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Compression Stockings Suppressed Reduced Muscle Blood Volume and Oxygenation Levels Induced by Persistent Sitting

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Abstract: This study quantitatively analyzed the effects of 3 h of constant sitting on skeletal muscle oxygenation in the lower extremities, using near-infrared time-resolved spectroscopy (NIR_{TRS}). The effects of compression stockings were also evaluated. Eleven healthy men (age, 30.0 ± 6.7 years) maintained their knee joints at 90° flexion during 3 h of constant sitting and wore a compression stocking on either the right or left leg. The side the stocking was worn was chosen randomly. Subsequently, leg circumference and extracellular water were measured. After 3 h of sitting, both factors increased significantly in uncompressed limbs. Furthermore, intracellular water and muscle oxygenation had significantly decreased. In contrast, extracellular water had not increased in the limbs wearing compression stockings. Furthermore, the increased circumference of compressed limbs was significantly smaller than that of uncompressed limbs. Decreases in oxygenated hemoglobin and total hemoglobin were significantly smaller in compressed limbs than in uncompressed limbs (oxy-Hb; $p = 0.021$, total-Hb; $p = 0.013$). Three hours of sitting resulted in decreased intracellular water and increased extracellular water in the lower extremities, leading to reduced blood volume and oxygenation levels in skeletal muscle. Compression stockings successfully suppressed these negative effects.

Keywords: 3-hour sitting; near infrared time-resolved spectroscopy; compression stocking; tissue oxygenation; extracellular water; intracellular water; circumference; gastrocnemius

1. Introduction

Sitting has gained attention because sitting for a long period of time can cause deep vein thrombosis (DVT). Long-distance travel has become common; therefore, DVT can occur in healthy individuals as well as in those at greater risk for DVT due to spending long periods in a sitting position [1]. It is reported that thrombi formed in the deep veins of the lower extremities can be carried to the lungs through the bloodstream, leading to pulmonary thromboembolism and death [2]. The time spent in a sitting position has gained attention over the past 10 years because it is a factor independent of exercise levels [3,4]. The longer an individual (even a healthy individual) remains in a sitting position during the course of daily activities, the higher the presence of biomarkers that are indicative of the development of diabetes and cardiovascular disease [5,6], resulting in increased prevalence of these diseases [7] and increased all-cause mortality [8]. Current data regarding acute changes in the body as a result of extended sitting are not sufficient. Several problems have been reported as a result of sitting for long periods, such as increased calf circumference, decreased blood flow velocity in the lower extremities, and worsening vascular endothelial function [9,10]. However, there are very few reports focusing on the influence of 3 h of sitting on lower limb skeletal muscle tissue, which is the final oxygen utilization site.

Near-infrared spectroscopy (NIRS) is a technique used to measure tissue oxygenation levels. It involves irradiating tissues with two or three types of near-infrared light of different wavelengths and then detecting and analyzing the light passing through the tissue, thereby allowing for quantitative measurements of oxygen saturation and evaluations of changes in oxygenated hemoglobin (oxy-Hb) and deoxygenated Hb (deoxy-Hb) levels. Because this technique is both convenient and non-invasive, its use for assessing oxygen dynamics in various tissues, including skeletal muscle and brain tissue, has become widespread. A broadly adopted form of NIRS is near-infrared continuous-wave spectroscopy (NIR_{CWS}), in which irradiation is performed using a continuous beam of light [11,12]. Hb concentrations assessed using NIR_{CWS} are calculated based on Lambert-Beer's law. However, NIR_{CWS} is unable to determine the optical path length. Therefore, this value can be calculated based on relative changes in concentration even though quantitative measurement is impossible [11,12]. Near-infrared time-resolved spectroscopy (NIR_{TRS}) was developed as a measurement method that could compensate for this defect. This technique involves irradiating the target tissue with a short pulse of light, thereby allowing for independent determination of the scatter and absorption coefficients, which indicate the optical characteristics of the object, based on the time responsiveness. Therefore, when measurements were performed using NIR_{TRS}, it was possible to determine the optical path lengths that could not be measured with NIR_{CWS}, due to which it was possible to evaluate the oxygen kinetics in tissues with absolute values [13,14]. It is now possible to measure changes over time in the same subject after maintaining a sitting position and to compare measured values among different individuals.

Several methods are recommended to prevent DVT and lower extremity varices, such as walking and active exercise, wearing compression stockings, intermittent pneumatic compression, and administration of heparin and warfarin [15–17]. The advantages of compression stocking usage are not only high cost performance but also no side effects of hemorrhage, which often occurs when heparin and warfarin are administered. Compression stockings can also be used by patients who cannot move and frail elderlies. The recommended compression stockings have a variable pressure design that exerts the highest pressure at the ankle joint and gradually decreases the pressure proximally toward the limbs; the ankle joint pressure is less than 20 mmHg (26.7 hPa). However, compression stockings have been criticized as being difficult to wear because of low flexibility, and patients with weak or damaged skin are at risk for developing dermatitis [18]. Although many people commonly maintain sitting positions for periods of 3 h or longer in daily life during activities such as office work, many previous studies investigated only the short-term impact of wearing compression stockings while sitting for periods of 1 h.

