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Effects of Prolonged Sitting with or without Elastic Garments on Limb Volume, Arterial Blood Flow, and Muscle Oxygenation

YUKO KUROSAWA[1,2], SHINSUKE NIRENGI[3,4], IZUMI TABATA[2], TADAO ISAKA[2], JOSEPH F. CLARK[5], and TAKAFUMI HAMAOKA[1]

[1]Department of Sports Medicine for Health Promotion, Tokyo Medical University, Shinjuku-ku, Tokyo, JAPAN; [2]Faculty of Sport and Health Science, Ritsumeikan University, Kusatsu, JAPAN; [3]Department of Physiology and Cell Biology, Dorothy M. Davis Heart and Lung Research Institute, The Ohio State University Wexner Medical Center, Columbus, OH; [4]Division of Preventive Medicine, Clinical Research Institute, National Hospital Organization Kyoto Medical Center, Kyoto, JAPAN; and [5]Department of Neurology, University of Cincinnati, Cincinnati, OH

ABSTRACT

KUROSAWA, Y., S. NIRENGI, I. TABATA, T. ISAKA, J. F. CLARK, and T. HAMAOKA. Effects of Prolonged Sitting with or without Elastic Garments on Limb Volume, Arterial Blood Flow, and Muscle Oxygenation. *Med. Sci. Sports Exerc.*, Vol. 54, No. 3, pp. 399–407, 2022. **Purpose:** The physiological response induced by acute prolonged sitting is not fully understood. Therefore, we examined the effects of 8-h constant sitting on microcirculation and associated factors in the lower extremity among healthy males. We also evaluated the protective effects of lower-pressure thigh-length elastic compression garments on these parameters. **Methods:** Nine healthy males (age, 22.6 ± 1.4 yr; body mass index, 22.4 ± 1.8 kg·m^{-2}) completed the 8-h constant sitting experiment. Following baseline measurements, each subject was randomized to wear a lower-pressure elastic garment on the right or left leg from the inguinal region to the ankle joint, with the noncompressed contralateral leg as a control. Circumferences of the calf and malleolus, extracellular water contents, blood flow and shear rate of the dorsal metatarsal artery, and oxygen dynamics in the gastrocnemius muscles were measured in both extremities before and during 8-h constant sitting. **Results:** Compared with baseline values, 8-h constant sitting caused enlargement of circumferences (calf, 2.4% ± 0.7%; malleolus, 2.7% ± 1.4%), retention of extracellular water in lower extremity muscles (10.1% ± 1.78%), deterioration of the blood flow (61.4% ± 16.2% of baseline) and shear rate of the dorsal metatarsal artery, and decrease in oxygenated hemoglobin and total hemoglobin levels in the gastrocnemius muscle ($P < 0.05$, respectively). When subjects wore the lower-pressure thigh-length compression garment, a significant reduction of these effects was observed ($P < 0.05$, for all). **Conclusions:** Prolonged sitting for 8 h induced edema, as well as deterioration of the arterial blood flow, shear rate, and microcirculation in lower limb muscles. Conversely, application of the lower-pressure elastic garment successfully prevented the pathophysiological deterioration associated with prolonged sitting. **Key Words:** 8-H CONSTANT SITTING, MUSCLE MICROCIRCULATION, NEAR-INFRARED TIME-RESOLVED SPECTROSCOPY, SHEAR STRESS, GASTROCNEMIUS MUSCLE

Epidemiological evidence suggests that sedentary behavior is significantly associated with all-cause mortality and the incidence of various diseases (1,2). Time spent in sedentary behavior has recently increased, particularly in developed countries (3), and work from home because of the COVID-19 pandemic has now accelerated this trend worldwide (4). The time at which prolonged sitting drastically deteriorates health outcomes is yet to be determined. However, a meta-analysis of prospective cohort studies demonstrated that a threshold of 6–8 h·d^{-1} of sitting increases the risk of all-cause and cardiovascular disease mortality (5), whereas prolonged sitting for >8 h·d^{-1} increased in a prospective cohort study the risk of all-cause mortality within the following 9 yr in older women (6). Acute prolonged sitting also has health impacts and may even be fatal, for instance, due to venous thromboembolism (VTE) after long-distance flights (7,8). Chandra et al. (9) have concluded that air and other forms of travel are associated with VTE risk in a time-dependent manner. Furthermore, Morio et al. (10) reported

Address for correspondence: Takafumi Hamaoka, M.D., Ph.D., Department of Sports Medicine for Health Promotion, Tokyo Medical University, 6-1-1 Shinjuku, Shinjuku-ku, Tokyo 160-8402, Japan; E-mail: kyp02504@nifty.com.
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that 35 of 36 patients with air travel–associated acute VTE had flown more than 8 h. Based on the aforementioned studies, we have chosen 8 h of sitting for the induction of pathophysiological changes in humans. To date, the effects of uninterrupted 8-h sitting on circumference, arterial blood flow, and tissue oxygenation in lower limbs have not been examined systematically.

