Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Assessing the acute effect of compression socks on improving arterial compliance in young volunteers

Kosuke Morinaga [a,b,*], Masako Nakahara [c,**], Kotaro Matsuura [a], Shigekazu Ishihara [b], Yasuhiro Idobata [d], Takafumi Kobata [d], Toshio Tsuji [a,***]

[a] *Graduate School of System Cybernetics, Hiroshima University, Higashi-Hiroshima, Japan*
[b] *Department of Assistive Rehabilitation, Hiroshima International University, Higashi-Hiroshima, Japan*
[c] *Department of Medical Technology, Hiroshima International University, Higashi-Hiroshima, Japan*
[d] *KNITIDO CO.,LTD., Kainan, Japan*

ARTICLE INFO

Keywords:
Compression socks
Brachial-ankle pulse wave velocity
Lower limb arteries

ABSTRACT

Background: Wearing compression socks increases mean deep venous velocity, reduces venous blood retention, and improves venous return. However, no existing studies reported their effect on arteries. Thus, we aimed to determine whether wearing compression socks decreases brachial-ankle pulse wave velocity (ba-PWV).
Methods: We compared ba-PWV measurements in 106 participants (40 men and 66 women) under three conditions: bare feet, wearing normal socks, and wearing compression socks for 10 min. Mean arterial blood pressures (MAPs) were measured at the upper arms and ankles on both sides. Sensor cuffs were attached over socks to estimate pressures exerted on arterial walls by the socks in the condition of wearing socks.
Results: Tukey's honestly significant difference test showed that PWVs for the compression sock condition were significantly lower than those for bare feet (95 % confidence intervals: 0.3051–0.9478 [right], 0.3454–0.9889 [left], $p < 0.0001$ on both sides) and normal sock conditions (0.0126–0.6552, 0.0656–0.7092, $p < 0.04$ on both sides). The mean ba-PWV of the right side decreased from 10.57 m/s (bare feet) to 9.94 m/s (compression socks) [absolute difference: 0.63 m/s; relative difference: 5.96 %]. The left-sided mean ba-PWV decreased from 10.79 m/s (bare feet) to 10.11 m/s (compression socks) [absolute difference: 0.67 m/s; relative difference: 6.21 %]. We observed no significant differences in PWVs between bare feet and normal sock conditions on either side. In the compression sock condition, the difference between upper-arm and ankle MAPs while wearing socks indicated the pressure exerted on the arterial wall by the compression socks. We found significant negative correlations between ba-PWV and the estimated pressure exerted on the arterial wall at both ankles (regression analysis, $F(1, 104) = 10.55$, $p < 0.02$) [right], $F(1, 104) = 12.92$, $p < 0.0005$ [left]).
Conclusions: Wearing compression socks reduced ba-PWV, indicating increased arterial compliance in lower limb arteries by applying external pressure to the arterial wall.

* Corresponding author. Graduate School of System Cybernetics, Hiroshima University, Higashi-Hiroshima, Japan.
** Corresponding author.
*** Corresponding author.
E-mail address: morinaga@hirokoku-u.ac.jp (K. Morinaga).

https://doi.org/10.1016/j.heliyon.2025.e41704
Received 23 January 2024; Received in revised form 25 December 2024; Accepted 3 January 2025
Available online 10 January 2025

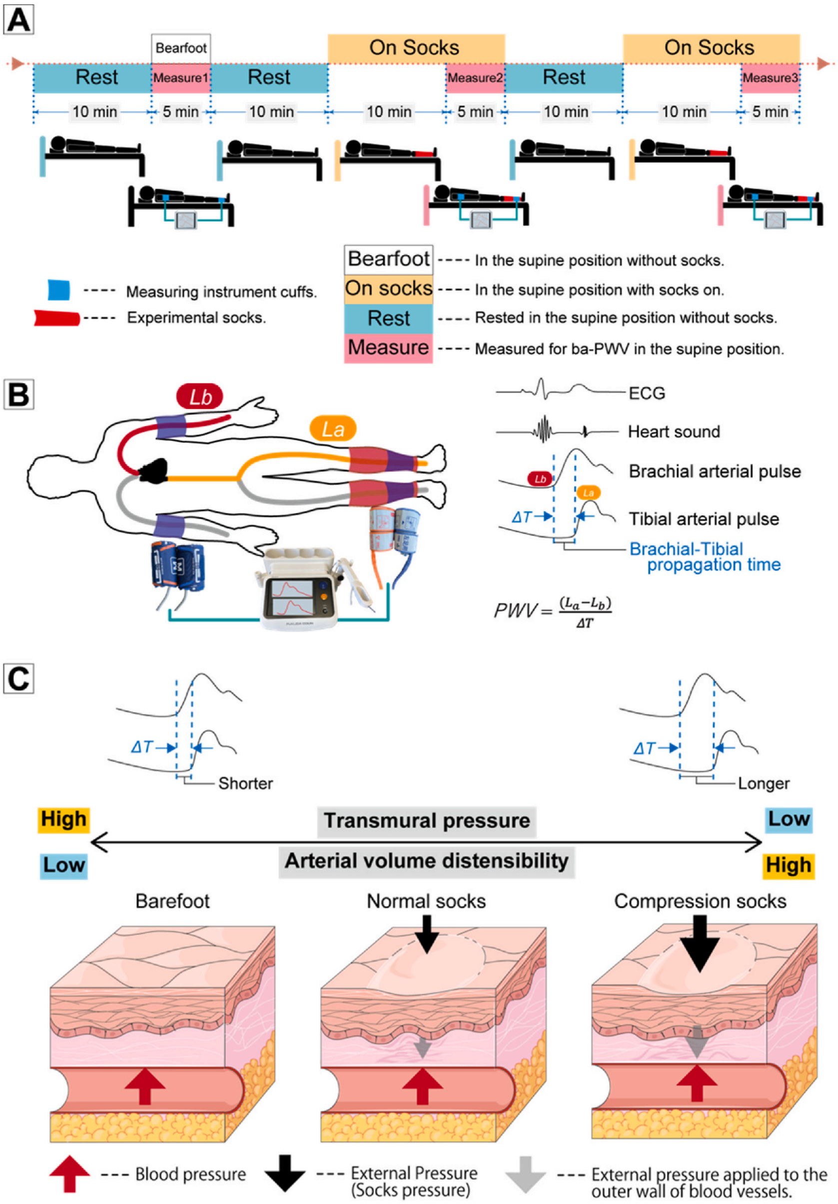

Fig. 1. Experimental workflow of socks affecting peripheral arterial volume distensibility.

