OPTIMIZATION OF CUSHION AND BACK ANGLES FOR LOWER LIMB BLOOD FLOW AND ITS VERIFICATION EXPERIMENT

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Abstract: In recent years, people sitting for many hours have some problems: pressure ulcer, congestion and etc. This study aims to clarify the optimal cushion and back angles to prevent these diseases by measuring the changes in lower limb blood flow in the cushion and back angles. The result shows the shear and compressive forces between the buttock and the seat, fluctuated by the cushion and back angles, affect the blood flow. This study also derives the optimal angles by the weighting factor method using the contribution ratio of these forces in blood flow as the weighting factors. Additionally, this study confirms the validity of the contribution ratios and the derived optimal angles. The result indicates a proportional relationship between the blood flow and the weighted sums of the forces, calculated using the contribution ratios, and the highest blood flow measured with the derived optimal angles.

Keywords: Ergonomic design, Lower limb blood flow, Seat

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 that the venous pump boosting the blood to the heart does 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 cannot move by themselves also have been increasing [2]. This causes the pressure ulcer 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 without returning to the heart due to gravity [4, 5]. 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 measured easily. Therefore, this study considers the lower limb blood flow is 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 to perform its verification experiment.

2. Blood Flow Measurement with Change in Cushion and Back Angles

2.1. Method

This study chose a railway vehicle seat (limited express train “Hatsukari”) with large change of the cushion and back angles 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 seat lifts the subject's foot off the floor and affects the lower limb blood flow by compressing the subject's buttock. Table 1 compares the measurement methods of blood flow: ultrasonic Doppler method, laser Doppler method and near-infrared spectroscopy (NIRS). This study employed laser Doppler blood flowmeter for measuring the blood flow in skin microcirculation related to the congestion and swelling of lower limbs.

Female sweating amount is lower than that of male due to the influence of estradiol cycle. Therefore, female thermal radiation by skin vasodilatation also occurs more frequently to compensate the lower sweating, causing female cutaneous blood flow fluctuates wildly [7]. Thus, this study chose three men in their twenties as the subjects. Their 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 to ensure the standard sitting posture (Figure 1)[8]:

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 six 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 humidity [2, 9];
2) The wind of the air conditioning does not direct at the subjects for preventing the decreased body temperature due to this wind [10];
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 [11];
4) The subjects sit down in a resting state more than 30 minutes before the measurement [12, 13];
5) The measurement is conducted three hours after meals for decreasing the measurement error due to the decrease of skin blood flow after eating [9, 12, 13, 14];
6) The subjects abstain from caffeine and smoking for 12 hours [13, 14, 15, 16, 17] and refrain from alcohol for 24 hours [16, 17].

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 [18];
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 [19];
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 (Figure 2(a));

<table>
<thead>
<tr>
<th>Table 1. Comparison of measurement method of blood flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement method</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Ultrasonic doppler method</td>
</tr>
<tr>
<td>Laser doppler method</td>
</tr>
<tr>
<td>Near-infrared spectroscopy (NIRS)</td>
</tr>
</tbody>
</table>

Figure 1. Standard sitting posture
2) The blood flow when they sit down on the chair in the standard sitting posture is measured (Figure 2(b));
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 (cushion angle $\theta_C$: 8°, 14° and 20° and back angle $\theta_B$: 20°, 30° and 40°) and all combinations are conducted;
5) The trimmed mean of the blood flow rates is calculated.

2.2. Results and Discussion

ANOVA was performed to identify the response of the cushion and back angles to the blood flow rate. Table 2 shows the ANOVA results for the blood flow rate with the cushion and back angles. This table also shows the variance ratio $F_0$ of the cushion angle is significant with 99% confidence compare to other factors. Figure 3 shows the change of the blood flow rate with respect to both cushion and back angles. This figure also shows the blood flow rate increases both with the cushion and back angles. Conventional study clarified that the compressive force in the buttock effects the lower limb blood flow [20]. Therefore, the result of the blood flow rate increase related to the back angle increase can be explained because this force in the buttock decreases when the back angle is large. However, that result related to the cushion angle increase cannot be explained because this force in the buttock increased when the cushion angle is large.