The sitting posture promotes reductions in blood flow and flow-mediated dilation in the lower extremity (11–13). It is assumed that the sitting-induced decrease in blood flow and flow-mediated dilation reduces oxygen availability and substrate exchanges in peripheral tissues. However, evidence regarding the effects of acute prolonged sitting on microcirculation and oxygenation in peripheral tissues of the lower extremity in healthy young adults is still lacking. Near-infrared spectroscopy is a technique applied to noninvasively monitor oxygenated hemoglobin ([oxy-Hb]), deoxygenated hemoglobin ([deoxy-Hb]), and hemodynamics *in vivo*. Near-infrared time-resolved spectroscopy (NIR_{TRS}) allows for the repeated quantitative comparison of muscle oxygenation and hemodynamics within and between subjects by measuring absolute values of oxygenated and deoxygenated hemoglobin (14,15). Hence, we applied NIR_{TRS} to quantitatively evaluate changes in muscle oxygenation and hemodynamics in lower extremities during an 8-h constant sitting task.

Although deep vein thrombosis (DVT) is a common vascular disorder not only among hospitalized patients but also in the general population, with an annual incidence of 0.1% (16), present DVT protective measures are limited. External lower extremity compression is among the promising strategies for DVT prevention in high-risk groups such as pregnant women or the elderly (17). In patient populations with peripheral vascular pathologies such as diabetes and congestive heart failure, the use of compression garments of the lower extremities has a long history of slowing the progression of these diseases. However, a Cochrane review pointed out that there remains a paucity of evidence to verify the effectiveness of these garments (18); further evidence concerning the use of compression garments is required to mitigate pathophysiological effects in the peripheral vasculature of otherwise healthy individuals. Furthermore, most studies evaluated the efficacy of under-knee graduated compression garments applying the greatest pressure on the ankle and gradually lowering the pressure toward proximal regions of the leg with a pressure of 20 mm Hg (26.7 hPa) applied to the ankle joint (17). The effectiveness of nongraduated, lower-pressure thigh-length garments, similar to those we used, in preventing the deterioration of peripheral vasculature and muscle oxygenation parameters in the lower extremities, remains to be investigated.

The objective of this study was to test the hypothesis that acute 8-h uninterrupted sitting deteriorates muscle oxygenation in the lower extremity with concomitant blood flow reduction and edema, and that nongraduated elastic garment applying relatively low pressure successfully prevents these effects.

METHODS

Nine healthy men (age, 22.6 ± 1.4 yr; height, 168.8 ± 6.8 cm; body weight, 63.8 ± 6.9 kg; body mass index, 22.4 ± 1.8 $kg \cdot m^{-2}$; %body fat, 15.2% ± 5.7%) participated in this study. Subjects were recreationally active, normotensive nonsmokers with no medication or clinical history of DVT or cardiovascular and metabolic diseases. The same researchers performed all procedures using identical techniques. All experimental procedures and measurements conformed to the Declaration of Helsinki and were approved by the Institutional Review Board of Ritsumeikan University (No. BKC-IRB-2013-038). All subjects were fully informed of all procedures and their potential risks and provided written informed consent before participating in this study.

Experimental procedures. A schematic representation of the study design appears in Figure 1 illustrating the sequence of events. Participants were instructed to refrain from any exercise, alcohol, and caffeine 24 h before the trial. Subjects were 2 h postprandial of a light meal upon arrival to the laboratory before 8:00 AM. All experiments were performed in a temperature-controlled room kept at 22°C ± 1°C. Baseline measurements of extracellular water content in lower extremities, circumferences of the calf and malleolus, blood flow of the dorsal metatarsal artery, and oxygen dynamics in the gastrocnemius muscles in both legs were carried out at 8:00–9:00 AM to minimize potential diurnal variations. All investigations were performed every hour until the 8-h sitting task had been completed, excluding body composition, which was measured before and after the 8-h sitting period. Following the baseline measures, each subject wore an elastic garment (Elaction Pro®; Asahi Kasei Corp., Tokyo, Japan) on one randomly chosen leg from the inguinal region through the ankle joint, with the noncompressed contralateral leg as a control. The elastic garment used in this study was developed for athletes, and its compression pressure was designed as 3:4:3 (~15:~20:~15 hPa) for ankle/calf/thigh (19). Of the nine study participants, four and five subjects wore an elastic garment on their right and left legs, respectively. After the application of the elastic garment, the subjects were seated in comfortable chairs (width, 46 cm; back angle, 110°) mimicking aircraft seats. Subjects were instructed to refrain from any leg movement throughout the 8-h sitting task, and all measurements during this period were performed in a sitting position with the knee flexed at 90°. The participants went to the lavatory *ad libitum* in a movable chair escorted by study personnel. During the experiment, the timing and quantity of caloric intake were identical among subjects, and the volume of *ad libitum* water intake was recorded in each subject (833.3 ± 106.1 mL during the 8-h sitting period). Subjects were asked to report any symptoms or signs of VTE during the experiment. All subjects completed the experiment.

Lower limb circumferences. Circumferences of the calf and malleolus were manually measured in both legs by a single researcher, with the participant in a sitting position and the knee flexed at 90°. The circumference of the calf was measured at the widest point of the lateral head of the gastrocnemius muscle, and the circumference of the malleolus was measured at the location with the maximal value. The researcher marked both locations with flexible colored tape to ensure repeat measurements at the same position. In legs wearing the elastic garment, the researcher measured for baseline assessment the circumferences