Furthermore, few studies have been performed to verify the effect of wearing compression stockings on oxygen kinetics in the lower leg skeletal muscles. To our knowledge, no study discussing the relationship between the level of lower leg tissue oxygenation, lower extremity extracellular water, and limb circumference has been published previously. Therefore, this study investigated the relationship between the oxygen dynamics of the lower leg skeletal muscles and changes in lower limb extracellular water and circumference based on quantitative measurements using near-infrared time-resolved spectroscopy (NIR_{TRS}) in 11 healthy adult male subjects before and after completion of a 3-hour sitting task. Additionally, we evaluated the impact of wearing a compression stocking on physiological changes in individual subjects during the 3-hour sitting task by applying the stocking to only a single leg.

2. Materials and Methods

2.1. Study Design

This study was approved by the Medical Ethics Committee at Tokyo Medical University (approval number: 2018-045) and was performed in accordance with the Declaration of Helsinki. Prior to study initiation, informed written consent was obtained from all participants. All subjects were briefed regarding the details and purpose of the study, related experimental procedures, and potential risks. The study was performed from May to July 2018.

The subjects were 11 healthy men (age: 30.0 ± 6.7 years, height: 171.5 ± 5.1 cm, weight: 73.0 ± 10.4 kg, BMI: 24.8 ± 3.3, body fat percentage: 20.7 ± 5.9%). Ten of the 11 subjects worked in professions that required them to stand for the majority of the day. All statistics are expressed as mean ± standard deviation. Subjects who were using medication were excluded from participation. In addition, subjects with a history of or a current diagnosis of hematological disorders, such as thrombosis, hypertension, and venous/arterial diseases, were excluded.

To eliminate the influence of diurnal variations, all baseline measurements were performed between 8 a.m. and 10 a.m. After measuring each item at baseline, subjects were instructed to maintain a sitting posture for 3 h with their knee joints in 90° flexion. During this task, subjects were instructed to wear a compression stocking (Elaction Pro, Asahi Kasei Corp, Tokyo, Japan) from the inguinal region to the ankle on a single leg selected randomly; no stocking was worn on the other leg. Subjects were surveyed regarding the subjective degrees of fatigue and stress using a self-reported visual analog scale (VAS), as well as the heart rate, blood pressure, tympanic membrane temperature, compression stocking pressure fit, lower leg circumference, body water measurements using bioelectrical impedance, and skeletal muscle oxygen dynamics, using NIR_{TRS}. The chair used for the sitting task had a width of 46 cm and a backrest angle of 110°; these standard dimensions are the same as those of an economy class seat on a passenger aircraft. During the 3-hour sitting task, spontaneous muscle activity in the lower limbs was completely prohibited. The room temperature of the laboratory was controlled at 22 ± 2 °C, and dehydration was prevented by allowing 100 mL of drinking water per hour during the 3-hour sitting task. No subjects withdrew before completion of the task.

2.2. Subjective Fatigue and Stress Survey

Using the self-reported VAS, the subjective degrees of physical fatigue, subjective degrees of mental fatigue degree, subjective physical stress levels, and subjective mental stress levels were evaluated. When no fatigue or stress was felt, the percentage was recorded as 0%; the maximum level was 100%.

2.3. Heart Rate, Systolic and Diastolic Blood Pressures, and Tympanic Membrane Temperature

Heart rate, systolic blood pressure, and diastolic blood pressure were measured using an automatic sphygmomanometer (HEM-1025; Omron KK, Kyoto, Japan). The tympanic membrane temperature was measured using a near-infrared thermometer (Omron Corporation, Kyoto, Japan).

2.4. Compression Stocking Pressure

In this study, the pressure of the ankle joint part was set at 15.7 ± 2.8 hPa, which is approximately 10 hPa lower than the recommended pressure, and the study investigation was performed using the compression stockings offering the highest pressure for the calf region, which exhibits the muscle pump action (compression stocking pressure ratio of the ankle joint: abdominal gastrocnemius muscle: thigh = 8:10:8). To measure compression pressure, the pressure sensor was attached at the ankle joint (1 cm above the lateral malleolus), calf (1 cm lateral to the location of the NIR probe placed over the lateral head of the gastrocnemius muscle), and thigh (15 cm above the upper end of the patella over the vastus lateralis). Compression stocking pressure was measured with a contact pressure gauge before and after the 3-hour sitting task (AMI 3037-SB with display; AMI Techno, Tokyo, Japan). Measurements were performed three times at each measurement point, and the average value of the three measurements was used as the compression stocking pressure.

