Optimization of Cushion and Back Angles for Lower Limb Blood Flow and Its Verification Experiment

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Abstract

In recent years, desk workers sitting in a chair for many hours have some problems: swelling of lower limbs, congestion, pressure ulcer and etc. This study aims to clarify the optimal cushion and back angles. For this aim, the changes in lower limb blood flow causing these symptoms were measured to each combination of the cushion and back angles. As a result, it was confirmed that the shear and compressive forces between the buttock and the seat fluctuated by the cushion and back angles strongly influence lower limb blood flow. This study derived the optimal cushion and back angles by the weighting factor method using the contribution ratio of the shear and compressive forces in lower limb blood flow as the weighting factors.

Keywords: ergonomic design, lower limb blood flow, seat, shear force

1 Introduction

Due to the developments in IT industry, workers sitting on the chair for many hours have been increasing. This causes some work-related diseases: stiff shoulders, swelling of lower limbs and congestion. Swelling of lower limbs and congestion are the symptoms that humor leaks from the blood vessels into the interstitium. The factor contributing to this leakage is the failure of the venous pump boosting the blood to the heart do not work and the capillary pressure goes up in the case of prolonged sitting [1].

On the other hand, due to the ultra-high age society, wheelchair users and elderly who can not move by themselves also have been increasing [2]. This causes the pressure ulcer. Pressure ulcer is the symptom that tissue around the blood vessels becomes necrosis due to the decrease of the blood flow for many hours when the buttocks, the backbone and the elbow are compressed [3].

These symptoms are caused by the blood stagnation in the lower limb vein. Especially, the blood is likely to pool in the lower limb without returning to the heart due to gravity [4], [5]. Therefore, it is important to prevent the blood pooling in the lower limb vein. Here, the lower limb vein has three kinds of the blood vessel: superficial vein, deep vein and perforator [6]. In these, superficial vein appears immediately beneath the skin at the calf and whose blood flow can be easily to be measured. Therefore, in this study, the lower limb blood flow is considered to be important in the design of the chair and be suitable to evaluate the superficial vein.

This study aims to derive the optimal cushion and back angles for preventing the lower limb blood flow decline causing the above symptoms and performs its verification experiment.

2 Blood Flow Measurement with Change in Cushion and Back Angles

2.1 Method

In this study, a railway vehicle seat (limited express train "Hatsukari") with large change of the cushion and back angles was chosen as the experimental seat. The height from the floor to the tip of the seat was decided to be adjusted in accordance with the subject physique using the footstool because the height lifts the subject's foot off the floor and affects the blood flow by compressing the subject's buttock. The blood flow was decided to be measured using the laser Doppler blood flowmeter for measuring the blood flow in skin microcirculation related to the congestion and swelling of lower limbs.

The subjects are three males in their twenties, whose height and weight are (1.75 m, 75 kg), (1.68 m, 58 kg) and (1.69 m, 60 kg). These values are ±0.04 m and ±12 kg from the average values of Japanese male (1.71 m, 63.3 kg). Sitting postures of the subjects follow the four conditions:

1) The lumbar is touched on the backrest and the head is touched on the headrest.
2) The legs are put together.
3) The hands are put on the thighs.
4) The knees are bent as the thighs put on the seat.

The measurement environment is set to the following five conditions:

1) The room air temperature is set at 26±1°C and the humidity at 60% (for decreasing the measurement error of blood flow in the vessel constriction due to the change of the room air temperature or the amount of sweating due to the change of the humidity) [2], [7].
2) The wind of the air conditioning does not direct at the subjects (for preventing the decreased body temperature due to this wind [8]).
3) The measurement is conducted from 1 pm to 5 pm because the daily skin blood flow is fluctuated due to the diurnal variation in the core body temperature [9].
4) The subjects have sat down in a resting state more than 30 minutes before the measurement [10].
5) The measurement is conducted three hours after meals (for decreasing the measurement error due to the decrease of skin blood flow after eating) [7].