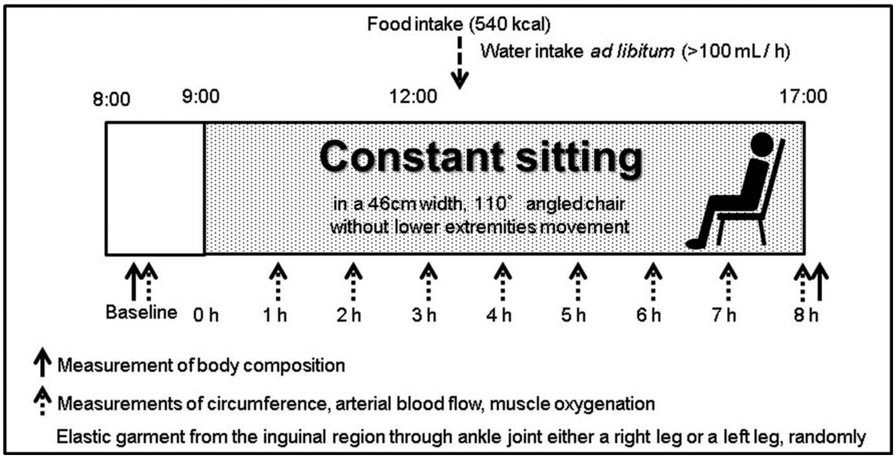

FIGURE 1—Schematic diagram of the experimental procedures. Measurements were taken at baseline and after 1, 2, 3, 4, 5, 6, 7, and 8 h while the subject was in a seated position without lower extremities movement. Following the baseline measurement, each subject was randomized into wearing a lower-pressure elastic garment either on the right or left leg from the inguinal region to the ankle joint.

of both the calf and the malleolus before and immediately after the garment had been worn. Measurements were performed three times at each location and time point, and the average value was used. The calf and the malleolus in both legs were not compressed by the chair throughout the 8-h sitting period.

Extracellular water content in lower extremities. The extracellular water content in lower extremities was assessed before and after the 8-h constant sitting period using multifrequency bioelectrical impedance measurements with eight tactile electrodes (InBody 720; Biospace, Tokyo, Japan). Extracellular water content in the lower extremity muscles was calculated as follows:

$$\text{muscle volume in the lower extremity} \times 0.78 \times \text{extracellular water content/total water content ratio in the lower extremity,}$$

where the factor 0.78 represents the water content inside the muscles as 78% (20,21).

Blood flow: Doppler ultrasonography. The mean blood flow velocity (V_{mean}) and vessel diameter of the dorsal metatarsal artery were measured using Doppler and B-mode ultrasound imaging (Vivid S6; GE Healthcare, Tokyo, Japan), performed by the same researcher. A 10-MHz linear array transducer was placed on the skin over the first dorsal metatarsal artery 1 cm downstream from the bifurcation with deep plantar artery. The sampling volume was maintained at 4.5 mm, and the angle of the beam used to determine the direction of the blood flow was automatically adjusted to 60°. The diameter of the blood vessel considering the relative time periods of the systolic (1/3) and diastolic (2/3) phases of the cardiac cycle was assumed to be the most representative diameter size in each cardiac cycle (22). The arterial diameters in each frame were measured using the distance-measuring system integrated into the Vivit S6, and mean values of 3 frames at each time point were calculated to determine the cross-sectional area of the vessel (area = πr^2, where r is the radius of the vessel). The beat-to-beat blood flow of the dorsal metatarsal artery was calculated by multiplying V_{mean} and πr^2. The shear rate was calculated as follows:

$$4 \times \text{mean blood velocity/diameter.}$$

Tissue oxygenation: NIR$_{\text{TRS}}$. Tissue oxygenation was measured using a NIR$_{\text{TRS}}$ unit (TRS-20; Hamamatsu Photonics, Hamamatsu, Japan) with the distance between the emitter and detector set at 3.0 cm, providing approximately 4-cm^3 measurement volume (23,24). The NIR$_{\text{TRS}}$ signal noninvasively monitors absolute concentration changes in [oxy-Hb], [deoxy-Hb], and their sum as total hemoglobin [total-Hb], an index of the blood volume. The principle of this system has been previously described in detail (14,15). Briefly, the absolute concentrations of [deoxy-Hb], [oxy-Hb], and [total-Hb], as well as the tissue oxygen saturation (SO_2), can be determined using three wavelengths as follows:

$$[\text{deoxy}-\text{Hb}] = \left(\varepsilon_1{}^{\lambda 2}{}_{\mu a}{}^{\lambda 1} - \varepsilon_1{}^{\lambda 1}{}_{\mu a}{}^{\lambda 2}\right) / \left(\varepsilon_2{}^{\lambda 1}\varepsilon_1{}^{\lambda 2} - \varepsilon_2{}^{\lambda 2}\varepsilon_1{}^{\lambda 1}\right) \quad [1]$$

$$[\text{oxy}-\text{Hb}] = \left(\varepsilon_2{}^{\lambda 1}{}_{\mu a}{}^{\lambda 2} - \varepsilon_2{}^{\lambda 2}{}_{\mu a}{}^{\lambda 1}\right) / \left(\varepsilon_2{}^{\lambda 1}\varepsilon_1{}^{\lambda 2} - \varepsilon_2{}^{\lambda 2}\varepsilon_1{}^{\lambda 1}\right) \quad [2]$$

$$[\text{total}-\text{Hb}] = [\text{deoxy}-\text{Hb}] + [\text{oxy}-\text{Hb}] \quad [3]$$

$$SO_2\ (\%) = [\text{oxy}-\text{Hb}] \times 100/[\text{total}-\text{Hb}] \quad [4]$$

where $\varepsilon 1^{\lambda 1}$ ($\varepsilon 1^{\lambda 2}$) and $\varepsilon 2^{\lambda 1}$($\varepsilon 2^{\lambda 2}$) are the extinction coefficient of oxy-Hb at wavelength λ1 (λ2) and the extinction coefficient of [deoxy-Hb] at wavelength λ1 (λ2), respectively. The parameters [deoxy-Hb], [oxy-Hb], [total-Hb], and SO_2 were calculated according to equations 1 to 4, respectively. At each time point, the NIR$_{\text{TRS}}$ system measured the [deoxy-Hb], [oxy-Hb], [total-Hb], and SO_2 every 10 s for 5 min in the lateral head of the gastrocnemius muscle. The probe was firmly attached to the belly of the lateral gastrocnemius head to reduce movement artifacts and was protected from ambient light. In the garment legs, the probe was attached through a small hole of 3 mm in diameter in the garment just over the belly of the lateral gastrocnemius head.

