency of 60 rpm for 3 min at four different exercise intensities. Using the work load and HR during a submaximal incremental cycling test and the estimated maximal HR (220-age), exercise intensity [30% and 60% heart rate reserve (HRR)] was estimated using the Karvonen Formula.

Assessment of venous compliance

To confirm that calf venous compliance at resting condition increased when subjects wore the GCS, the forearm and calf venous volume were also measured on a different day of main experiment. Subjects rested in the supine position with the left arm and left leg elevated above heart level. To measure changes in forearm and calf venous volume, the venous collecting cuff was wrapped around the left upper arm and left thigh, and a mercury strain gauge was placed on the forearm and calf at the sites of maximal thickness. Then the collecting cuff was inflated to 60 mmHg for 8 min, after which the cuff pressure was manually reduced at a rate of 1 mmHg/s from

60 mmHg to 0 mmHg (over 1 min) according to a previously described cuff deflation protocol (*Halliwill et al.* 1999). Throughout the cuff deflation protocol, changes in forearm and calf venous volume were measured noninvasively using a venous occlusion plethysmograph (EC4, D. E. Hokanson, WA, USA). All data on venous volume were recorded in a personal computer using a digital-to-analog converter (15BX, Dacs electpnics Co., Ltb, Okayama, Japan).

The relationship between cuff pressure and change in forearm and calf venous volume (i.e., the pressure-volume curve) was determined from data points for cuff pressures between 10 mmHg and 60 mmHg during the cuff deflation protocol. To avoid any *a priori* assumption regarding the pressure (P)-limb venous volume (V) curve and to obtain a physiologic venous compliance curve, venous compliance was calculated as the numerical derivative of each pair of pressure-venous volume data points with the following equation (*Freeman et al.* 2002).

$$\text{venous compliance}_{Pi} = \frac{V_i - V_{i-10}}{P_i - P_{i-10}} \text{ where } 20 \leq i \leq 60$$

In addition, venous capacitance was evaluated as the value of venous volume 8 min from the start of cuff inflation (0 mmHg) to 60 mmHg. Maximal venous outflow was calculated from the rate of change in venous volume for 1 min during deflation of cuff pressure from 60 to 0 mmHg.

Protocol of the main experiment

Subjects entered the experimental room, maintained at 26.2 ± 0.5 °C, and then rested on the semi-reclining cycle ergometer for at least 20 min. After baseline data was recorded for 5 min, each subject performed a cycling exercise at 30%HRR and 60%HRR for 5 min with an intervening recovery period for 5 min in a random order. A rest of at least 15 min was allowed between trials to allow HR to return to pre-exercise levels. Cycling exercise was carried out under two conditions (GCS and CON) on separate days.

Measurements

Systolic (SBP) and diastolic (DBP) arterial blood pressure from the left brachial artery was measured every 1.5 min by brachial auscultation, using a sphygmomanometer (KM-380, Kenzmedico, Saitama, Japan). Mean arterial pressure (MAP) was calculated as the DBP plus one-third of the pulse pressure. HR was monitored with the heart rate monitor and recorded every 1 min.

Forearm blood flow (FBF) from the right upper limb was evaluated every 15 s during baseline assessments, exercise, and recovery for last 2 min, using venous occlusion plethysmography with the aid of a mercury in silastic strain gauge (*Whitney* 1953). The forearm was supported and elevated above heart level. Pressure in the venous occlusion cuff was maintained at 40 mmHg. FBF was recorded 4 times each minute for a minimum of 10 s after the upper arm cuff was inflated. Forearm vascular resistance (FVR) was calculated as MAP divided by FBF.

Data analysis and statistics

For BP and HR, all data before exercise were averaged as baseline values. In addition, all data for FBF and FVR during baseline, exercise, and recovery periods were averaged as representative for each period. Data are expressed as the mean ± standard error (SE).

To compare the changes in cuff pressure between CON and GCS, a two-way analysis of variance (ANOVA) with repeated measures was applied to the venous volume and venous compliance obtained during cuff pressures of 10-60 mmHg under each condition (CON and GCS), using cuff pressure and condition as fixed factors. If a main effect of condition and/or interaction was detected, post hoc analysis with a paired t-test was performed every 10 mmHg. In addition, venous capacitance and maximal venous outflow were compared between CON and GCS using the paired *t*-test.