The sensor (probe) position is decided to be middle of the calf because of the following four reasons:

1) The thigh pressed by the seat is eliminated because the pressure fluctuates the measurement values [11].
2) The distal portion of the extremities having large fluctuation in blood flow is excluded [5].
3) The shin is removed due to the concavity and convexity that makes the attachment of the probe be difficult [12].
4) The inside of the leg under which the great saphenous vein (one of the longest superficial vein from the dorsum of foot to the groin area) flows is favorable [6].

The measurement procedures are as follows:

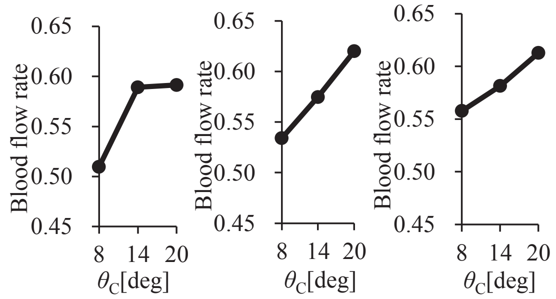
1) The blood flow when the subjects lie down on the air bed in the supine position is measured.
2) The blood flow when they sit down on the chair in the standard sitting posture is measured.
3) The blood flow rate (the ratio of 1) and 2)) is calculated because the values measured by the flowmeter can only be compared relatively between the experimental conditions: probe attachments.
4) The calculation of the blood flow rate (1) through 3)) is repeated five times for each combination of the cushion and back angles, which the levels of each angle are the maximum, the minimum and the intermediate value in the general angle of the seat (back angle: θ_B = 20°, 30° and 40° and cushion angle: θ_C = 8°, 14° and 20°) and all combinations are conducted.
5) The trimmed mean of the blood flow rates is calculated.

2.2 Results and Discussion

Statistical analysis of variance (ANOVA) was performed to identify the response of the cushion and back angles to the blood flow rate. **Table 1** shows the ANOVA results for the blood flow rate with the cushion and back angles. From this table, it is concluded that the variance ratio F_0 of the cushion angle is significant with 99% confidence compare to other factors. **Figure 1** shows the change of the blood flow rate with respect to both cushion and back angles. This figure shows that the blood flow rate increases both with the cushion and back angles. This suggests two hidden factors of the blood flow rate. The first is the compressive force in the buttock that is fluctuated with the back angle. This force decreases when the back angle is large. Thus this is considered to be increased the blood flow rate. Now, it is known that this force influences the lower limb blood flow in the conventional study. The second is the shear force in the buttock that is fluctuated with the cushion angle. This force increases when the cushion angle is large. Thus the change of the blood flow rate in **Figure 1** is estimated that it issued because the shear force in the buttock is small when the cushion angle is large. Hence, we focused on the shear force in the buttock in addition to the compressive force as the factors of the blood flow, and conducted the measurement of the blood flow regarding these force, shown in the next chapter.

Table 1 ANOVA table for back angle and cushion angle

Factor	Sum of square	D.F.	Mean of quare	F_0	F-value
θ_B	0.00191	2	0.000957	1.93	3.55
θ_C	0.0254	2	0.0127	25.6**	3.55
θ_B and θ_C	0.00314	4	0.000786	1.58	2.92
Repeatability error	0.00892	18	0.000495		
Total	0.0394	26			



(a) θ_B=20° (b) θ_B=30° (c) θ_B=40°

Fig. 1 Blood flow rate regarding cushion angle

3 Blood Flow Measurement with Change in Share Force and Compressive Force

3.1 Method

In this experiment, the cushion and back angles are used as the parameters for setting the shear and compressive forces. Other conditions are the same as the ones of the second chapter. This study derives the cushion and back angles by the following procedures:

1) The shear and compressive forces are estimated by the rigid link model of human body and seat (**Figure 2**) [13].
2) The cushion and back angles, where the shear and compressive forces are distributed in the two-way layout, are derived by Genetic Algorithm (GA).

The details of these procedures are described as follows.