The coefficients of variation for repeated measurements of [oxy-Hb], [deoxy-Hb], and [total-Hb] were 4.7%, 7.5%, and 4.9%, respectively (25).

Statistical analyses. Our sample size was based on the number of participants needed to detect an acute effect of sitting on muscle oxygenation in the lower extremities. We assumed these effects were the premise for evaluating relationships among oxygen availability in peripheral tissues, water retention, and reduction of arterial blood flow in lower extremities due to prolonged sitting. We calculated the sample size using the G*Power software (Version 3.1; Bonn University, Bonn, Germany), based on our previous work evaluating the changes in [oxy-Hb] in calf muscles of men before and after 3-h uninterrupted sitting (19). Using an 80% power and 95% confidence level, nine participants were required to detect a significant change in [oxy-Hb] in calf muscles due to prolonged sitting (critical $t = 1.833$, $P < 0.05$).

Data were analyzed in three stages. First, Wilcoxon's rank sum test was used for statistical analysis of the percent changes in extracellular water content in lower extremity muscles after the 8-h constant sitting period, and legs with and without elastic garments were compared. Second, the effects of 8-h uninterrupted sitting on calf and malleolus circumferences, blood flow and shear rate of the dorsal metatarsal artery, and oxygen kinetics in the lateral head of the gastrocnemius muscle were compared regarding elastic garment use (with garment vs without garment) and time (at baseline vs after 1, 2, 3, 4, 5, 6, 7, and 8 h of sitting) using the repeated two-way ANOVA, followed by Bonferroni's multiple comparisons tests, if necessary. The effects of 8-h constant sitting on the extracellular water content in lower extremity muscles were compared regarding elastic garment use (with garment vs without garment) and time (at baseline vs after 8 h of sitting) using the repeated two-way ANOVA. Third, Spearman's correlation analysis was performed to determine the relationships of the rate of changes in calf circumference with the rate of changes in extracellular water content in lower extremity muscles and the rate of changes in blood flow of the dorsal metatarsal artery after 8-h constant sitting. The relationship between the rate of changes in malleolus circumference and that in blood flow of the dorsal metatarsal artery was also analyzed.

Data are represented as the mean ± SD. Statistical analyses were performed using SPSS version 26 (IBM SPSS Japan, Tokyo, Japan), and the level of statistical significance was set at <5% for all tests.

RESULTS

All subjects completed the study. No clinically evident VTE was reported during the experiment.

Circumferences. During the sitting period, circumferences both in the calf and malleolus were progressively enlarged in the control legs ($P < 0.05$, respectively; Figs. 2A, B). Conversely, no significant change was observed in the legs wearing the lower-pressure thigh-length elastic garment (Figs. 2A, B).

Extracellular water content in lower extremity muscles. Body composition analysis revealed a significant increase in extracellular water content in the lower extremity muscles after 8-h constant sitting, both in the control and garment legs (control: 2.41 ± 0.32 to 2.65 ± 0.34 L, garment: 2.43 ± 0.32 to 2.59 ± 0.32 L, $P < 0.05$, respectively). However, the percent changes in extracellular water content of lower extremity muscles after the 8-h sitting were significantly higher in the control legs compared with the garment legs (control: 10.1% ± 1.8%, garment: 6.5% ± 1.9%, $P < 0.05$; Fig. 2C). Furthermore, after 8-h constant sitting, changes in the extracellular water content of lower extremity muscles were positively correlated with changes in the calf circumference ($r = 0.57$, $P < 0.05$; Fig. 2D). These results indicate that enlargement in lower thigh circumferences due to 8-h constant sitting was closely related to the accumulation of extracellular water. Alternatively, external compression induced by lower-pressure thigh-length elastic garment reduced the retention of extracellular water and successfully prevented the enlargement of circumferences during the 8-h sitting period.

Arterial blood flow. The control legs exhibited a significantly lower blood flow of the dorsal metatarsal artery during the 8-h constant sitting compared with the elastic garment legs ($P < 0.05$; Fig. 3A, Table 1). The shear rate, an estimate of shear stress without blood viscosity, was also significantly lower in the control legs than in the garment legs during the 8-h constant sitting ($P < 0.05$; Fig. 3B). Changes in blood flow of the dorsal metatarsal artery were also negatively correlated with changes in circumferences of the calf ($r = -0.73$, $P < 0.05$; Fig. 3C) and malleolus ($r = -0.61$, $P < 0.05$; Fig. 3D) after 8-h constant sitting.