To compare the time-course changes between CON and GCS, a two-way ANOVA with repeated measures was applied to the parameters under CON and GCS, using time (baseline, exercise, and recovery) and condition as fixed factors. If a main effect of condition and/or interaction was detected, post hoc analysis with a paired t-test was performed. Statistical analysis was performed using SPSS software (version 19; IBM Corp., Armonk, NY, USA). P-value of < 0.05 was considered significant.

Results

Effect of wearing GCS on venous compliance in the calf and forearm at rest

Fig. 1 shows the effects of GCS on venous volume and venous compliance in the calf and the forearm at rest. The change in calf ve-

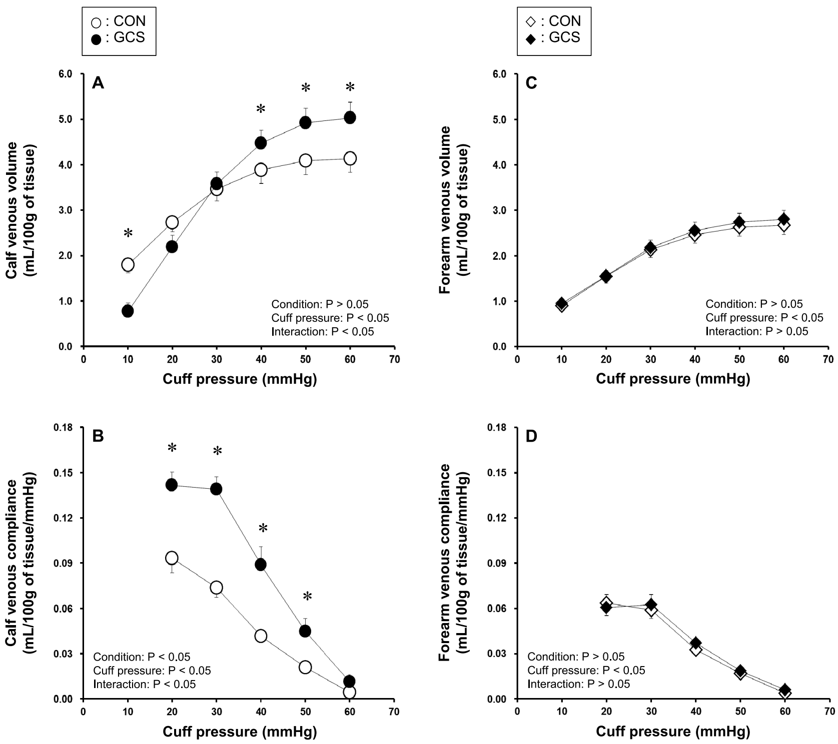

Fig. 1 Relationship of cuff pressure-venous volume and cuff pressure-venous compliance in the calf and the forearm with subjects wearing and not wearing graduated compression stockings (GCS and control: CON). Values are mean ± standard error (SE). * P < 0.05, significant difference between CON and GCS.

nous volume with the cuff pressure was steeper in GCS than CON (Fig. 1-A). ANOVA yielded a significant interaction effect ($P < 0.05$), and a post hoc test showed a significant difference in mean venous volume between CON and GCS at cuff pressures of 10, 40, 50, and 60 mmHg ($P < 0.05$). The change in calf venous compliance with cuff pressure was greater in GCS than CON (Fig. 1-B). ANOVA showed significant main and interaction effects ($P < 0.05$), and a post hoc test showed a significant difference in the mean values obtained between CON and GCS at cuff pressures below 50 mmHg. On the other hand, in the forearm, venous volume and venous compliance did not differ between CON and GCS (Fig. 1-C and D).

Furthermore, in the calf, both venous capacitance (4.71 ± 0.97 vs. 3.69 ± 0.28 mL/100 g of tissue, $P < 0.05$) and maximal venous outflow (4.94 ± 0.97 vs. 3.43 ± 0.95 mL/100 g of tissue/min, $P < 0.05$) were greater in GCS than CON, although these parameters in the forearm did not differ between conditions (venous capacitance in GCS and CON: 2.36 ± 0.20 vs. 2.29 ± 0.17 mL/100 g of tissue, maximal venous outflow in GCS and CON: 2.20 ± 0.68 vs. 2.04 ± 0.19 mL/100 g of tissue/min).