A. Peripheral arterial volume distensibility among three groups (bare feet, normal socks, and compression socks) was measured for ba-PWV using a blood pressure pulse wave device. Socks were worn bilaterally during measurements, and ankle cuffs for measurements were wrapped over the socks. **B.** Wrap blood pressure-measuring cuffs around the extremities (both upper arms and ankles). The time difference between the rise of the volume pulse wave at the distance from the aortic valve opening to the upper arm (L_b) and the distance from the aortic valve opening to the ankle (L_a) is ΔT. ba-PWV was calculated by dividing the brachial-to-ankle distance by ΔT. **C.** Three pressures are described. The first (red thick arrow) is the pressure exerted on the arterial wall from the inside, corresponding to the blood pressure. The second (black thick arrow) is the pressure on the skin surface of the lower leg where the socks (normal or compression) are worn. The third (grey thick arrow) is the pressure transmitted from the socks through the skin as well as the biological tissue of the lower leg to the outer vascular wall. The ankle blood pressure when wearing socks was measured with a cuff set over the socks, so that the mean blood pressure of the measured ankle blood pressure was equal to the true mean blood pressure minus the pressure applied to the arterial wall by the sock. The mean blood pressure at the upper arm minus the mean ankle blood pressure over the sock is defined as the external pressure applied to the arterial wall by the sock through the skin layer and the tissue. This made it possible to analyse the effect of the pressure applied by the sock to the outer wall of the vessel.

1. Introduction

Compression wear, including shirts, leggings, leg cuffs, and socks, has various applications in sports, beauty, and medicine. Compression therapy has been used since 450–350 B.C [1,2]. The development of compression wear began in the 1950s with Conrad Jobst's compression socks, inspired by the relief of varicose vein symptoms attributed to hydrostatic pressure in swimming pools [3,4]. Chronic venous insufficiency is among the most commonly reported chronic diseases and a significant cause of morbidity. Venous diseases, including venous thromboembolism and chronic venous insufficiency, vary according to geographical region and disease classification [5–7]. Compression socks are used for post-phlebitis (post-thrombosis) syndrome, venous insufficiency, lymphoedema, lipoma, intermittent claudication, and congestive heart failure [8–11] associated with chronic venous insufficiency. Moreover, it is used for treating patients with lower limb mobility limitations or immobilisation [12].

Compression socks apply external pressure to the lower limb in a graded manner, with less pressure applied distally to proximally [13,14]. This pressure compresses the veins, reducing the vessel diameter, increasing blood flow velocity, facilitating blood return to the heart, and reducing blood retention [4,8,15,16]. Studies have demonstrated increased mean deep venous velocity, reduced venous blood retention, and improved venous return in patients wearing compression socks [8,14,17–20]. In sports, compression socks reportedly assist in removing muscle-oxygenated metabolic waste products, reducing oedema, and preventing the decrease in oxygen saturation [14,21,22]. Previous studies [13–15,19,22–25] have examined changes in venous blood flow and oxygenation using Doppler and near-infrared spectroscopy. However, no studies have mentioned its effect on lower limb arteries.

This study aimed to determine whether wearing compression socks decreased brachial-ankle pulse wave velocity (ba-PWV). The socks assessed in this study were previously confirmed to affect the circumference and volume of the lower limb [26]. We assessed only ba-PWV as the primary outcome of this study to test the hypothesis that the pressure applied on the arterial wall by compression socks increases arterial compliance and decreases ba-PWV, even in short time periods. We examined whether wearing compression socks affected ba-PWV and improved arterial compliance by decreasing arterial transmural pressure (Fig. 1C).

Table 1
Baseline characteristics of study participants.

	Mean	Standard deviation	Median
Number of participants	106 (66 female)	–	–
Age (years)	21.25	±1.37	21.00
Height (m)	1.62	±6.22	1.62
Weight (kg)	54.69	±9.95	53.05
BMI (kg/m^2)	20.64	±0.80	20.56
Right upper arm SYS (mmHg)	109.66	±0.55	109.00
Left upper arm SYS (mmHg)	109.02	±0.99	108.00
Right upper arm DIA (mmHg)	60.15	±0.45	60.00
Left upper arm DIA (mmHg)	60.22	±0.68	59.50
Right upper arm MAP (mmHg)	76.66	±5.88	76.43
Left upper arm MAP (mmHg)	76.49	±6.12	76.30
Right ankle MAP (mmHg)	78.90	±8.56	78.90
Left ankle MAP (mmHg)	79.09	±8.20	78.35
Right ankle pulse pressure (mmHg)	56.37	±6.82	56.60
Left ankle pulse pressure (mmHg)	56.56	±60.44	57.05
Right ba-PWV (m/s)	10.57	±0.04	10.45
Left ba-PWV (m/s)	10.78	±0.01	10.72
Right ABI	1.05	±0.08	1.05
Left ABI	1.05	±0.08	1.06

2. Materials and methods

2.1. Study design and data sources

Participants, 106 healthy individuals (40 men and 66 women), were recruited among Hiroshima International University students through an advertisement. Table 1 shows the physical characteristics of the patients. The eligibility criteria were adult men and women with normal health and blood pressure, as determined in medical examinations performed on campus. All experiments were conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all study participants before conducting the experiments.

2.2. Experimental protocol

The experiment was conducted in a quiet room maintained at a temperature of 24–25 °C [27,28] to prevent temperature influence on the measurement results (Fig. 2). On the day of the measurement, the participants were asked to refrain from exercising and to assemble in the experimental room. The participants were required to rest in a sitting position for 10 min before measurements to eliminate the influence of heart rate variability due to physical activity. The barefoot measurement was conducted first, and the other two measurements were performed randomly (Fig. 1A). Two types of socks were used as follows: normal high socks without any function and compression socks (made by KNITIDO Co. Ltd., Japan) with increased pressure in the triceps area of the posterior lower leg (Fig. 3 and Table 2). The values in Table 2 were measured using an adult female foot mannequin (MPS-20, NANASAI CO., LTD., Japan) and a measuring instrument (AMI 3037-2, AMI Techno Co., Ltd., Japan). The results represent the average of three measurements; the measurement error of AMI 3037-2 under a 23 °C environment is less than ±0.1 kPa for 0–14.00 kPa and ±0.25 kPa for 14.00–34.00 kPa.

The BP-203RPE III form (FUKUDA COLIN Co., Ltd., Japan) was used to measure ba-PWV and simultaneously measure phonocardiogram, electrocardiogram, pulse wave, and blood pressure to evaluate vascular stiffness noninvasively. The participants wore the cuffs of a blood pressure pulse wave device around both ankles and on both upper arms. The ankle cuff for PWV measurement was wrapped over the sock while the participant was wearing the sock to evaluate the pressure applied by the sock on the arterial wall. The blood pressure and volume pulse rate were obtained from each cuff. The time difference (ΔT) between the rise of the pulse wave in the upper arm and the ankle was measured. The length of the ankle from the aortic valve opening (La) and the length of the upper arm from the aortic valve opening (Lb) were determined from the height, and ba-PWV was calculated using the formula in Fig. 1B. Additionally, systolic blood pressure (SYS), diastolic blood pressure (DIA), mean blood pressure, and pulse pressure of both ankles were obtained. A clinical laboratory technician performed PWV measurements. For the experiment, socks were worn for 10 min in order to test whether wearing socks for a short time period is effective in improving baPWV; the 10-min break between PWV measurements was set based on previous studies [27–29].

2.3. Statistical analysis

Statistical analyses were performed using JMP Ver. 14.2.0 (SAS Institute, Inc., Cary, North Carolina). The significance level of the statistical treatment was set at a risk rate of less than 5 %. Classification and Regression Tree (CART) and Random Forest (Scikit-learn ver. 0.24.1) were run in the Python 3.6 environment, branching at the most influential points on the ba-PWV [30–32].