Tissue oxygenation. In the lateral heads of gastrocnemius muscles, the changes in [oxy-Hb] and [total-Hb] levels decreased significantly in the control legs ($P < 0.05$, respectively; Figs. 4A, C) during 8-h constant sitting, whereas no significant difference was recorded in the legs with the elastic garment (Figs. 4A, C). Moreover, the changes in [oxy-Hb], [total-Hb], and SO_2 were higher in the legs with elastic garment than in the control legs ($P < 0.05$, respectively; Figs. 4A, C, D). However, the changes in [deoxy-Hb] were not different between the control and elastic garment legs (Fig. 4B). The optical path length of 800 nm during the 8-h constant sitting increased both in the control and garment legs (Table, Supplemental Digital Content 1, Near-infrared time-resolved spectroscopy response to 8-h constant sitting with or without an elastic garment, http://links.lww.com/MSS/C453).

DISCUSSION

Previous evidence suggests that prolonged sitting may reduce oxygen availability via reduction of arterial blood flow in peripheral tissues. The purpose of this study was to demonstrate the effects of an 8-h constant sitting task on muscle oxygen dynamics and associated factors in the lower extremities in healthy young men. In addition, the efficacy of lower-pressure elastic garments on those factors during the 8-h sitting period was evaluated. The main findings of this study were that 8-h uninterrupted sitting

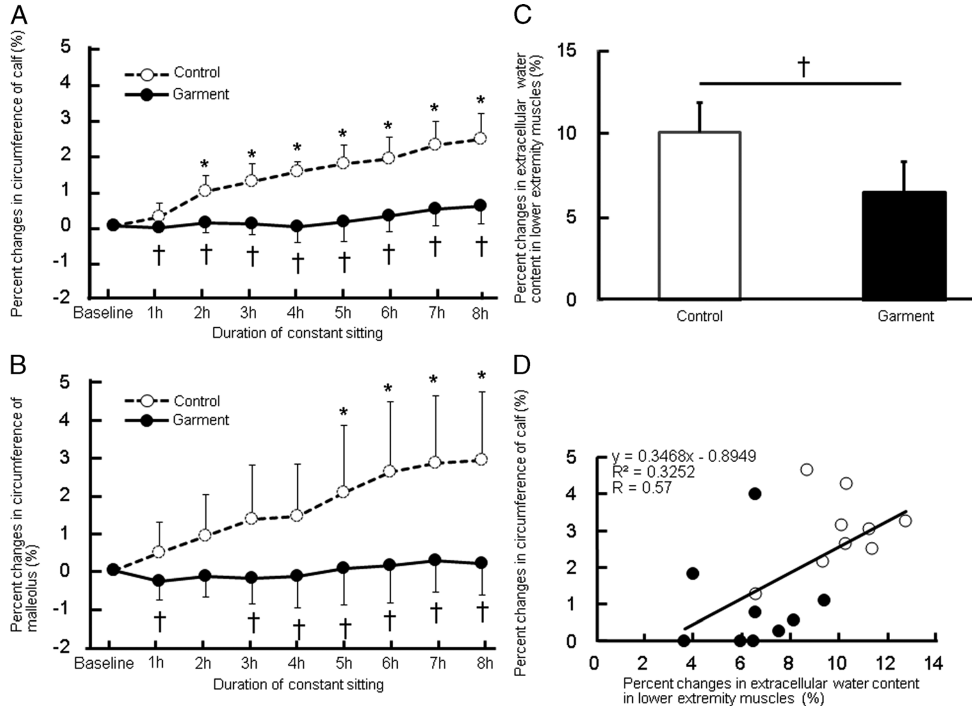

FIGURE 2—Circumferences and extracellular water in lower extremity. Percent changes in circumferences of the calf (A) and the malleolus (B) in the control (without garment, *open symbols*) and garment (*closed symbols*) legs before and during 8 h of constant sitting. C, Percent changes in extracellular water content of lower extremity muscles in the control (*open bar*) and garment (*closed bar*) legs after 8-h constant sitting. D, Correlation between percent changes in extracellular water content of lower extremity muscles and percent changes in calf circumferences in the control (*open symbols*) and garment (*closed symbols*) legs after 8-h constant sitting. A–C, Group data expressed as the mean ± SD. D, Individual data of nine healthy males. A, B, Significance for an effect of sitting time (baseline vs 1, 2, 3, 4, 5, 6, 7, and 8 h of sitting) or elastic garment (with or without) was quantified with a two-way ANOVA for repeated measures, followed by Bonferroni *post hoc* testing as appropriate. C, Wilcoxon's signed-rank test was performed between the control and garment legs. D, Spearman correlations between changes in extracellular water content of lower extremity muscles and changes in calf circumferences after 8-h constant sitting were determined. *$P < 0.05$ between baseline and each time point of sitting within a group; †$P < 0.05$ between the control and the garment leg at the same time point.

resulted in 1) a significant retention of extracellular water in the lower limb muscles, 2) enlargement of the calf and malleolus circumferences, 3) deterioration of the blood flow and shear rate of the dorsal metatarsal artery, and 4) decrease in the levels of [oxy-Hb] and [total-Hb] in the lateral heads of the gastrocnemius muscles. In addition to the changes in calf circumference, we observed a positive correlation with the changes in extracellular water content in lower extremity muscles and a negative correlation with the changes in the blood flow of the dorsal metatarsal artery. The results of this study indicate a reduction of the blood flow and shear rate, and blunted oxygen diffusion and substance exchange in peripheral tissues during the 8-h sitting period. Moreover, the lower-pressure elastic garment provided protection against these effects.