2.5. Lower Limb Circumference

The circumference of the calf was measured by the same examiner using the same method with a tape measure. The measurement site was one-third (or the largest circumference) the distance from the midpoint of the straight line connecting the head of the fibula to the lateral malleolus and the knee joint was maintained at 90° of flexion. After determining the measurement site, the same site was repeatedly measured by marking it with flexible tape. Measurements were performed three times at each measurement site, and the average value was used as the limb circumference.

2.6. Body Water Volume

The body water volume (intracellular water/extracellular water) was evaluated using bioelectrical impedance (InBody 720; BioSpace Corporation, Tokyo, Japan). This technique uses a multifrequency bioelectrical impedance device that displays a high correlation with body water content calculated by using the deuterium oxide (D_2O) dilution technique (r = 0.974) [19]. The ratio of extracellular water to total body water (extracellular water + intracellular water) was obtained as a relevant index of edema. The ratio of intracellular water to total body water was also evaluated.

2.7. Skeletal Muscle Oxygen Kinetics

The oxygen kinetics of the lateral head of the gastrocnemius was measured using NIR_{TRS} (TRS-20; Hamamatsu Photonics K.K., Hamamatsu, Japan) [13,14]. The distance between the components irradiating and receiving the near-infrared light was set to 3.0 cm, and detection of the light in a region of skeletal muscle tissue with a depth of 1–2 cm was attempted. The measurement was performed for 3 min before and after the 3-hour sitting task was started, and the average values during these 3-minute periods were used as the measurement value.

The methods for calculating oxy-Hb, deoxy-Hb, total Hb, and oxygen saturation SO_2 were as follows: The target tissue was repeatedly irradiated using semiconductor pulse laser lights of three different wavelengths (760, 800, 830 nm) under the conditions of half-width 100 ps, pulse rate of 5 MHz, and average power level of 100 μW. The pulsed light scattered and absorbed inside the living tissue was detected by a photomultiplier tube capable of single-photon detection. Time-resolved measurements were conducted using the time-correlated single photon counting method. The absorption coefficient and reduced scattering coefficient for the obtained tissue were determined by fitting the photon diffusion equation R (ρ,t) (Equation (1)) that convolved the instrument response function to the time-response properties of the samples.

Where (t) is the response time, (ρ) is the distance between light source and detection, μ_a and μ_s' are the absorption coefficient and equivalent scattering coefficient, $D = 1/3\mu_s']$ is the photon diffusion coefficient, c is the light velocity inside the light scattering medium (20 cm ns^{-1}), Z_0 $(= 1/\mu_s')$ is the transport mean free path, and average path length (L) $(= \int[R(\rho, t)\, t\, dt]\, c/\int [R(\rho, t)\, dt]$. [Deoxy-Hb] and [oxy-Hb] were obtained using simultaneous equations with μ_a and μ_s' obtained from Equation (1) using the least-squares fitting method [20], and [total-Hb] and SO_2 were calculated from the following calculation formula.

$$R(\rho, t) = (4\pi Dc)^{-3/2} \cdot Z_0 t^{-5/2} \exp(-\mu_a ct) \exp[-(\rho^2 + Z_0^2)/4Dct] \quad (1)$$

$$[\text{total-Hb}] = [\text{deoxy-Hb}] + [\text{oxy-Hb}] \quad (2)$$

$$SO_2\ (\%) = [\text{oxy-Hb}] \times 100/[\text{total-Hb}] \quad (3)$$

2.8. Statistical Analysis

The measured values are expressed as mean ± standard deviation. All statistical analyses were performed using SPSS statistics version 25 (IBM SPSS, Tokyo, Japan). Data were analyzed in three stages. First, Wilcoxon's rank-sum test was used for statistical analysis of subjective fatigue before and after the 3-hour sitting task, and the subjective stress level, heart rate, systolic and diastolic blood pressures, tympanic membrane temperature, and compression stocking pressure were also analyzed. Similarly, the rates of change in calf circumference, extracellular water, intracellular water, and NIR_{TRS} indices after the 3-hour sitting task were also analyzed using the Wilcoxon rank-sum test, and the limbs with and without compression stockings were compared. Second, the effects of the 3-hour sitting task on lower limb circumference, lower limb extracellular water, and lateral head of gastrocnemius muscle oxygen kinetics were compared regarding compression stocking wear status and wear time (at baseline vs. after the 3-hour sitting task), after which a repeated two-way analysis of variance was conducted, followed by Bonferroni's multiple comparisons tests as necessary. Third, Spearman's correlation analysis was performed to determine the relationship between the rate of change in limb circumference, extracellular water, and each index measured with NIR_{TRS} before and after the 3-hour sitting task. The level of statistical significance was set at less than 5% for all tests (two-tailed test).