2.4. Ethics approval

This study was approved by the Hiroshima International University Research Ethics Committee (Protocol #19–027).

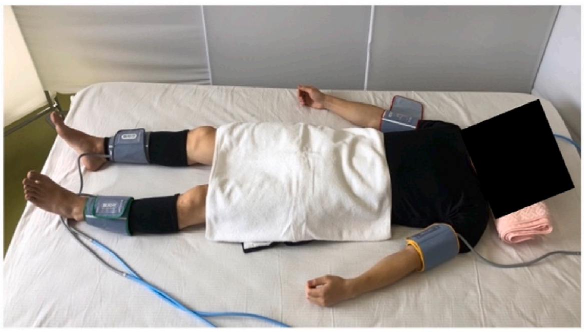

Fig. 2. Environment during PWV measurement.
The cuff for measuring blood pressure in the upper limb is worn on the upper arm, and the cuff for measuring blood pressure in the lower limb is worn on the ankle. To ensure that PWV values are not affected by the environment, measurements are performed in a controlled space with regulated room temperature and maintained sound insulation.

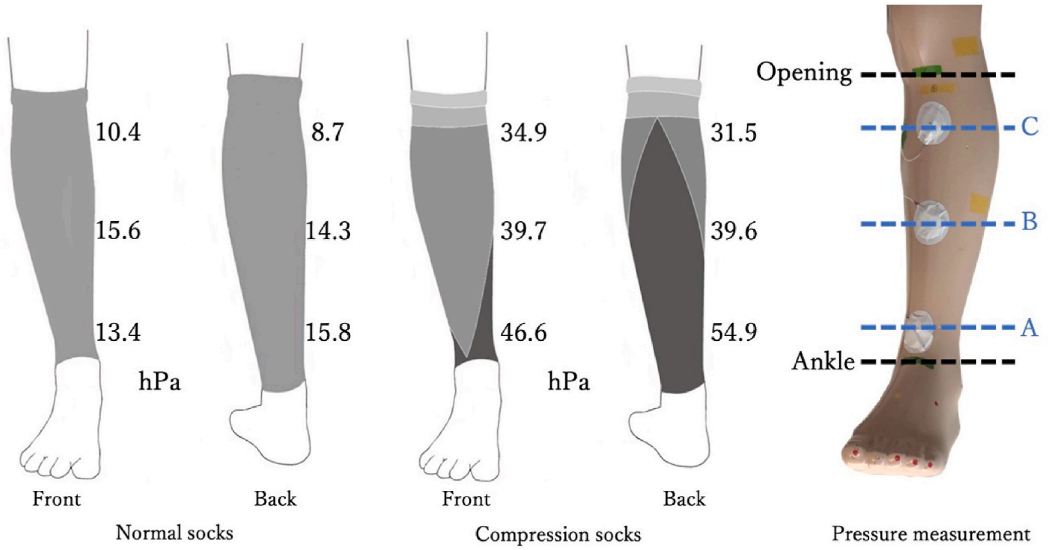

Fig. 3. Measurement of sock pressure.
The dark grey areas of the compression socks are designed to exert higher pressure than the lighter areas on the front. The diagram on the right shows the positions of the mannequins and sensors from which the pressures were measured. Mannequins wore normal socks and compression socks, and the pressure at each location was measured. Measurements were taken at a total of six points on the mannequin: three on the anterior surface of the lower leg and three on the posterior surface of the lower leg.

Table 2
Information on socks pressure.

	Normal socks		Compression socks	
Front	hPa	mmHg	hPa	mmHg
A 30 mm below the footwear opening (triceps muscle of calf)	10.4	7.80	34.9	26.18
B Middle part of A-C	15.6	11.70	39.7	29.78
C 30 mm above the footwear opening (ankle)	13.4	10.05	46.6	34.95
Back				
A 30 mm below the footwear opening (triceps muscle of calf)	8.7	6.35	31.5	23.63
B Middle part of A-C	14.3	10.73	39.6	29.70
C 30 mm above the footwear opening(ankle)	15.8	11.85	54.9	41.18

3. Results

One-way analysis of variance was used to assess three conditions as follows: bare feet, wearing normal socks, and wearing compression socks. The Tukey honestly significant difference (HSD) tests were utilised to evaluate differences among the three conditions (Fig. 4). The measured mean blood pressure (Fig. 4A) and pulse pressure (Fig. 4B) at the right and left upper arms showed no significant differences among the conditions. Moreover, no significant differences were observed in the pulse pressure at the ankle among the conditions (Fig. 4C).

The differences between upper-arm and ankle mean arterial blood pressures (MAP) while wearing socks, which can be regarded as the pressure exerted on the arterial wall by the compression sock condition, were significantly different for each condition on the right (F (2, 315) = 107.8926, $p < 0.0001$) and left sides (F (2, 315) = 107.5683, $p < 0.0001$) (Fig. 4D). The Tukey HSD test showed a significantly higher difference in pressure for the compression sock condition than for the bare feet (95 % confidence intervals: 8.8459–12.2622 [right], 8.9816–12.4466 [left]), $p < 0.0001$ on both sides) and normal sock conditions (4.8383–8.2547, 4.7354–8.2004, $p < 0.0001$ on both sides). Conversely, ba-PWV was significantly different for each condition on the right (F (2, 315) = 10.5571, $p < 0.0001$) and left sides (F (2, 315) = 12.0249, $p < 0.0001$) (Fig. 4E), and the Tukey HSD test showed significantly lower PWVs for the compression sock condition than for the bare feet (95 % confidence intervals: 0.3051–0.9478 [right], 0.3454–0.9889 [left]), $p < 0.0001$ on both sides) and normal sock conditions (0.0126–0.6552, 0.0656–0.7092, $p < 0.04$ on both sides). The mean value of PWV when wearing compression socks was significantly lower compared with that for barefoot. The mean PWV of the right side decreased from 10.57 m/s (bare feet) to 9.94 m/s (compression socks) [absolute difference: 0.63 m/s; relative difference: 5.96 %], and the left-sided mean PWV decreased from 10.79 m/s (bare feet) to 10.11 m/s (compression socks) [absolute difference: 0.67 m/s; relative difference: 6.21 %]. No significant differences were observed in PWVs between the bare feet and normal sock conditions on either side. Fig. 4F shows the relationship between ba-PWV and resting heart rate (RHR) under the three conditions. As the participants in this study were young volunteers, no significant relationship between ba-PWV and RHR was found ([Right]: Bare [F (1, 104) =