The equilibrium of the lateral force in the middle part of the patella is derived from:

$$F_1 = \frac{-F_2 \cos \theta_C}{\cos \theta_{An}} \tag{1}$$

where, F_1 is the axial force in the section of lower thigh and F_2 is the axial force in the section of thigh. The balancing of the longitudinal force in the middle part of the patella is derived from:

$$F_2 = \frac{M_1 l_{1b} g + M_2 l_{2a} g}{\sin\theta_C - \cos\theta_C \tan\theta_{An}} \quad (2)$$

The equation of the axial force in the section of lumbar and chest in third lumbar spine is derived from:

$$F_3 = \frac{F_4 + (M_4 l_{4a} g + M_3 l_{3b} g)(\cos\theta_B - \kappa \sin\theta_B)}{-\cos\theta_{Ab} + \kappa \sin\theta_{Ab}} \quad (3)$$

where, F_3 is the axial force in the section of pelvis and F_4 is the axial force in the section of lumbar and chest. The equilibrium of the axial force in the section of lumbar and chest in tenth thoracic spine is derived from:

$$F_4 = (M_5 g + M_4 l_{4b} g)(\cos\theta_B - \kappa \sin\theta_B) \quad (4)$$

The lateral force F_h and the longitudinal force F_v on the trochanter major are derived using these forces, such that:

$$F_h = F_2 \cos\theta_C - F_3 \cos(\theta_{Hi} + \theta_C) \quad (5)$$

$$F_v = F_2 \sin\theta_C + F_3 \sin(\theta_{Hi} - \theta_C) + M_2 l_{2b} g + M_3 l_{3a} g \quad (6)$$

The shear force F_S and the compressive force F_C in the buttock are derived from these formulas, such that:

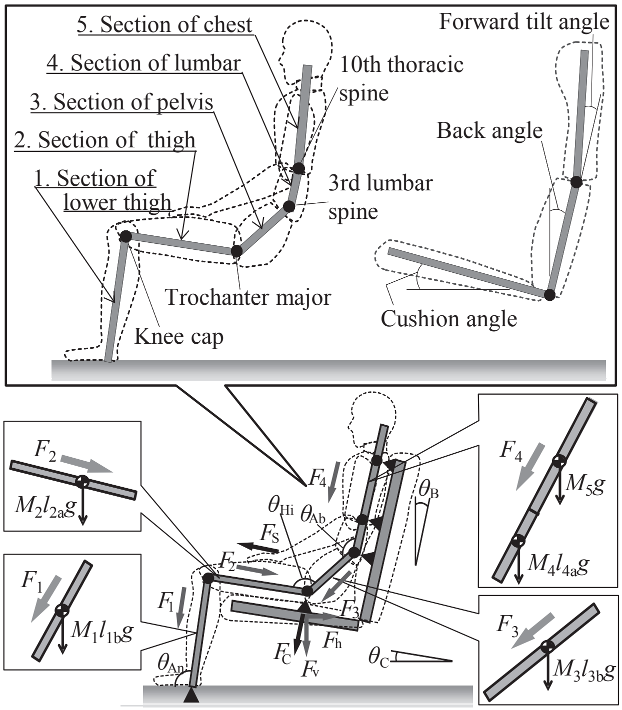
$$F_S = -F_h \cos\theta_C - F_v \sin\theta_C - \kappa(-F_h \sin\theta_C + F_v \cos\theta_C) \quad (7)$$

$$F_C = -F_h \sin\theta_C + F_v \cos\theta_C \quad (8)$$

GA is one of the most common meta-heuristics that can search the approximate solutions effectively to the optimization problems requiring the huge amount of calculation. The combinations of the cushion and back angles are derived by this method because this is a combinatorial optimization problem requiring the huge amount of calculation. Therefore, GA in which gene is allocated to four combinations of the cushion and back angles searches the solution. Moreover the total of the difference between the shear and compressive forces in four combinations is set as the fitness. Four combinations (θ_B, θ_C) derived by GA are (52.17, 20.00), (24.37, 17.45), (48.74, 9.33) and (20.63, 9.07), and the experiment was conducted in each combination.