3. Results

3.1. Subjective Degree of Fatigue and Mental Fatigue Levels

After maintaining sitting for 3 h, the subjects' degree of physical fatigue showed an increasing trend, and mental fatigue increased significantly (physical fatigue: 32.4% ± 19.7% to 54.1 ± 20.4%, $p = 0.075$; mental fatigue: 34.7% ± 27.8% to 59.2 ± 26.6%, $p < 0.05$). Furthermore, the subjective levels of physical and mental fatigue increased significantly (physical fatigue: 19.6 ± 15.2% to 51.1 ± 23.7%; mental fatigue: 25.4% ± 28.2% to 48.6 ± 29.3%; $p < 0.05$).

3.2. Heart Rate, Systolic and Diastolic Blood Pressures, and Tympanic Membrane Temperature

Heart rate, systolic and diastolic blood pressures in the right upper arm, and tympanic membrane temperature did not show any significant changes after the 3-hour sitting task (heart rate: 58.5 ± 10.6 to 58.5 ± 10.6 beats/min; systolic blood pressure: 127.2 ± 11.2 to 127.7 ± 11.9 mmHg; diastolic blood pressure: 81.0 ± 8.0 to 80.7 ± 6.9 mmHg; tympanic membrane temperature: 35.2 ± 0.5 to 35.2 ± 0.3 °C).

3.3. Compression Stocking Pressure

Changes in compression stocking pressure at each of the three measurement sites after the 3-hour sitting task were as follows: ankle joint, 15.7 ± 2.8 to 16.4 ± 2.8 hPa; gastrocnemius muscle, 20.4 ± 1.1 to 21.1 ± 1.3 hPa; and thigh, 15.6 ± 2.2 to 16.5 ± 2.5 hPa. Significant increases were observed for pressure at the gastrocnemius muscle and thigh (all $p < 0.05$).

3.4. Calf Circumference

Figure 1 illustrates the changes in the lower limb circumference after the 3-hour sitting task. There was a significant interaction of the lower limb circumference between the compression stocking wear status and wear time (baseline value and after the 3-hour sitting task, $p < 0.05$). For limbs without compression stockings, the circumference of the gastrocnemius muscle significantly increased (+2.0 ± 0.6%; minimum value: 1.0%; maximum value: 3.1%; $p < 0.05$, Figure 1) after the 3-hour sitting task. For limbs with compression stockings, this increase was significantly lower (0.4 ± 0.3%); however, the circumference still slightly increased after the 3-hour sitting task ($p < 0.05$, Figure 1).

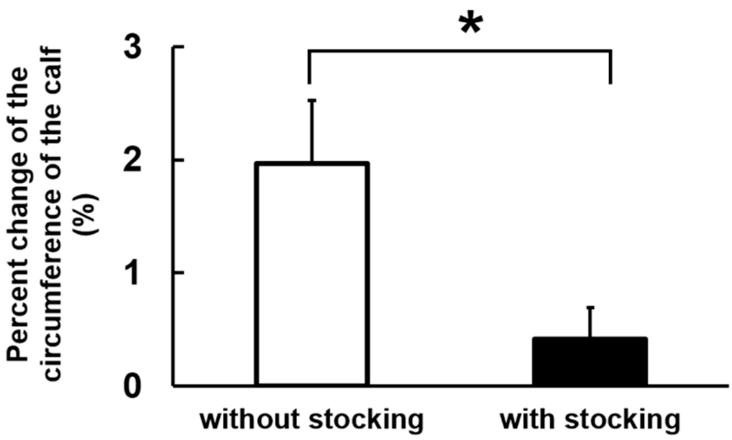

Figure 1. Percent changes of the circumference of the calf before and after 3-hour constant sitting with- or without compression stocking. * $p < 0.05$ between groups.

3.5. Extracellular and Intracellular Water in the Lower Limbs

Figure 2A shows the change in the extracellular water/total body water ratio in the lower limbs with and without the compression stocking before and after the 3-hour sitting task. There was a significant interaction of the extracellular water/total body water ratio in the lower limbs between the compression stocking wear status and wear time (baseline value and after the 3-hour sitting task, $p < 0.05$). The main effect of compression stocking use and wear time were also found ($p < 0.05$, respectively). For limbs without compression stockings, the extracellular water/total body water ratio significantly increased after the 3-hour sitting task (0.371 ± 0.008 to 0.375 ± 0.009 $p < 0.05$, Figure 2A), and edema was observed. In contrast, for limbs with the compression stocking, extracellular water did not increase (0.370 ± 0.009 to 0.371 ± 0.009, $p = 0.062$, Figure 2A).