Hence, we decided the shear and compressive forces as the factors of the lower limb blood flow and conducted the measurement of the lower limb blood flow regarding these forces.


3.1. Method

This experiment employed the cushion and back angles as the parameters for setting the shear and compressive forces. Other conditions (experiment device, sitting posture, measurement environment, sensor position and measurement procedures) are same as those in 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 4) [8];
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 detail of the rigid link model and GA is described as follows.

The axial force in the lower thigh section $F_1$ is derived as below:

$$F_1 = \frac{-F_2 \cos \theta_C}{\cos \theta_B},$$

where, $F_2$ is the axial force in the thigh section. This force is

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sum of square</th>
<th>D.F.</th>
<th>Mean of square</th>
<th>$F_0$</th>
<th>$F$-value</th>
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</thead>
<tbody>
<tr>
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<td>2</td>
<td>0.000957</td>
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<td>3.55</td>
</tr>
<tr>
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<td>0.0127</td>
<td>25.6**</td>
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<tr>
<td>Interaction</td>
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<td>0.000786</td>
<td>1.58</td>
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</tr>
<tr>
<td>Repeatability error</td>
<td>0.00892</td>
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<td>0.000495</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.0394</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Waveform of blood flow volume

Figure 3. Blood flow rate regarding cushion angle
calculated by the following equation:

\[ F_2 = \frac{M_1 c_{1b} g + M_2 c_{2a} g}{\sin \theta_C - \cos \theta_C \tan \theta_{An}} \]  \hspace{1cm} (2)  

where, \( c \) is the ratio between total length and distance to the center of gravity for each human body section as shown in Figure 5.

The axial force in the pelvis section is derived as below:

\[ F_3 = \frac{F_4 + (M_4 c_{4a} g + M_5 c_{3b} g)(\cos \theta_B - \kappa \sin \theta_B)}{-\cos \theta_{Ab} + \kappa \sin \theta_{Ab}} \]  \hspace{1cm} (3)  

where, \( F_4 \) is the axial force in the lumbar and chest section. This force is derived as below:

\[ F_4 = (M_5 g + M_4 c_{4b} g)(\cos \theta_B - \kappa \sin \theta_B) \]  \hspace{1cm} (4)  

The horizontal force \( F_h \) and the vertical force \( F_v \) on the trochanter major are determined as follows:

\[ F_h = F_2 \cos \theta_C - F_3 \cos(\theta_{Hi} + \theta_C) \]  \hspace{1cm} (5)  

\[ F_v = F_2 \sin \alpha + F_3 \sin(\theta_{Hi} - \alpha) + M_2 c_{2b} g + M_3 c_{3a} g \]  \hspace{1cm} (6)  

The shear force \( F_s \) and the compressive force \( F_c \) in the buttock are calculated according to the following equations:

\[ F_s = -F_h \cos \theta_C - F_v \sin \theta_C - \kappa(-F_v \sin \theta_C + F_v \cos \theta_C) \]  \hspace{1cm} (7)  

\[ F_c = -F_h \sin \theta_C + F_v \cos \theta_C \]  \hspace{1cm} (8)  

GA is one of the most common meta-heuristics that can search the approximate solutions effectively in the optimization problems requiring the huge amount of calculation. This study derived the combinations of the cushion and back angles using this method because this problem is a combinatorial optimization problem requiring the huge amount of calculation. To employ GA, the four combinations of the cushion and back angles are set as the genes and the total of the difference between the shear and compressive forces in four combinations is set as the fitness.