Effect of wearing GCS on circulatory responses during cycling exercise

At baseline, during cycling exercise at both 30%HRR and 60%HRR, and during the recovery period, there were no significant differences in time courses of SBP, DBP, MAP, and HR between CON and GCS (Fig. 2 and Fig. 3). In addition, the time courses of FBF

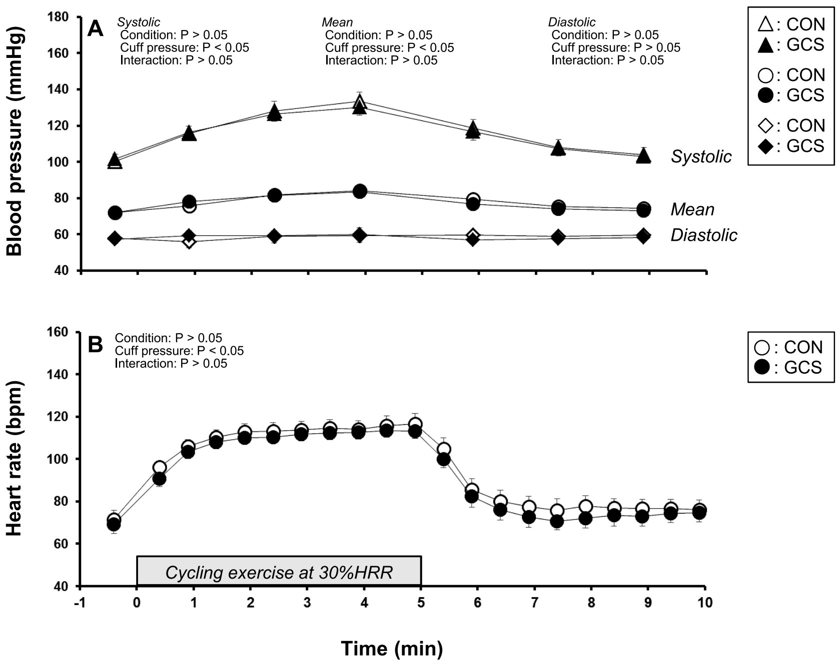

Fig. 2 Time courses of blood pressure and heart rate during cycling exercise at 30% heart rate reserve (HRR) and during recovery period under control conditions (CON) and with graduated compression stockings (GCS conditions). Values are mean ± standard error (SE).

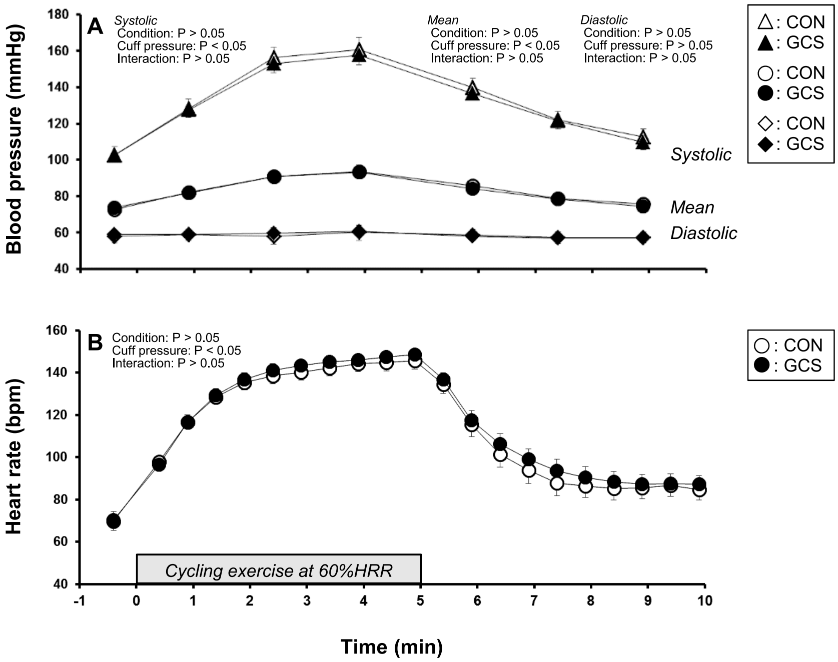

Fig. 3 **Time courses of blood pressure and heart rate during cycling exercise at 60%HRR and during the recovery period under control conditions (CON) and with graduated compression stockings (GCS conditions). Values are mean ± standard error.**

Table 1 **Forearm blood flow and forearm vascular resistance at baseline, during exercise and during recovery.**