3.2 Results and Discussion

ANOVA was performed to identify the response of the shear and compressive forces to the blood flow rate. **Table 2** shows the ANOVA results for the blood flow rate with the shear and compressive forces. This means the significance of the factor and the interaction between factors is concluded that the variance ratio F_0 of the shear force, the back angle and the interaction have effect on the blood flow rate with 99% confidence. **Figure 3** shows the change of the blood flow rate in the shear and compressive forces. This shows that the blood flow rate decreases with increasing both of the shear and compressive forces. Equally from this figure, the

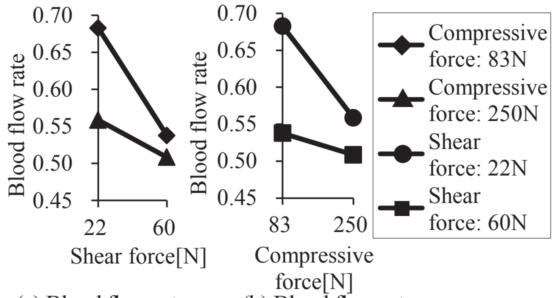


θ_C: seat cushion angle, θ_B: seat back angle, θ_{Hi}: hip angle, θ_{Ab}: abdomen angle, θ_{An}: ankle angle, M_1: weight of lower thigh, l_{1b}: length from lower thigh lower-edge to gravity center, M_2: weight of thigh, l_{2a}: length from thigh upper-edge to gravity center, M_3: weight of pelvis, l_{3b}: length from pelvis lower-edge to gravity center, M_4: weight of lumbar, l_{4a}: length from lumber upper-edge to gravity center, κ: coefficient of frictional resistance, M_5: weight of chest, F_h: horizontal force on trochanter major, F_v: vertical force on trochanter major, F_S: shear force, F_C: compressive force

Fig. 2 Rigid link model of human body and seat

Table 2 ANOVA table for shear and compressive forces

Factor	Sum of square	D.F.	Mean of square	F_0	F-value	Contribution ratio
Shear force	0.0285	1	0.0285	34.6**	5.31	46.60%
Compressive force	0.0176	1	0.0176	21.4**	5.31	28.30%
Shear and Compressive	0.0067	1	0.00674	8.19**	5.31	9.90%
Repeatability error	0.0066	8	0.000823			
Total	0.0594	11				



(a) Blood flow rate in change of shear force
(b) Blood flow rate in change of compressive force

Fig. 3 Blood flow rate regarding shear and compressive forces

interaction is confirmed from that each blood flow rate decreases at the different rate in each graph. Moreover, each contribution ratio of the factors in the blood flow rate is 28.3% in the compressive force and 46.6% in the shear force. Therefore, it is estimated that the rate of the shear force influences the blood flow rate greater than that of compressive force.

This study derived the optimal cushion and back angles for preventing lower limb blood flow decline using these contribution ratios, shown in the next chapter.

4 Derivation of Optimal Cushion and Back Angles

In this study, optimal cushion and back angles are derived using objective functions (shear and compressive forces), design variables (cushion and back angles) and weighting factors (contribution ratios of the shear and compressive forces in the blood flow rate: 46.6% and 28.3%). This study applied a multi-objective optimization method because there is a trade-off relationship between the shear and compressive force. Multi-objective optimization methods derive an optimal solution by minimizing (maximizing) several objective functions with trade-off relationship and include weighting factor method [14], [15], weighted Tchebycheff norm method [14], [16], weighted l_p norm [14], [17], ε-constraint method [14, 18], surrogate worth trade-off method [14], [19], [20] and etc. This study employed the weighting factor method for the following two reasons:

1) The contribution ratios of the shear and compressive forces in the blood flow rate were quantitatively clarified and can be used as the weighting factors.
2) The feasible solution sets $\boldsymbol{F}(\boldsymbol{X})$, which are all combinations of shear and compressive forces derived by the cushion and back angles in their design ranges, are convex as shown in **Figure 4**.

Figure 4 also shows the weighted sum W is minimized in the feasible solution sets $\boldsymbol{F}(\boldsymbol{X})$. Also, the shear and compressive forces in this figure are derived by substituting Japanese male's mean height and weight: 1.71 m and 63.3 kg into the model (**Figure 2**). The dash lines in this figure mean the contour line of the weighted sum. This study minimized (optimized) the weighted sum using quasi-Newton's method and derived the minimum value of the weighted sum and the optimal cushion and back angles: W_1=58.11, θ_C=25° and θ_B=35°.