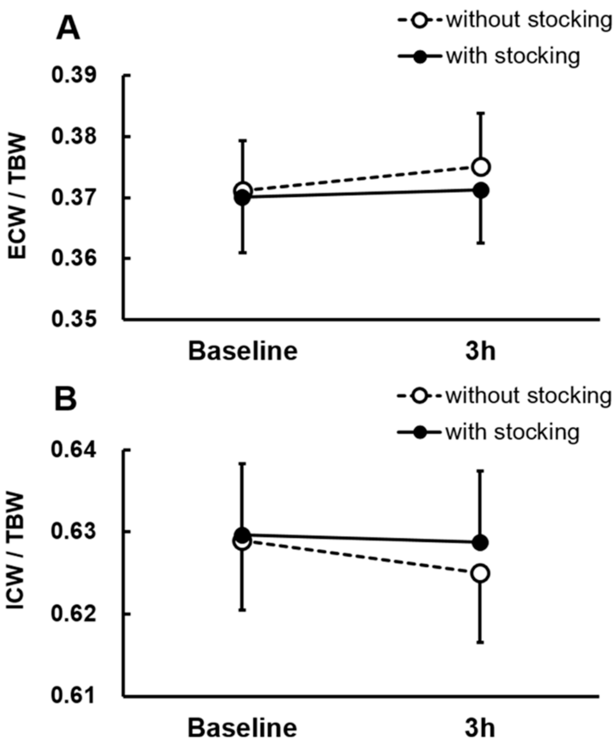

Figure 2. (**A**) Extracellular water/total water ratio (ECW/TBW) and (**B**) intracellular water/total water ratio (ICW/TBW) in the lower limbs before and after 3-hour constant sitting with or without compression stocking.

Changes in the intracellular water/total body water ratio (an indicator of intracellular water in the lower extremities) after the 3-hour sitting task are shown in Figure 2B. There was a significant interaction of intracellular water/total body water ratio in the lower limbs between the compression stocking wear status and wear time ($p < 0.05$, Figure 2B). The main effect of wear time was also found ($p < 0.05$, Figure 2B). However, the main effect of the presence or absence of wearing compression stockings remained insignificant ($p = 0.07$, Figure 2B). Intracellular water in the lower limbs without compression stockings decreased (from 0.629 ± 0.008 to 0.625 ± 0.008, $p < 0.05$, Figure 2B) whereas intracellular water in the limbs with compression stockings did not change (0.630 ± 0.009 to 0.629 ± 0.009, $p < 0.05$, Figure 2B).

3.6. NIR_{TRS} Data

Table 1 displays the values of the NIR_{TRS} indicators before and after 3 h of sitting with and without compression stockings. Figure 3 displays the rates of change in these values after 3 h of sitting with and without compression stockings.

Table 1. Near-infrared time-resolved spectroscopy parameters before and after 3-hour constant sitting with or without compression stocking.

	without Stocking		with Stocking	
	Bassline	**3 h**	**Bassline**	**3 h**
μ_a (cm^{-1})	0.24 ± 0.08	0.22 ± 0.07 *	0.25 ± 0.08	0.24 ± 0.08 *
μ_s' (cm^{-1})	14.8 ± 6.5	15.4 ± 6.7 *	17.7 ± 12.1	17.9 ± 12.1
Path Length (cm)	15.6 ± 2.9	16.5 ± 3.3 *	15.1 ± 2.7	15.5 ± 2.6 *
[oxy-Hb] (μM)	103.7 ± 37.4	91.1 ± 33.3 *	108.1 ± 32.3	100.9 ± 35.2 *
[deoxy-Hb] (μM)	48.4 ± 13.0	48.6 ± 12.0	45.6 ± 12.1	47.2 ± 11.2
[total-Hb] (μM)	152.1 ± 50.2	139.9 ± 44.4 *	153.8 ± 43.8	148.1 ± 44.8 *
SO_2 (%)	67.7 ± 2.4	64.4 ± 4.1 *	70.2 ± 1.8	67.5 ± 3.6 *

* $p < 0.05$ vs. Baseline.