In this study, circumferences in the limbs increased (Figs. 2A, B) and the changes in extracellular water content in the lower extremity muscles had positive correlations with the changes in the calf circumference after the 8-h sitting (Fig. 2D). These results indicate that retention of interstitial fluid in the lower limbs progressed during the 8-h sitting period. This is consistent with previous findings by Winkel and Jørgensen reporting that the foot volume of healthy subjects increased more during 8 h of seated work compared with 4 h of seated work (26). In this study, the percent circumference changes due to 8-h constant sitting were similar for the calf and the malleolus (Figs. 2A, B). The calf volume is largely determined by the gastrocnemius muscle, but tendons of other muscles (tibialis anterior, tibialis posterior, flexor pollicis longus, flexor digitorum longus, peroneus longus, peroneus brevis, extensor digitorum longus) also contribute to the shape of the malleolus. Furthermore, the malleolus region may have been affected more by gravity-dependent changes than the calf during the 8-h constant sitting period. This may explain the similar changes in circumferences of the malleolus and the calf in this study. It is generally accepted that retention of venous blood and marked increase in capillary pressure in the lower extremities lead to substantial filtration of blood plasma into the interstitial space. Prolonged sitting causes the continuous filtration of plasma into the interstitial space and insufficient reabsorption of interstitial fluid via the venous/lymphatic system induces edema (27).

The arterial blood flow and shear rate of the dorsal metatarsal artery were significantly reduced after 8-h constant sitting (Figs. 3A, B). A reduction of blood flow and shear rate impairs endothelium function (28–31). In human subjects, several studies reported a simultaneous reduction of blood flow, shear rate, and endothelial dysfunction after 3–6 h of constant sitting (11–13). This is one of the several mechanisms of blood clot formation caused by prolonged sitting; here, impairment of the endothelial function of lower limb vessels may have occurred after 8-h constant sitting. Compromised peripheral circulation influenced

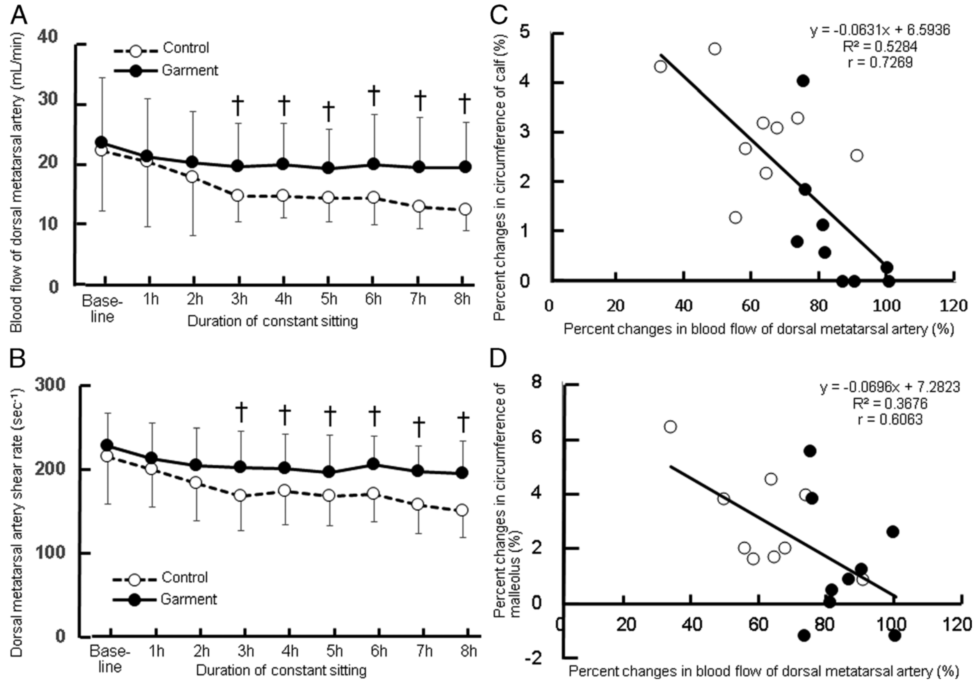

FIGURE 3—Arterial blood flow and shear rate. Blood flow (A) and shear rate (B) of the dorsal metatarsal artery in the control (without garment, *open symbols*) and garment (*closed symbols*) legs as measured by Doppler ultrasonography before and during 8-h constant sitting. C and D, Correlations of percent changes in blood flow of the dorsal metatarsal artery with percent changes in the circumferences of the calf (C) and malleolus (D) in the control (*open symbols*) and garment (*closed symbols*) legs after 8-h constant sitting. A and B, Group data expressed as the mean ± SD, C and D, individual data of nine healthy males. A and B, Significance for an effect of sitting time (baseline vs 1, 2, 3, 4, 5, 6, 7, and 8 h of sitting) or elastic garment (with or without) was quantified with a two-way ANOVA for repeated measures, followed by Bonferroni *post hoc* testing as appropriate. C and D, Spearman correlations of changes in blood flow of the dorsal metatarsal artery with changes in calf (C) and malleolus (D) circumferences after 8-h constant sitting were determined. **P* < 0.05 between baseline and each time point of sitting within a group; †*P* < 0.05 between the control and garment legs at the same time point.