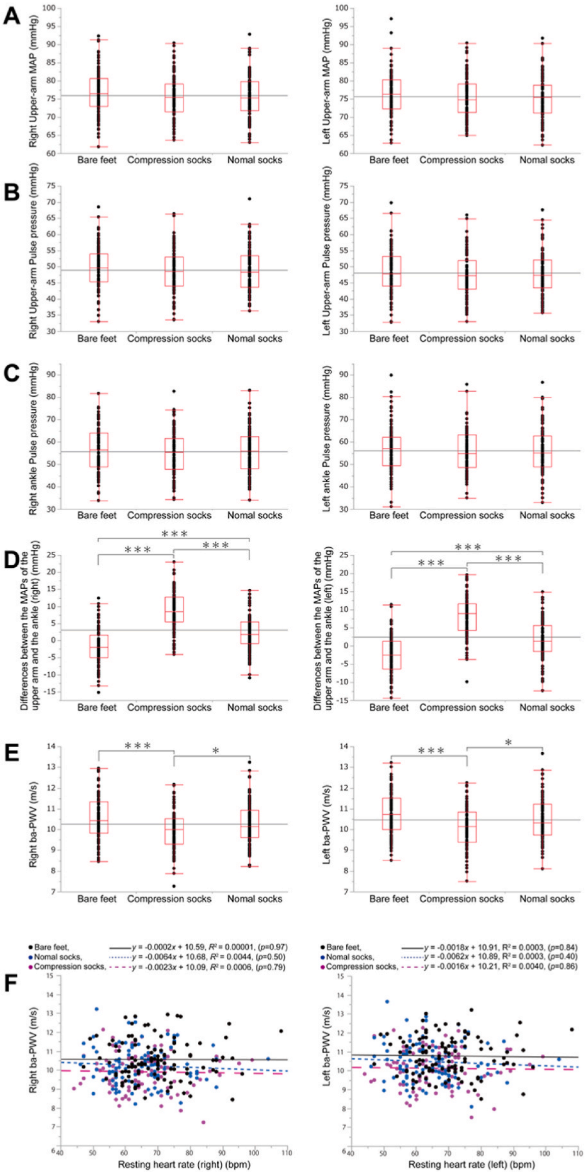

Fig. 4. Statistical comparison for the three conditions.
Box plot diagrams showing the comparison of three conditions (bare feet, normal socks, and compression socks). The notches on the box plots indicate the 95 % confidence intervals of the median calculated as median plus $\pm 1.5 \times \mathrm{IQR}/(n)$, with IQR being the difference between the third and first quartiles. (A) Comparison of mean blood pressure in the upper arm among the three groups; (B) comparison of mean pulse pressure in the upper arm among the three groups; (C) comparison of pulse pressure in the ankle among the three groups; (D) for each participant, the result of the upper-arm MAP minus the ankle MAP was compared among the three groups; and (E) comparison of ba-PWVs among the three groups.
A p value less than 0.05 was considered statistically significant. *$p < 0.05$, **$p < 0.01$, ***$p < 0.005$.

0.0010, $p = 0.97$], Normal [F (1, 99) = 0.44, $p < 0.50$], Compression [F (1, 99) = 0.066, $p = 0.79$]), ([Left]: Bare [F (1, 104) = 0.039, $p < 0.84$], Normal [F (1, 99) = 0.40, p = 0.52], Compression [F (1, 99) = 0.030, $p = 0.86$]).

Fig. 5 illustrates the relationship between the pressure exerted on the arterial wall by the compression socks and ba-PWV when wearing compression socks. Notably, a significant negative correlation was observed (F (1, 104) = 12.92, $p < 0.0005$ [right ankle], F (1, 104) = 5.49, $p < 0.002$ [left ankle]). Both the right and left sides showed a similar negative relationship with a larger pressure exerted on the arterial wall by the compression socks, resulting in a lower ba-PWV.

As shown in Fig. 6, the factors influencing ba-PWV were analysed using the dictionary tree. The objective variable was the improvement in PWV between the bare feet and wearing compression sock conditions, while the explanatory variables for factors affecting PWV (height, weight, body mass index, DIA, SYS, MAP, pulse pressure) were used in the Random Forest analysis. Therefore, the right ankle DIA value was chosen as the root node; the right ankle DIA value branched at 70.6 mmHg, resulting in nine participants

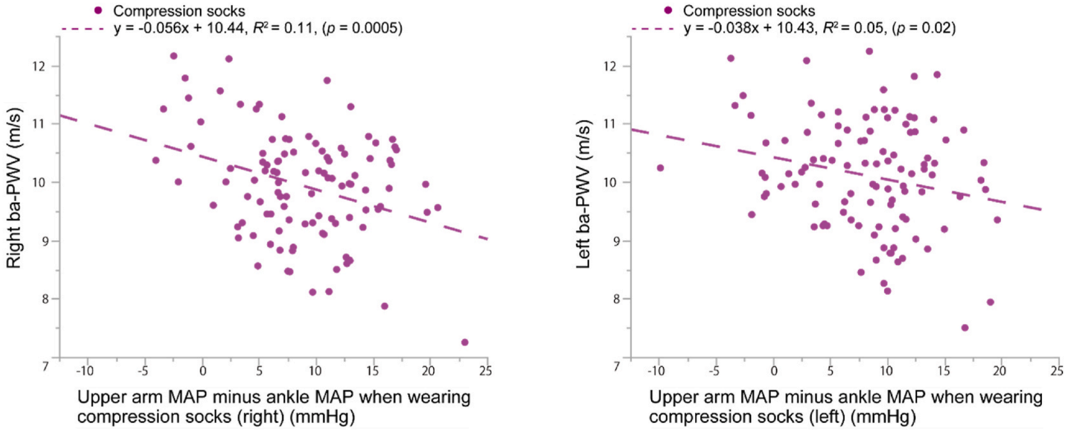

Fig. 5. Relationship between ba-PWV and differences in MAPs between upper arm and ankle when wearing compression socks.
The horizontal axis shows the differences in MAPs between the upper arm and ankle after 10 min of wearing compression socks. The vertical axis shows the ba-PWV. Both right and left sides illustrate a similar negative relationship, with a larger difference in MAPs between upper arm and ankle resulting in a lower ba-PWV.