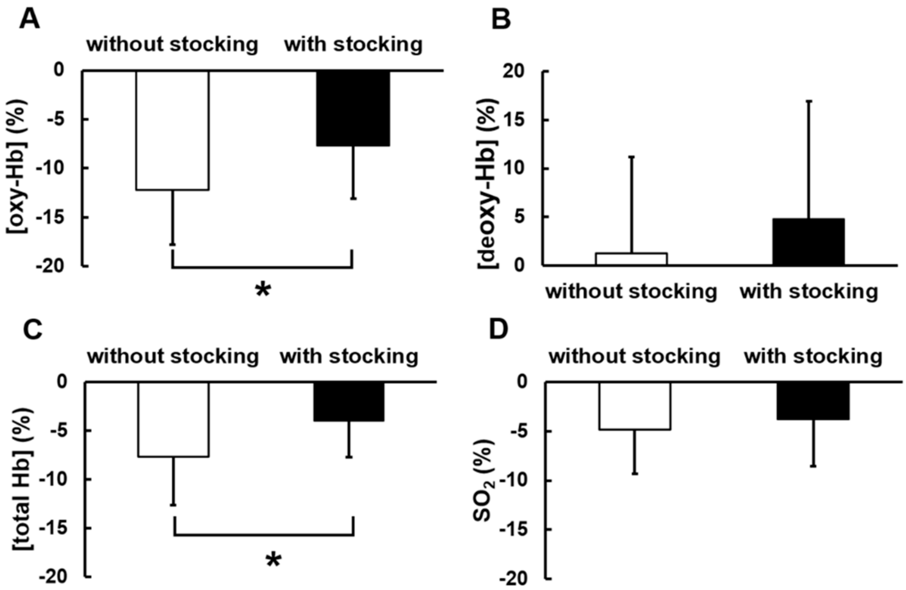

Figure 3. Percent changes in the near-infrared time-resolved spectroscopy parameters before and after 3-hour constant sitting with or without compression stocking; (**A**) oxy-Hb, (**B**) deoxy-Hb, (**C**) total Hb, (**D**) SO_2. * $p < 0.05$ between groups.

There was a significant decrease in the absorption coefficient of both limbs with and without compression stockings after the 3-hour sitting task (each $p < 0.05$) (Table 1). However, the reduced scattering coefficient showed a significant increase in limbs without the compression stocking, but it did not change in limbs with the compression stocking after the 3-hour sitting task (Table 1). The average optical path length increased significantly in both limbs (each $p < 0.05$) (Table 1). The oxy-Hb levels decreased significantly in both limbs after the 3-hour sitting task (Table 1), and the rate of decrease was significantly greater in the limbs without compression stockings (limbs without compression stockings: −12.2 ± 5.6%; limbs with compression stockings: −7.7 ± 5.3%; $p < 0.05$) (Figure 3A). Total Hb decreased significantly in both limbs after the 3-hour sitting task (Table 1), but the rate of decrease was lower in the limbs with compression stockings (limbs without compression stockings: −7.7 ± 4.9%; limbs with compression stockings: −4.0 ± 3.7%; $p < 0.05$) (Figure 3C). The deoxy-Hb levels showed no significant changes before and after the 3-hour sitting task (Table 1, Figure 3B). In addition, although SO_2 decreased in both limbs after the 3-hour sitting task, there was no significant difference between the rates of decrease (Figure 3D).

3.7. Relationship Between Lower Limb Circumference, Lower Limb Extracellular Water, and NIR_{TRS} Indicators

Figure 4 shows the relationship between the rate of change in lower limb extracellular water/total body water ratio and the rate of change in the lower limb circumference with and without compression stockings.

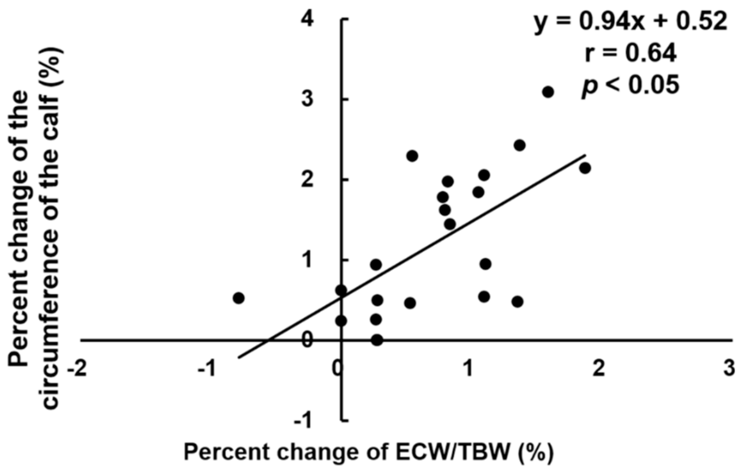

Figure 4. Relationship between percent change of ECW/TBW ratio and percent change of calf circumference before and after 3-hour constant sitting with or without compression stocking.

There was a significant positive correlation between the rates of change in extracellular water and lower limb circumference before and after 3 h of constant sitting ($r = 0.64$; $p < 0.05$), and we believe this was caused by an increase in extracellular water.

Figure 5 shows the relationship between the rate of change in the extracellular water/total body water ratio of the lower limbs and the rate of change in each NIR_{TRS} index in lower limbs with and without compression stockings due to 3-hour sitting task. A significant negative correlation was observed between the changes in extracellular water/total body water ratio and oxy-Hb ($r = -0.40$, $p < 0.05$) and SO_2 percentages ($r = -0.49$, $p < 0.05$).