muscle microcirculation and particularly oxygen delivery, as evidenced by the decrease in [oxy-Hb] and [total-Hb] in the lateral heads of gastrocnemius muscles (Figs. 4A, C). In addition to the reduction in oxygen delivery, the increased oxygen diffusion distance from capillaries to peripheral tissues in lower limb muscles due to edema is another risk of hypoxia-induced thrombosis. Although a blood flow reduction may induce the impairment of endothelial function, making the endothelium more susceptible to coagulation, the degree of decrease in [oxy-Hb], or oxygenation itself, required to induce blood clot formation remains unclear. Zderic and Hamilton (32) showed that in humans, lipid phosphate phosphatase-1 (*LPP1*), a key gene for degrading prothrombotic and proinflammatory lysophospholipids, is locally suppressed in muscle tissue after 12-h sitting. The relationship between *LPP1* gene expression and oxygen status inside muscle tissues remains unclear in Zderic and Hamilton's report; however, the *LPP1* mRNA transcript level is affected under acute hypoxic conditions (33). Zderic and Hamilton indicated that, apart from being a pumping contractile machinery, skeletal muscles exert important paracrine and endocrine functions for thrombosis/thrombolysis. Subjects in this study were instructed to refrain from any leg movement throughout the 8-h sitting period, and altered expression of genes related to thrombosis may have been induced in peripheral muscle tissues during the 8-h constant sitting period. Further research will clarify the connection between the reduction of blood flow, shear rate, and muscle oxygenation caused by acute prolonged sitting and thrombosis.

The elastic garment used in clinical practice, commonly an under-knee stocking, is a graduated compression garment. To facilitate venous return, the highest pressure (20 mm Hg = 26.7 hPa)

TABLE 1. Dorsal metatarsal artery response to the 8-h constant sitting without or with elastic garment.

		Baseline	1 h	2 h	3 h	4 h	5 h	6 h	7 h	8 h
Diameter, cm	Without garment leg	0.21 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.03	0.19 ± 0.03	0.19 ± 0.03	0.19 ± 0.02	0.19 ± 0.02	0.19 ± 0.02
	With garment leg	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04
Velocity, $cm \cdot s^{-1}$	Without garment leg	10.6 ± 1.3	9.9 ± 1.7	8.9 ± 1.5	8.0 ± 1.0*	8.2 ± 1.0*	8.0 ± 0.9*	8.0 ± 1.2*	7.4 ± 1.2*	7.1 ± 1.0*
	With garment leg	11.3 ± 1.4	10.4 ± 1.2	10.0 ± 1.3	9.8 ± 1.1†	9.8 ± 0.8†	9.6 ± 0.9†	10.0 ± 1.1†	9.7 ± 1.0†	9.6 ± 0.9†
ΔBlood flow, %	Without garment leg	100.0 ± 0.0	90.7 ± 10.4	80.2 ± 13.4	70.9 ± 14.5	71.8 ± 15.2	69.8 ± 14.5	68.8 ± 14.9	63.5 ± 16.5	61.4 ± 16.2
	With garment leg	100.0 ± 0.0	91.6 ± 5.6	88.0 ± 8.0	86.2 ± 9.5†	88.1 ± 9.4†	86.0 ± 10.5†	86.6 ± 8.0†	84.4 ± 9.3†	84.9 ± 10.3†

Data are expressed as mean ± SD. Significance for an effect of sitting time (baseline vs 1, 2, 3, 4, 5, 6, 7, 8 h of sitting) or elastic garment (without or with) was quantified with a two-way ANOVA for repeated measures, followed by, when appropriate, Bonferroni *post hoc* testing was conducted.

* *P* < 0.05 between baseline and sitting within group.

† *P* < 0.05 between without garment leg and with garment leg at the same time point.