5 Verification experiment of Optimal Cushion and Back Angles

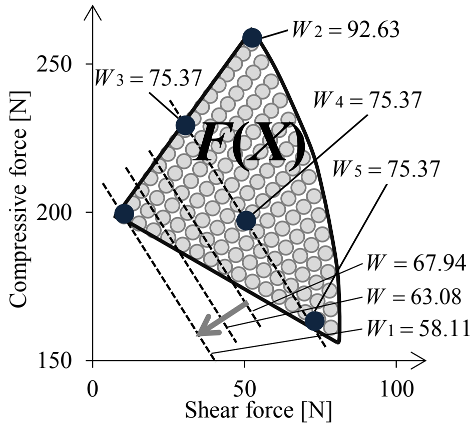
5.1 Method

This study measured the lower limb blood flow with 5 combinations of the cushion and back angles for confirming the validity of the contribution ratios of shear and compressive forces and the derived optimal angles. These angles were decided by the following three types of the weighted sums (**Figure 4**): the minimum weighted sum W_1, the maximum weighted sum W_2 and the intermediate weighted sums $W_3 = W_4 = W_5 = (W_1 + W_2)/2$ derived using different shear and compressive forces in order to confirm the change of the lower limb blood flow regarding the weighted sums.

The subjects are five males in their twenties whose physiques are normal (1.71 ± 0.04 m and 63.3 ± 8.3 kg) (**Table 3**). Other conditions (experiment device, sitting posture, measurement environment, sensor position and measurement procedures) are the same as chapter 2.

5.2 Results and Discussion

ANOVA was performed to identify the effect of the subjects and the weighted sums to the blood flow rate (**Table 4**). In this table, contribution ratio of the subjects is 70.4% and larger than that of the weighted sums (21.1%). Therefore, the effect of the weighted sums on the blood flow rate cannot be confirmed due to a lot of variation in the blood flow rate caused by the subjects. This study normalized the blood flow rate among the subjects by subtracting the average blood



$$\text{minimize} \quad \boldsymbol{W} = w_1 f_1(x_1, x_2) + w_2 f_2(x_1, x_2)$$

$$\text{subject to} \quad (x_1, x_2) \in X = \{(x_1, x_2) \mid 10° \le x_1 \le 25°, 20° \le x_2 \le 35°, x_2 \ge x_1 + 10°\}$$

$f_1(\boldsymbol{x})$: Shear force; $f_2(\boldsymbol{x})$: Compressive force
x_1 : Cushion angle; x_2 : Back angle
w_1 : Contribution ratio of shear force; w_2 : Contribution ratio of compressive force

Fig. 4 Weighted factor method in shear and compressive forces

Table 3 Subject's height and weight

	No.1	No.2	No.3	No.4	No.5
Height [m]	1.70	1.69	1.67	1.70	1.72
Weight [kg]	60	60	59	58	55

Table 4 ANOVA table for weighted sum and subjects

Factor	Sum of square	D.F.	Mean of square	F_0	F-value	Contribution ratio
Weighted sum	0.407	4	0.101	119**	3.71	21.1%
Subjects	1.35	4	0.337	396**	3.71	70.4%
Interaction	0.112	16	0.00703	8.26**	2.38	5.16%
Repeatability error	0.0425	50	0.000851			
Total	1.91	74				

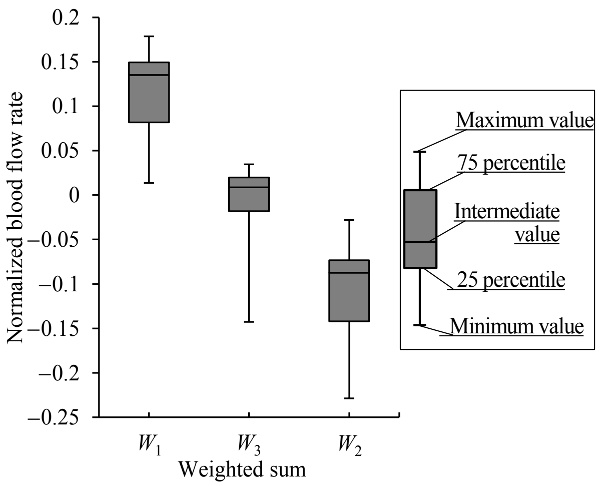


Fig. 5 Normalized blood flow rate of maximum, minimum and intermediate weighted sums