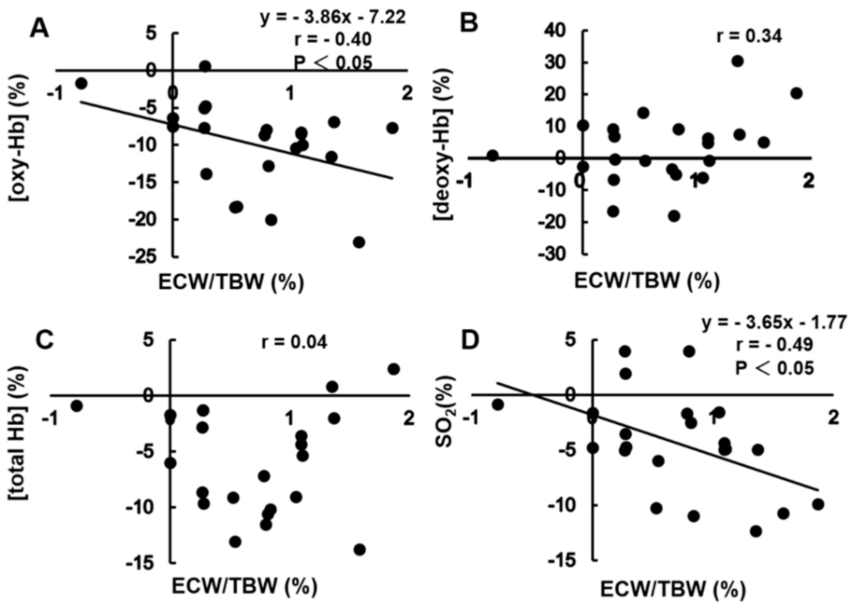

Figure 5. Relationship between percent change of ECW/TBW ratio and percent change of near-infrared time-resolved spectroscopy parameters (**A**) oxy-Hb, (**B**) deoxy-Hb, (**C**) total Hb, (**D**) SO_2, before and after 3-hour constant sitting with or without compression stocking.

4. Discussion

Time spent in a sitting position is believed to have increased dramatically in recent years, particularly in industrialized countries, and situations that require people to sit for long periods are increasing. Long periods of sitting during not only long-distance travel but also deskwork have been found to increase the risks of lifestyle-related diseases such as diabetes and cardiovascular disease [5,6]. They also present the possibility of increasing the all-cause mortality risk [4,8]. In this study, we investigated the effects of sitting for 3 h on the body; we placed particular focus on indices related to the lower extremities. The circumference of the calf region was found to have significantly increased after the 3-hour sitting task. The extracellular water/total body water ratio also increased, indicating a significant positive correlation between these two factors. Moreover, oxy-Hb and total Hb levels at the lateral head of the lower leg gastrocnemius muscle measured using NIR_{TRS} decreased after the 3-hour sitting task, as did the degree of oxygen saturation. In contrast, for limbs with compression stockings, extracellular water did not change after the 3-hour sitting task and, although the lateral head of the gastrocnemius muscle circumference increased, the rate of increase was significantly lower compared to limbs without compression stockings. In addition, although oxy-Hb, total Hb, and SO_2 in the lateral head of the gastrocnemius muscle decreased in the limbs with compression stockings after the 3-hour sitting task, the rates of decrease for the oxy-Hb and total Hb levels were significantly lower compared to those of limbs without compression stockings. Decreases in the level of oxygen saturation in the lower leg skeletal muscle tissue were also suppressed.

The results of the self-reported survey conducted during this study revealed that the physical and mental fatigue experienced by the subjects increased significantly as a result of the 3-hour sitting task. Ten of the 11 subjects had professions that required them to stand for the majority of the day. Therefore, these subjects were not accustomed to sitting for long periods. Additionally, during this study, we restricted subjects from moving their lower limbs during the 3-hour sitting task. This may have led to increased subjective mental fatigue, which could have also contributed to elevated stress levels.

Typically, the rate of water filtration in the capillary is determined by the hydrostatic pressure gradient and the osmotic pressure gradient between the capillary and the interstitial fluid. Sitting for a long period is strongly influenced by gravity, particularly in the lower extremities, and can lead to increased hydrostatic pressure in capillary blood vessels, eventually disrupting the equilibrium of the hydrostatic pressure gradient. In typical cases, venous pressure decreases due to the muscle pump action in the vasculature of the lower extremities, and outflow of intravascular fluid to the interstitium is suppressed by decreasing the hydrostatic pressure in capillaries. However, in this study, we believed that this muscle pump action was ineffective because voluntary contractions of the lower limb skeletal muscles were strictly restricted during the 3-hour sitting task. Therefore, extracellular water/total body water ratio increased by 1.1% (from 0.371 to 0.375; $p < 0.05$). As a result, the circumference of the gastrocnemius muscle was found to have increased significantly by 1.9% after the 3-hour sitting task (from 39.6 ± cm to 40.4 cm; $p < 0.05$).