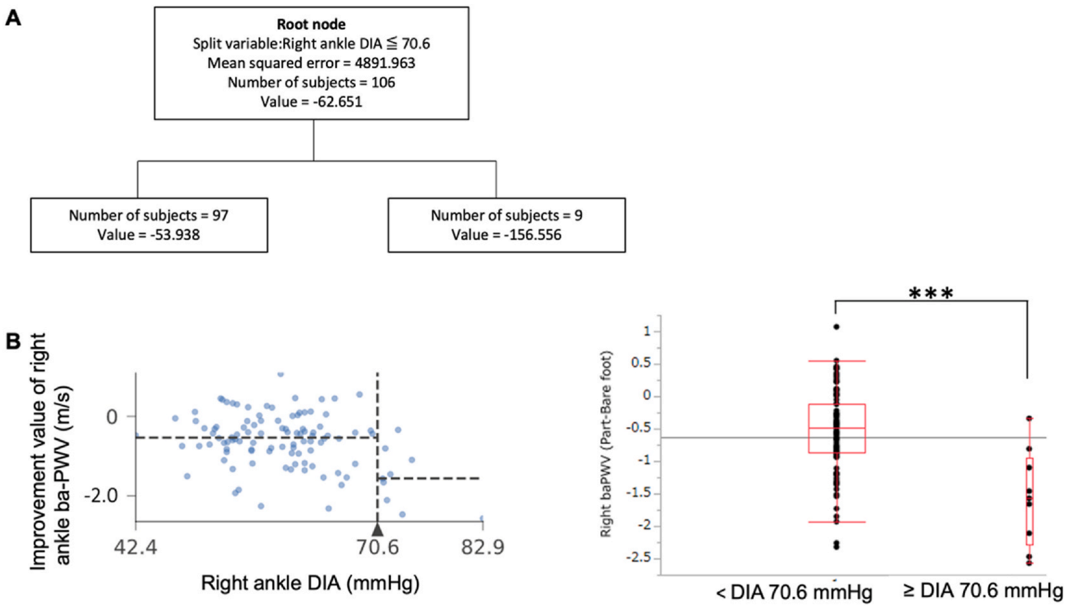

Fig. 6. Improvement value of ba-PWV.
(A) Results of a random forest to explore dependent variables closely related to improved ba-PWV. There were seven independent variables, but only DIA was closely associated with ba-PWV. (B) The bifurcation and scatterplots of the analysis. The Random Forest analysis resulted in a bifurcation of the right ankle DIA values at 70.6 mmHg. There was a statistically significant difference in improved ba-PWV between the groups with ankle DIA less than 70.6 mmHg and those with ankle DIA greater than 70.6 mmHg ($p < 0.005$).

with a right ankle DIA of 70.6 mmHg or higher (Fig. 6A). The average improvement in ba-PWV for the nine participants was −1.57 m/s, while the average improvement in ba-PWV for all participants was −0.63 m/s. The ba-PWV value was significantly decreased by wearing compression socks for those participants who had an ankle joint DIA above 70.6 mmHg (Fig. 6B).

4. Discussion

In this study, ba-PWV was measured under three conditions as follows: bare feet, wearing normal socks, and wearing compression socks. ba-PWV with compression socks was significantly lower than that without socks and with normal socks. ba-PWV with compression socks was significantly lower than that without socks and with normal socks. According to our hypothesis, when the socks pressurise the skin surface of the lower leg, the pressure is transmitted through the tissue to the arterial wall, pressurising the arterial wall and decreasing the arterial transmural wall pressure (Fig. 1C). As a result, arterial compliance of the wall increases so that the

PWV decreases.

Since we measured ankle blood pressure over a sock, the mean blood pressure of the measured ankle blood pressure is equal to the true mean blood pressure minus the pressure applied to the arterial wall by the sock. As the experimental condition was the supine position, the mean blood pressure measured at the upper arm is almost equal to the mean blood pressure in the whole body for young volunteers. Therefore, in this paper, the mean blood pressure at the upper arm minus the mean ankle blood pressure over the sock is defined as the external pressure applied to the arterial wall by the sock through the skin layer and the tissue. Compression socks are considered to apply external pressure to the arterial walls through the subcutaneous tissue. The external pressure reduces the transmural pressure, which in turn increases the arterial distensibility. The consequence of this is a decrease in ba-PWV.

The linear regression lines between ba-PWV and differences between upper-arm MAP and ankle MAP over socks showed a significant negative correlation for both the right and left sides, as shown in Fig. 5. Notably, compression socks tended to be more effective in participants with higher diastolic blood pressure, as shown in Fig. 6. The results of this study are consistent with our hypothesis that the pressure applied to the arterial wall by compression socks decreases ba-PWV and suggest that the pressure exerted on the arterial wall increases arterial compliance.

The following equation is the arterial PWV based on the Moens-Korteweg equation [33–36]:

$$PWV = \sqrt{\frac{Eh}{\rho 2r}}, \tag{1}$$

where E denotes Young's elastic modulus, h is the arterial wall thickness, ρ is the blood density, and r is the internal radius of the vessel. During the experiments, the blood density (ρ) is constant. If blood vessels are considered to have a similar shape, the thickness of blood vessels (h) and the diameter of blood vessels ($2r$) could be considered constant. Furthermore, the only parameter that influences the value of PWV is Young's elastic modulus. Hence, wearing compression socks in the experiments decreased Young's elastic modulus; particularly, ba-PWV decreased with increasing compliance of the peripheral arterial vessels [29,37–39]. Bank et al. demonstrated changes in Young's elastic modulus and vascular compliance during experimental changes in arterial transmural pressure [40,41]. The experiment resulted in a decrease in Young's elastic modulus and an increase in vascular compliance as arterial transmural pressure approached zero [40–42]. Moreover, Altunkan et al. [43] reported that vascular compliance is very high when the transmural pressure is small. Reduced compliance causes an increase in PWV [38,42].

Chen et al. [36] quantified the differences in the effects of external pressure of the pneumatic cuff on arterial volume distensibility between peripheral arteries with different compliance and confirmed that Young's elastic modulus decreased as transmural pressure decreased. In our experiment, compression socks, rather than the pneumatic cuff, decreased transmural pressure. Compression socks exert pressure on the skin, which is transmitted through the tissue to the arterial wall, pressurising the arterial wall and decreasing the arterial transmural wall pressure. As a result, Young's elastic modulus decreases due to the decrease in transcutaneous pressure, which is considered to increase arterial compliance. Accordingly, the stiffness of the peripheral arterial vasculature was reduced, which may have resulted in the differences between upper-arm and ankle MAP over socks, as shown in Fig. 4D.

The relationships between the external cuff pressures and arterial volume distensibility and between the external cuff pressures and PWV, according to Zheng et al., are shown in Fig. 7 [27]. In their study, a cuff was wrapped around the upper limb, external cuff pressure was applied, and the relationships between external cuff pressure, arterial volume distensibility, and pulse wave velocity were investigated as shown in Fig. 7. A total of 100 healthy normotensive subjects wore a specially designed 50-cm-long cuff, and five different external pressures (0, 10, 20, 30, and 40) were applied. Finger and ear photoplethysmograms were recorded simultaneously to measure pulse propagation time, PWV, and arterial volume dilation rate in the arm. As shown in Fig. 5, our study showed that ba-PWV improves by 0.63 m/s at an external pressure of roughly 10 mmHg. Similarly, in Zheng's study, the PWV of the upper limb was

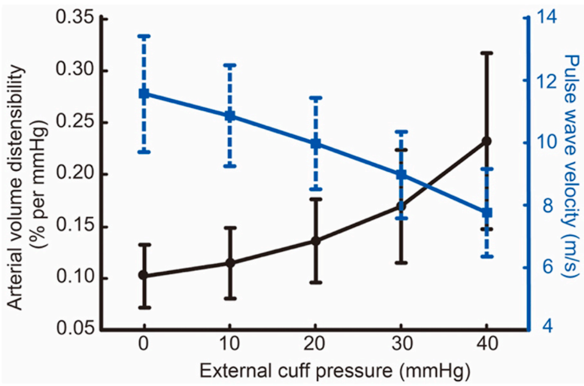

Fig. 7. Relationships among external cuff pressure, arterial volume distensibility, and pulse wave velocity in the upper extremity.
In the case of external cuff pressures on the horizontal axis and arterial volume distensibility on the vertical axis, the mechanical characteristics are as shown by the black line. As the external cuff pressures increase, arterial volume distensibility increases. In addition, external cuff pressure increases, and pulse wave velocity decreases (adapted from Zheng et al. [27]).

decreased by approximately 0.6 m/s at an external cuff pressure of 5–10 mmHg. While the previous study focused on the upper limb, our study was conducted on the lower limb; nevertheless, we observed a similar improvement in ba-PWV with the application of a comparable pressure. Additionally, arterioles are downstream of resistance vessels. This contributes to blood pressure and capillary pressure control and significantly influences the determination and management of vascular resistance and blood pressure [44–46]. The blood pressure in the microvessels is reportedly approximately 35 mmHg [47]. The pressure of the socks was close to the blood pressure of the arterioles, suggesting that the pressure of the soft tissue-mediated compression socks reduced the arteriolar transmural pressure difference.