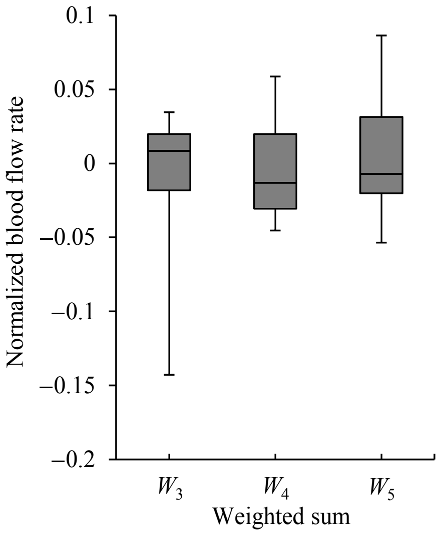


Fig. 6 Normalized blood flow rate of intermediate weighted sums

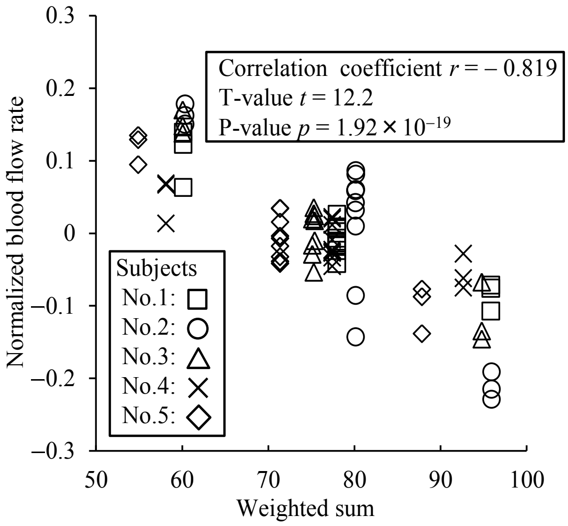


Fig. 7 Correlation analysis of weighted sum and normalized blood flow rate

flow rate of each subject, in order to confirm the effect of the weighted sums on the blood flow rate.

Figures 5 and 6 show the boxplot of normalized blood flow rate in two groups of the weighted sums: (W_1, W_2 and W_3) and (W_3, W_4 and W_5), respectively. **Figure 5** shows that the normalized blood flow rate decreases with increasing the weighted sums (i.e., the normalized blood flow rate of the minimum (optimized) weighted sum W_1 is the highest). On the other hand, **Figure 6** shows that the normalized blood flow rate does not vary with the constant weighted sums.

Figure 7 shows the scatterplots of the weighted sums and the normalized blood flow rate and the result of the correlation analysis. The scatterplots shows that the blood flow rate decreases with increasing the weighted sum. Meanwhile, the correlation coefficient is –0.819. Additionally, the result of the test for no correlation shows that the derived correlation coefficient is significant with 99% confidence.

Consequently, the validity of the contribution ratios of the shear and compressive forces and the optimal angles were confirmed.

6 Conclusions

This study clarified the influence of the shear and compressive forces to the blood flow by measuring the lower limb blood flow with change in the cushion and back angles. As a result, the influence of the shear force to the blood flow rate was larger than that of the compressive force. The contribution ratios of these forces were derived 46.6% and 28.3%, respectively.

This study derived the optimal cushion and back angles for preventing lower limb blood flow decline using these contribution ratios. The optimal angles (θ_C=25° and θ_B=35°) were derived using the weighting factor method because these contribution ratios can be used as the weighting factors.

The experiment for confirming the validity of the contribution ratios of the shear and compressive forces and the optimal angles clarified the following:

- The blood flow rate decreases with increasing the weighted sums; it does not vary with the constant weighted sums.
- The normalized blood flow rate of the minimum (optimized) weighted sum is the highest.
- There is the proportional relationship of the weighted sum and the normalized blood flow rate and the correlation coefficient is –0.819.

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