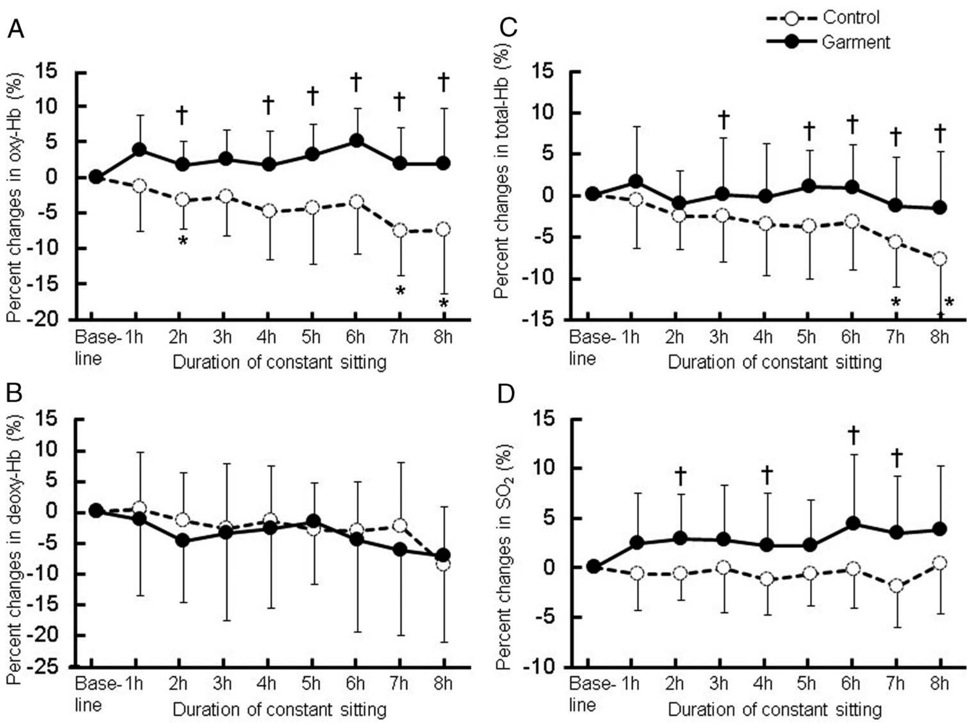

FIGURE 4—NIR_{TRS} parameters. Changes in [oxy-Hb] (A), [deoxy-Hb] (B), [total-Hb] (C), and SO_2 (D) in the lateral heads of gastrocnemius muscles in the control (without garment, *open symbols*) and garment (*closed symbols*) legs as measured by NIR_{TRS} before and during 8-h constant sitting. Data are expressed as the mean ± SD in nine healthy males. Significance for an effect of sitting time (baseline vs 1, 2, 3, 4, 5, 6, 7, and 8 h of sitting) or elastic garment (with or without) was quantified with a two-way ANOVA for repeated measures, followed by Bonferroni *post hoc* testing as appropriate. *$P < 0.05$ between baseline and each time point of sitting within a group; †$P < 0.05$ between the control and garment legs at the same time point.

is applied to the ankle and gradually lowered toward the proximal leg (17). In contrast, we examined the physiological changes of an elastic thigh length nongraduated garment with a lower pressure (15 hPa) at the ankle level than the pressure recommended by current guidelines (17) during the 8-h constant sitting. As expected, the lower-pressure elastic garment reduced water retention in lower limb muscles (Fig. 2C) and prevented significant changes in lower limb circumferences of the calf and the malleolus (Figs. 2A, B) during the 8-h constant sitting period. Moreover, the nongraduated lower-pressure thigh-length garment suppressed the decrease in peripheral arterial blood flow (Fig. 3A) and shear rate (Fig. 3B), whereas the oxygenation level in the peripheral muscles of the lower extremity was maintained during the 8-h sitting period (Figs. 4A, C, D). These results strongly indicate that in healthy individuals, nongraduated, lower-pressure, thigh-length elastic garments protect against physiological deterioration induced by prolonged sitting. These data may be helpful for elderly patients because the compliance rate of wearing a compression garment is very low (26%) among outpatients due to the tightness and poor fit of these garments (34). Unwanted effects like dermatitis may also occur when wearing a higher-pressure, graduated compression garment (35). Our results are consistent with the findings of a previous study in normal volunteers that antigraduated compression stockings with higher pressure over the calf than over the ankle prevent increment of leg volume as occupational edema during work of sitting or standing more than graduated stockings (36). Another study demonstrated that graduated compression stockings with mild pressure decrease the cross-sectional areas and increase the peak blood flow of popliteal veins; no significant difference has been recorded in blood flow of the popliteal veins among stockings with mild, moderate, and strong pressure (37). The main function of a compression garment is the reduction in blood vessel diameter by external mechanical pressure and the prevention of venous stasis. This may eventually prevent endothelium dysfunction and gene expression associated with thrombosis/thrombolysis by preventing the reduction of shear stress. However, it remains unclear whether a shorter length of a nongraduated, lower-pressure garment has the same effects on these parameters. Additional acquisition of data regarding the efficacy of nongraduated, lower-pressure, under-knee-long elastic garments on physiological parameters during prolonged sitting may establish strategies preventing DVT and edema in lower extremities. This is useful for healthy subjects, individuals at higher thrombosis risk, and elderly patients.

This study has some limitations. First, the participants of this study were all young healthy men; women were not included. Our reasons for enrolling only male participants were as follows: 1) young and middle-age men have a higher prevalence of arteriosclerosis than women (38), and 2) Vranish et al. (12) demonstrated that young healthy men exhibit more reduction in flow-mediated dilation due to 3 h of uninterrupted sitting than women. Because endothelial dysfunction is the onset of blood clot formation and arteriosclerosis, we designed this study on the effects of prolonged sitting only with young male participants. However, the physiological changes induced by an 8-h constant sitting session among subjects with a higher risk of thrombosis, such as pregnant women, the elderly, and certain patient populations, have not been identified. Furthermore, the efficacy of lower-pressure garments for subjects who have a higher risk of thrombosis has not been assessed either. Recruiting subjects who have a higher risk of thrombosis would provide further evidence on the efficacy of lower-pressure garments. Another limitation of this study is that the thickness of the adipose tissue at the site of NIR_{TRS} measurement was not determined. In another study, 20 Japanese healthy men with age, body mass index, and percent body fat similar to our participants showed on average an adipose tissue thickness of 0.19 cm (range, 0.11–0.30 cm) at the site of NIR_{TRS} measurement (19). Therefore, we consider the adipose tissue thin enough for NIR_{TRS} measurements with 3-cm optode separation.

CONCLUSIONS

This study supports the hypothesis that prolonged sitting leads to deterioration of oxygenation in peripheral muscle tissues of the lower extremities. In addition, we revealed that the blood flow and shear rate of the peripheral artery near the toe declined gradually over time. Moreover, a negative correlation was found with changes in calf circumferences, reflecting extracellular fluid retention due to prolonged uninterrupted sitting. These results may have an implication for the risks of endothelial dysfunction and thrombosis. Finally, stasis of the arterial blood flow and changes in muscle oxygen dynamics caused by prolonged sitting may be ameliorated by wearing lower-pressure garments.

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The authors declare no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute an endorsement by the American College of Sports Medicine.

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