Fig. 6A shows the results of a random forest to search for dependent variables that are closely related to the improved ba-PWV. The independent variables included height, weight, body mass index (BMI), DIA, SYS, MAP, and pulse pressure, but the only parameter closely related to ba-PWV was ankle joint DIA. For the group of participants whose ankle joint DIA was above 70.6 mmHg, wearing compression socks tended to largely decrease the ba-PWV value, while those with DIA less than 70.6 mmHg experienced a smaller effect. Between the two groups, the extent of the decrease in ba-PWV was significantly different (Fig. 6B, $p < 0.05$).

This study evaluated the acute effect of compression socks on arterial compliance for the first time. Further investigations are warranted to explore the long-term effects of compression socks on vascular health and to determine the optimal compression level, sock design, and duration of use across different populations. Studies examining the impact of compression socks on endothelial function and markers of inflammation could provide valuable insights into their potential role in preventing peripheral arterial disease. To date, compression therapy has primarily been applied to the venous system and is generally contraindicated in patients with peripheral artery disease (PAD). However, clinical trials have demonstrated that both intermittent pneumatic compression devices and sustained compression from bandages and stockings can enhance arterial blood flow beneath compression and improve limb haemodynamics in patients with PAD [48]. In a study involving patients with PAD or diabetes mellitus, compression therapy did not significantly impair microcirculatory parameters, such as haemoglobin oxygen saturation and blood flow [49]. Clarifying the mechanisms through which compression socks and other compression therapies affect arterial function could help maintain low PWV, thereby promoting arterial compliance. On the contrary, patients with blood circulation problems in the lower limbs must be excluded, and this warrants further investigation.

5. Study limitations

A limitation of this study is the lack of age variation, which may limit the generalisability of the results. Moreover, since many participants in this study had relatively low blood pressure, it will be necessary in the future to verify the effect of compression socks on individuals with higher blood pressure. The correlation between ba-PWV and RHR should also be explored in future experiments involving middle-aged and older participants.

The measurements in this experiment followed the common and widely accepted protocol for PWV measurement. Since ankle blood pressure measurements were used as temporal data for the PWV measurements, changes in the radius of curvature of the ankle likely had a minimal effect on PWV. However, given that changes in the radius of curvature may still have influenced the results of this study, this aspect should be considered in future investigations. Furthermore, the effects of ageing, higher BMI, and reduced glomerular filtration rate have already been documented [50,51], and these factors must be accounted for in future analyses.

This study adopted the wearing time of the socks for 10 min to demonstrate that even a short duration of use is effective in improving ba-PWV. Although the long-term effect was evaluated in relation to swelling and the results indicated effectiveness [26], the long-term impact on ba-PWV has not yet been verified, which remains to be evaluated in future research.

Bandage pressure or intermittent pneumatic compression of the foot and calf increases lower limb perfusion, improves intermittent claudication, and increases walking distance. It is also effective in improving the ejection fraction of the venous pump and in increasing popliteal artery volume flow [51–53]. However, caution must be exercised regarding the strength of pressure. In fact, inappropriate compression therapy has been reported to cause prolonged healing, pain, traumatic injury, and even limb amputation [54]. Previous studies [54–56] suggest that the strength class of pressure applied to the foot via medical compression socks varies between countries; the socks used in this study were classified as Class IV within the Compression Class classification, and thus, it is likely they did not apply substandard pressure to the lower leg [54,57]. Nevertheless, further studies are needed to determine the appropriate pressure range applied to the skin surface or arterial wall.

6. Conclusion

This study provides evidence that wearing compression socks is beneficial for arterial function, which may have important implications for people with impaired vascular function, although individual factors and effects of external pressure need to be explored to validate the effects of compression socks further.

CRediT authorship contribution statement

Kosuke Morinaga: Writing – original draft. **Masako Nakahara:** Validation. **Kotaro Matsuura:** Data curation. **Shigekazu Ishihara:** Software, Formal analysis. **Yasuhiro Idobata:** Resources. **Takafumi Kobata:** Resources. **Toshio Tsuji:** Supervision.

Ethical statement

This study was approved by the Hiroshima International University Research Ethics Committee (Protocol #19–027). All experiments were conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all study participants before conducting the experiments.

Data availability statement

The datasets generated during and/or analysed in the present study are available from the corresponding authors on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the JSPS KAKENHI grant (23K11973). We are also grateful to the study volunteers for their participation.