In contrast, for limbs with compression stockings, the rate of change in the gastrocnemius muscle circumference increased only slightly after the 3-hour sitting task (+1.9 ± 0.6% for limbs without compression stocking vs. +0.4 ± 0.3% limbs with compression stocking; $p < 0.05$), and the lower limb extracellular water/total body water ratio did not exhibit any significant change. This is believed to be due to the following effects of wearing compression stockings: Tightening of the veins due to increased skin surface pressure, reduction of blood stagnation, and increased venous reflux while preventing physiological counterflow due to the physiological venous valve function. Due to these effects, compression stockings were successful for optimizing the equilibrium of the hydrostatic pressure gradient between the intravascular and interstitial spaces, thereby suppressing the onset of edema.

The elastic stockings recommended by the Lower Leg Ulcer/Varices Diagnosis and Treatment Guidelines published by the Japanese Dermatological Association [16] are those that place the greatest pressure on the ankle and gradually lower the pressure toward the proximal aspect of the leg; the pressure applied to the ankle joint is less than 20 mmHg (26.7 hPa). In clinical practice, it is generally recommended that compression stockings should be applied to the ankle joint (ankle joint:calf:thigh pressure ratio of 10:7:4 or 26.7:18.7:10.6 hPa). Variable pressure is recommended to increase blood reflux from the periphery to the center. However, the robustness of evidence concerning the prevention of DVT and varices of the lower extremities in Japan is still extremely poor, and few details regarding the mechanism of the effects of wearing compression stockings on edema have been reported. Compression stockings used in this study had a pressure ratio of 8:10:8, exerting 15.7 ± 2.8 hPa at the ankle joint, 20.1 ± 1.1 hPa at the lateral head of the gastrocnemius muscle, and 15.6 ± 2.2 hPa at the thigh; it was designed to place the greatest pressure at the calf region to promote muscle pump action. The pressure exerted by the compression stocking used in this study (15.7 hPa) was lower than the clinically recommended ankle pressure of 20 mmHg (26.7 hPa). Nevertheless, we observed the suppression of increases in limb circumference, of increases in extracellular water, and of decreases in skeletal muscle tissue oxygenation. Because of the low elasticity characteristic of conventional compression stockings, the potential difficulty of wearing such stockings can become an issue, resulting in decreased use [18] and an increased risk of dermatitis. The results of this study suggested the effectiveness of wearing compression stockings with lower ankle joint pressure than what is currently recommended. We investigated the effects of the compression stockings only on men in this study. However, the prevalence rate of edema among healthy subjects is 2.8 times higher in women than in men [21] The incidence of edema among aged dialysis patients is much higher in women than in men as well [22]. With this variable pressure design, we believe the utilization of compression stockings will increase in the future, in women as well as men.

The absorption coefficient decreased in both limbs after the 3-hour sitting task. This was believed to be the result of decreased absorbing substance in the NIR_{TRS} measurement region. In addition, in limbs without compression stockings, increases in the reduced scattering coefficient after the 3-hour sitting task were attributed to increased photon migration distances due to the decrease in the absorbing substance (mainly hemoglobin) in the measurement region after sitting (Table 1). The average optical path length actually increased in both limbs after the 3-hour sitting task with and without the compression stockings (Table 1). The oxy-Hb, total Hb, and SO_2 levels decreased in both limbs after the 3-hour sitting task as a result of gravity effects and decreased blood flow in the lower extremities due to reduced muscle pump action, leading to the possibility of stagnation and edema [23]. Among previous studies, one report stated that the average blood flow velocity in the popliteal artery decreased significantly compared to the task value before sitting [10]. Therefore, it can be inferred that decreased blood flow in the lower extremities can lead to decreases in the central circulation volume and that the level of oxygenation in peripheral skeletal muscle tissue decreased as a result of the decreased supply of arterial blood to the periphery. Additionally, limbs without compression stockings were determined to exhibit edema (increase in interstitial water volume) in the measurement region based on the observation of increased extracellular water and lower limb circumference compared to limbs with compression stockings, which was thought to have resulted in decreased (dilution) oxy-Hb, deoxy-Hb, and total Hb levels. The deoxy-Hb level exhibited no significant changes in both limbs after the 3-hour sitting task. This result is believed to be attributable to a decrease in concentration caused by an increase in interstitial fluid in the NIR_{TRS} measurement region as well as the accumulation of deoxy-Hb caused by decreased peripheral blood circulation volume.

5. Conclusions

The use of compression stockings with pressure lower than that currently recommended was found to help prevent increases in extracellular water and decreases in intracellular water, as well as to suppress decreases in oxy-Hb, total Hb, and SO_2 levels in the gastrocnemius. However, this study had a small sample size and included only men; therefore, the results cannot be generalized to a normal population. Wearing this type of compression stockings might have a higher positive impact on the elderly and/or women, who often have higher subjective symptoms of edema in the lower extremities. In the future, we plan to conduct further investigations to clarify the full effects of sitting for extended periods on the body and to further verify the effects of wearing devices such as compression stockings to prevent DVT and other conditions during the perioperative period, to generally improve quality of life, and to establish measures to prevent increases in the prevalence of lifestyle-related diseases and the all-cause mortality rate for healthy individuals.

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