		At baseline	During exercise	During recovery
			30%HRR	
Forearm blood flow, mL/100g of tissue/min	CON	2.65 ± 0.27	2.17 ± 0.33	2.96 ± 0.30
	GCS	3.36 ± 0.34	2.46 ± 0.29	3.69 ± 0.34
			*60%*HRR	
	CON	2.99 ± 0.40	2.02 ± 0.31	3.44 ± 0.50
	GCS	3.12 ± 0.30	1.92 ± 0.18	3.56 ± 0.42
			30%HRR	
Forearm vascular resistance, mmHg/mL/100g of tissue/min	CON	29.9 ± 3.1	44.6 ± 4.6	27.2 ± 2.7
	GCS	23.8 ± 2.7	38.1 ± 4.1	21.4 ± 2.1
			60%HRR	
	CON	27.8 ± 3.5	53.1 ± 5.7	25.9 ± 3.5
	GCS	25.3 ± 2.6	52.2 ± 5.2	23.7 ± 3.1

Values are means ± SE.

and FVR did not differ between conditions (Table 1).

Discussion

The primary findings in our study were that 1) wearing GCS caused an increase in venous compliance, venous capacitance, and maximal venous outflow in the calf, but did not change these variables in the forearm; and 2) the responses of BP, HR, FBF and FVR to exercise did not differ when wearing or not wearing GCS. These results suggest that the increase in calf venous compliance accompanied by wearing GCS did not influence the circulatory responses to cycling exercise in healthy young humans.

In present study, by wearing GCS, the venous compliance, venous capacitance and maximal venous outflow in the calf increased at resting condition (Fig. 1). This agreed with previous studies (*Agu et al.* 2004, *Hayata et al.* 2006, *Ibegbuna et al.* 2003). Two possibilities of the greater calf venous compliance during GCS might be speculated. One possibility is the elevation of venous external pressure by wearing GCS. Venous compliance is represented by the ratio of venous volume to transmural pressure which is difference between internal and external pressure in vein (*Rothe* 1983). It means that venous compliance is greater as the transmural pressure is smaller when venous volume is constant or increased. In present study, it might be speculated that wearing GCS caused the mechanical compression of the calf and the secondary elevation of venous external pressure, so that the decreased transmural pressure and the increased venous volume (Fig. 1-A) might be obtained. Another possibility is that enhanced shift of blood and/or interstitial fluid from peripheral to central sites could influence the venous compliance (*Louisy et al.* 1997). In our study, the compression from skin surface by wearing GCS might shift blood of capillaries and superficial veins and interstitial fluid to the truncus, which could improve the balance between hydrostatic pressure and colloid osmotic pressure and the balance between filtration and resorption in capillaries, so that calf venous compliance increased during GCS.

On the other hand, the forearm venous compliance was not changed by wearing GCS in present study. It is unlikely that the elevated external venous pressure and shift of blood and/or interstitial fluid were observed in the forearm in our study because the forearm was not compressed by wearing GCS, resulting in similar forearm venous compliance between GCS and CON.

The circulatory responses to cycling exercise did not differ between CON and GCS conditions in our study (Fig. 2, Fig. 3 and Table 1). These results did not support our hypothesis. Although we had no certain idea, two reasons might be peculated. First, wearing GCS in healthy young subjects might not enhance venous return when compared with CON. GCS are thought to assist the skeletal-muscle pump and possibly enhance venous return (*Mayberry et al.* 1991), and GCS decrease blood pooling in the lower limbs and enhance venous return when patients with venous disorders are upright or walking (*Agu et al.* 2004, *Ibegbuna et al.* 2003). On the other hand, it was reported that healthy subjects such as athletes already have an adequate blood flow from the lower leg to the heart during exercise even in the absence of GCS (*Kuipers et al.* 1989). Second, the greater calf venous compliance during wearing GCS at rest might not be eliminated during exercise because of the elevated internal venous pressure which is due to the exercise-induced pressor response and the increased pressure in the capillaries via vasodilation (*Takamata et al.* 2000) and/or the expansion of active muscular tissue (*Convertino et al.* 1981, *Sjogaard et al.* 1982) during exercise.

In conclusion, to clarify the effect of increased calf venous compliance on circulatory responses to exercise, we investigated changes in HR, BP, FBF and FVR during cycling exercise with and without GCS. We found that these variables did not differ between conditions. These results suggest that the increase in calf venous compliance with wearing GCS might not influence circulatory responses during short-term cycling exercise at light-to-moderate workload in healthy young humans.

Conflict of Interest

The authors have no financial conflicts of interest to declare.

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