References

[1] J.P. Galanaud, J.P. Laroche, M. Righini, The history and historical treatments of deep vein thrombosis, J. Thromb. Haemostasis 11 (2013) 402–411, https://doi.org/10.1111/jth.12127.
[2] C.L. Felty, T.W. Rooke, Compression therapy for chronic venous insufficiency, Semin. Vasc. Surg. 18 (2005) 36–40, https://doi.org/10.1053/j.semvascsurg.2004.12.010.
[3] L.J. Loss, F. Lurie, G. Kasper, F.C. Brunicardi, J.J. Sferra, Conrad Jobst: from illness to innovation, Am. Surg. 89 (2020) 000313482095243, https://doi.org/10.1177/0003134820952434.
[4] R.R. Attaran, C.I.O. Chaar, Compression therapy for venous disease, Phlebology 32 (2017) 81–88, https://doi.org/10.1177/0268355516633382.
[5] J.L. Beebe-Dimmer, J.R. Pfeifer, J.S. Engle, D. Schottenfeld, The epidemiology of chronic venous insufficiency and varicose veins, Ann. Epidemiol. 15 (2005) 175–184, https://doi.org/10.1016/j.annepidem.2004.05.015.
[6] R.B. McLafferty, J.M. Lohr, J.A. Caprini, M.A. Passman, F.T. Padberg, T.W. Rooke, R.L. Bush, A.A. Zakaria, W.R. Flinn, B.G. Eklof, M.C. Dalsing, S.J. Markwell, T. W. Wakefield, Results of the national pilot screening program for venous disease by the American venous forum, J. Vasc. Surg. 45 (2007) 142–148.e4, https://doi.org/10.1016/j.jvs.2006.08.079.
[7] R.M. Kaplan, M.H. Criqui, J.O. Denenberg, J. Bergan, A. Fronek, Quality of life in patients with chronic venous disease: San Diego population study, J. Vasc. Surg. 37 (2003) 1047–1053, https://doi.org/10.1067/mva.2003.168.
[8] G.K. Nandasiri, A.M. Shahidi, T. Dias, Study of three interface pressure measurement systems used in the treatment of venous disease, Sensors 20 (2020) 5777, https://doi.org/10.3390/s20205777.
[9] A.J. van Geest, J.C.J.M. Veraart, P. Nelemans, H.A.M. Neumann, The effect of medical elastic compression stockings with different slope values on edema, Dermatol. Surg. 26 (2000) 244–247, https://doi.org/10.1046/j.1524-4725.2000.09200.x.
[10] M. de A. Correia, G.G. Cucato, F.C. Lanza, R.A.O. Peixoto, A.E. Zerati, P. Puech-Leao, N. Wolosker, R.M. Ritti-Dias, Relationship between gait speed and physical function in patients with symptomatic peripheral artery disease, Clinics 74 (2019) e1254, https://doi.org/10.6061/clinics/2019/e1254.
[11] K.T. Dahm, H.T. Myrhaug, H. Strømme, B. Fure, K.G. Brurberg, Effects of preventive use of compression stockings for elderly with chronic venous insufficiency and swollen legs: a systematic review and meta-analysis, BMC Geriatr. 19 (2019) 76, https://doi.org/10.1186/s12877-019-1087-1.
[12] K. Baige, F. Noé, T. Paillard, Wearing compression garments differently affects monopodal postural balance in high-level athletes, Sci. Rep. 10 (2020) 15331, https://doi.org/10.1038/s41598-020-72347-2.
[13] C.R. Lattimer, M. Azzam, E. Kalodiki, G.C. Makris, G. Geroulakos, Compression stockings significantly improve hemodynamic performance in post-thrombotic syndrome irrespective of class or length, J. Vasc. Surg. 58 (2013) 158–165, https://doi.org/10.1016/j.jvs.2013.01.003.
[14] T. Dermont, L. Morizot, M. Bouhaddi, A. Ménétrier, Changes in tissue oxygen saturation in response to different calf compression sleeves, J. Sports Med. 2015 (2015) 857904, https://doi.org/10.1155/2015/857904.
[15] R. Liu, T.T. Lao, Y.L. Kwok, Y. Li, M.T.-C. Ying, Effects of graduated compression stockings with different pressure profiles on lower-limb venous structures and haemodynamics, Adv. Ther. 25 (2008) 465, https://doi.org/10.1007/s12325-008-0058-2.
[16] C.S. Lim, A.H. Davies, Graduated compression stockings, Can. Med. Assoc. J. 186 (2014) E391–E398, https://doi.org/10.1503/cmaj.131281.
[17] D. Lawrence, V.V. Kakkar, Graduated, static, external compression of the lower limb: a physiological assessment, Brit, J. Surg. 67 (1980) 119–121, https://doi.org/10.1002/bjs.1800670214.
[18] T.F. O'Donnell, D.A. Rosenthal, A.D. Callow, B.L. Ledig, Effect of elastic compression on venous hemodynamics in postphlebitic limbs, JAMA 242 (1979) 2766–2768, https://doi.org/10.1001/jama.1979.03300250022022.
[19] O. Agu, D. Baker, A.M. Seifalian, Effect of graduated compression stockings on limb oxygenation and venous function during exercise in patients with venous insufficiency, Vascular 12 (2004) 69–76, https://doi.org/10.1258/rsmvasc.12.1.69.
[20] V. Ibegbuna, K.T. Delis, A.N. Nicolaides, O. Aina, Effect of elastic compression stockings on venous hemodynamics during walking, J. Vasc. Surg. 37 (2003) 420–425, https://doi.org/10.1067/mva.2003.104.
[21] B.R. Cavalcante, R.M. Ritti-Dias, A.H.G. Soares, W.J.R. Domingues, G.F. Saes, F.H. Duarte, A. de P. da Cruz, N. Wolosker, P. Puech-Leão, G.G. Cucato, A. E. Zerati, Graduated compression stockings does not decrease walking capacity and muscle oxygen saturation during 6-minute walk test in intermittent claudication patients, Ann. Vasc. Surg. 40 (2017) 239–242, https://doi.org/10.1016/j.avsg.2016.10.027.
[22] K. Rennerfelt, S. Lindorsson, H. Brisby, A. Baranto, Q. Zhang, Effects of exercise compression stockings on anterior muscle compartment pressure and oxygenation during running: a randomized crossover trial conducted in healthy recreational runners, Sports Med. 49 (2019) 1465–1473, https://doi.org/10.1007/s40279-019-01103-y.
[23] M.C. Moloney, G.M. Lyons, P. Breen, P.E. Burke, P.A. Grace, Haemodynamic study examining the response of venous blood flow to electrical stimulation of the gastrocnemius muscle in patients with chronic venous disease, Eur. J. Vasc. Endovasc. 31 (2006) 300–305, https://doi.org/10.1016/j.ejvs.2005.08.003.

[24] F. Vercruyssen, C. Easthope, T. Bernard, C. Hausswirth, F. Bieuzen, M. Gruet, J. Brisswalter, The influence of wearing compression stockings on performance indicators and physiological responses following a prolonged trail running exercise, Eur. J. Sport Sci. 14 (2014) 144–150, https://doi.org/10.1080/17461391.2012.730062.

[25] M. Kinoshita, Y. Kurosawa, S. Fuse, R. Tanaka, N. Tano, R. Kobayashi, R. Kime, T. Hamaoka, Compression stockings suppressed reduced muscle blood volume and oxygenation levels induced by persistent sitting, Appl. Sci. 9 (2019) 1800, https://doi.org/10.3390/app9091800.

[26] K. Morinaga, S. Ishihara, S. Tarumoto, N. M, T. Tsuji, T. Tsuji, Comparison of fully and partly compression socks for prevention of leg swelling during the working daytime, J. Vasc. Med. Surg. 11 (2023) 1–7, https://doi.org/10.35248/2329-6925.23.11.497.

[27] D. Zheng, A. Murray, Peripheral arterial volume distensibility: significant differences with age and blood pressure measured using an applied external pressure, Physiol. Meas. 32 (2011) 499–512, https://doi.org/10.1088/0967-3334/32/5/001.

[28] D. Zheng, A. Murray, Non-invasive quantification of peripheral arterial volume distensibility and its non-linear relationship with arterial pressure, J. Biomech. 42 (2009) 1032–1037, https://doi.org/10.1016/j.jbiomech.2009.02.011.

[29] M. Chen, A. Chen, X. Si, M. Ji, D. Zheng, Peripheral arterial volume distensibility changes with applied external pressure: significant difference between arteries with different compliance, Sci. Rep. 7 (2017) 40545, https://doi.org/10.1038/srep40545.

[30] G. James, D. Witten, T. Hastie, R. Tibshirani, An Introduction to Statistical Learning, with Applications in R, second ed., Springer Texts Statistics, 2021, pp. 553–595, https://doi.org/10.1007/978-1-0716-1418-1_13.

[31] L. Breiman, Random forests, Mach. Learn. 45 (2001) 5–32, https://doi.org/10.1023/a:1010933404324.

[32] S. Seifert, Application of random forest based approaches to surface-enhanced Raman scattering data, Sci. Rep. 10 (2020) 5436, https://doi.org/10.1038/s41598-020-62338-8.

[33] N. Aguirre, E. Grall-Maës, L.J. Cymberknop, R.L. Armentano, Blood pressure morphology assessment from photoplethysmogram and demographic information using deep learning with attention mechanism, Sensors Basel Switz 21 (2021) 2167, https://doi.org/10.3390/s21062167.

[34] T. Takano, M. Iwai-Takano, Y. Tsuboko, Y. Shiraishi, T. Yambe, T. Igarashi, H. Yokoyama, Reflected wave intensity increases based on aortic diameter after endovascular aortic therapy in a goat model, Sci. Rep. 11 (2021) 3830, https://doi.org/10.1038/s41598-020-80920-y.

[35] Y. Aggoun, I. Szezepanski, D. Bonnet, Noninvasive assessment of arterial stiffness and risk of atherosclerotic events in children, Pediatr. Res. 58 (2005) 173–178, https://doi.org/10.1203/01.pdr.0000170900.35571.cb.

[36] A. Avolio, Arterial stiffness, Pulse 1 (2013) 14–28, https://doi.org/10.1159/000348620.

[37] B.M. Pannier, A.P. Avolio, A. Hoeks, G. Mancia, K. Takazawa, Methods and devices for measuring arterial compliance in humans, Am. J. Hypertens. 15 (2002) 743–753, https://doi.org/10.1016/s0895-7061(02)02962-x.

[38] M. Cecelja, P. Chowienczyk, Role of arterial stiffness in cardiovascular disease, J. Cardiovasc. Dis. 1 (2012) 1–10, https://doi.org/10.1258/cvd.2012.012016.

[39] S. Laurent, J. Cockcroft, L.V. Bortel, P. Boutouyrie, C. Giannattasio, D. Hayoz, B. Pannier, C. Vlachopoulos, I. Wilkinson, H. Struijker-Boudier, Expert consensus document on arterial stiffness: methodological issues and clinical applications, Eur. Heart J. 27 (2006) 2588–2605, https://doi.org/10.1093/eurheartj/ehl254.

[40] A.J. Bank, R.F. Wilson, S.H. Kubo, J.E. Holte, T.J. Dresing, H. Wang, Direct effects of smooth muscle relaxation and contraction on in vivo human brachial artery elastic properties, Circ. Res. 77 (1995) 1008–1016, https://doi.org/10.1161/01.res.77.5.1008.

[41] A.J. Bank, Physiologic aspects of drug therapy and large artery elastic properties, Vasc, Méd. 2 (1997) 44–50, https://doi.org/10.1177/1358863x9700200107.

[42] S.P. Glasser, D.K. Arnett, G.E. McVeigh, S.M. Finkelstein, A.J. Bank, D.J. Morgan, J.N. Cohn, Vascular compliance and cardiovascular disease: a risk factor or a marker? Am. J. Hypertens. 10 (1997) 1175–1189, https://doi.org/10.1016/s0895-7061(97)00311-7.

[43] S. Altunkan, K. Oztas, B. Seref, Arterial stiffness index as a screening test for cardiovascular risk: a comparative study between coronary artery calcification determined by electron beam tomography and arterial stiffness index determined by a VitalVision device in asymptomatic subjects, Eur. J. Intern. Med. 16 (2005) 580–584, https://doi.org/10.1016/j.ejim.2005.06.011.

[44] W.F. Jackson, Myogenic tone in peripheral resistance arteries and arterioles: the pressure is on, Front. Physiol. 12 (2021) 699517, https://doi.org/10.3389/fphys.2021.699517.

[45] P.C. Johnson, Overview of the microcirculation, Microcirculation (2008), https://doi.org/10.1016/b978-0-12-374530-9.00022-x xi–xxiv.

[46] G.D. Thomas, Neural control of the circulation, Adv. Physiol. Educ. 35 (2011) 28–32, https://doi.org/10.1152/advan.00114.2010.

[47] W.M. Chilian, C.L. Eastham, M.L. Marcus, Microvascular distribution of coronary vascular resistance in beating left ventricle, Am. J. Physiol. 251 (1986) H779–H788, https://doi.org/10.1152/ajpheart.1986.251.4.h779.

[48] M.A. Nickles, W.J. Ennis, T.F. O'Donnell Jr., I.A. Altman, Compression therapy in peripheral artery disease: a literature review, J. Wound Care 32 (2023) S25–S30, https://doi.org/10.12968/jowc.2023.32.Sup5.S25.

[49] U. Rother, A. Grussler, C. Griesbach, et al., Safety of medical compression stockings in patients with diabetes mellitus or peripheral arterial disease, BMJ Open Diabetes Res (2020) e001316, https://doi.org/10.1136/bmjdrc-2020-001316. Care. 8.

[50] S.W. Lee, S.H. Han, T.H. Yoo, W. Chung, S.K. Park, D.W. Chae, C. Ahn, K.H. Oh, Relationship between brachial-ankle and heart-femoral pulse wave velocities and the rapid decline of kidney function, Sci. Rep. 8 (2018) 821, https://doi.org/10.1038/s41598-018-19334-w.

[51] Y.H. Lin, K.T. Sung, C.T. Tsai, P.C. Wu, Y.H. Lai, C.I. Lo, F.C. Yu, H.P. Wu, W.R. Lan, J.Y. Kuo, C.J. Hou, C.H. Yen, M.C. Peng, T.C. Hung, C.L. Hung, E. Lai, H. I. Yeh, The relationship of renal function to segmental vascular stiffness, ankle-brachial index, and peripheral artery disease, J. Clin. Hypertens. 20 (2018) 1027–1035, https://doi.org/10.1111/jch.13297.

[52] S.K. Kakkos, G. Geroulakos, A.N. Nicolaides, Improvement of the walking ability in intermittent claudication due to superficial femoral artery occlusion with supervised exercise and pneumatic foot and calf compression: a randomised controlled trial, Eur. J. Vasc. Endovasc. Surg. 30 (2005) 164–175, https://doi.org/10.1016/j.ejvs.2005.03.011.

[53] G. Mosti, M.L. Iabichella, H. Partsch, Compression therapy in mixed ulcers increases venous output and arterial perfusion, J. Vasc. Surg. 55 (2012) 122–128, https://doi.org/10.1016/j.jvs.2011.07.071.

[54] D. Mikucioniene, L. Halavska, L. Melnyk, R. Milašius, G. Laureckiene, S. Arabuli, Classification, Structure and Construction of functional orthopaedic compression knits for medical application: a review, Appl. Sci. 14 (2024) 4486, https://doi.org/10.3390/app14114486.

[55] H.F. Siddique, A.A. Mazari, A. Havelka, Z. Kus, E. Akcagun, Washing Characterization of compression socks, Autex Res. J. 23 (2023) 323–339, https://doi.org/10.2478/aut-2022-0009.

[56] M. Lozo, Ž. Penava, I. Lovričević, Z. Vrljičak, The structure and compression of medical compression stockings, Materials 15 (2022) 353, https://doi.org/10.3390/ma15010353.

[57] M. Stücker, O. Danneil, M. Dörler, M. Hoffmann, E. Kröger, S. Reich-Schupke, Safety of a compression stocking for patients with chronic venous insufficiency (CVI) and peripheral artery disease (PAD), J. Ger, Soc. Dermatol. 18 (2020) 207–213, https://doi.org/10.1111/ddg.14042.