Four combinations of the cushion and back angles \((\theta_c, \theta_b)\) derived by GA are \((20.00^\circ, 52.17^\circ), (17.45^\circ, 24.37^\circ), (9.33^\circ, 48.74^\circ)\) and \((9.07^\circ, 20.63^\circ)\), and the blood flow measurement 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 3 shows the ANOVA results for the blood flow rate with the shear and compressive forces. This shows the variance ratio \( F_0 \) of the shear force, the compressive force and the interaction have effect on the blood flow rate with 99% confidence. Figure 6 shows the change of the blood flow rate in the shear and compressive forces. This shows the blood flow rate decreases with increasing both of the shear and compressive forces. This also shows the interaction is
confirmed by a decrease in each blood flow rate 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 more than that of compressive force.

This study derived 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

This study derived optimal cushion and back angles using objective functions: shear and compressive forces (the rigid link model (Figure 4)), 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 [21, 22], weighted Tchebycheff norm method [21, 23], weighted $l_p$ norm [21, 24], $\varepsilon$-constraint method [21, 25], surrogate worth trade-off method [21, 26, 27] 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 $F(X)$, 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 7.

Figure 7 also shows the weighted sum $W$ is minimized in the feasible solution sets $F(X)$. 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 rigid link model (Figure 4). The dash lines in this figure mean the contour line of the weighted sum value. 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: $W_{\text{min}}=63.27\,\text{N}$, $\theta_{C1}=25^\circ$ and $\theta_{B1}=35^\circ$.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sum of square</th>
<th>D.F.</th>
<th>Mean of square</th>
<th>F0</th>
<th>F-value</th>
<th>Contribution ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear force</td>
<td>0.0285</td>
<td>1</td>
<td>0.0285</td>
<td>34.6**</td>
<td>5.31</td>
<td>46.60%</td>
</tr>
<tr>
<td>Compressive force</td>
<td>0.0176</td>
<td>1</td>
<td>0.0176</td>
<td>21.4**</td>
<td>5.31</td>
<td>28.30%</td>
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<tr>
<td>Interaction</td>
<td>0.00674</td>
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<td>0.00674</td>
<td>8.19**</td>
<td>5.31</td>
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</tr>
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<td>Total</td>
<td>0.0594</td>
<td>11</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 3. ANOVA table for shear and compressive forces
5. Verification experiment of Optimal Cushion and Back Angles

5.1. Method

This study measured the lower limb blood flow in the five combinations of the cushion and back angles in order to confirm the validity of the contribution ratios of shear and compressive forces and the derived optimal angles. The five combinations were decided on the basis of the weighted sums as follows:

1) \((q_{C1}, q_{B1})\) to minimize weighted sum;
2) \((q_{C2}, q_{B2})\) to maximize weighted sum;
3) \((q_{C3}, q_{B3}), (q_{C4}, q_{B4})\) and \((q_{C5}, q_{B5})\) to approximate the intermediate weighted sum between the minimum and the maximum weighted sum \(W_{mid} = (W_{min} + W_{max})/2\), where \(W_{min}\) and \(W_{max}\) denote the minimum and maximum weighted sum respectively. The three angle combinations are the minimum shear force (the maximum compressive force): \((q_{C3}, q_{B3})\), the minimum compressive force (the maximum shear force): \((q_{C4}, q_{B4})\) and the force intermediate between both: \((q_{C5}, q_{B5})\) on the contour line of \(W_{mid}\).

Figure 7 shows an example of the five angle combinations and three types of the weighted sums derived using Japanese male’s mean height and weight.

The subjects are seven males in their twenties whose physiques are close to the average of Japanese male (1.71 ± 0.04 m and 63.3 ± 8.3 kg) (Table 4). Other conditions (experiment device, sitting posture, measurement environment, sensor position and measurement procedures) are same in the second chapter.

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 5). This table shows the contribution ratio of the subjects is 65.0% larger than that of the weighted sums (23.4%). Therefore, the effect of the weighted sums on the blood flow rate cannot be confirmed due to the large variation of the blood flow rate between the subjects. This study normalized the blood flow rate among the subjects by subtracting the average blood flow rate of each subject in order to confirm the effect of the weighted sums on the blood flow rate.

Figures 8 and 9 show the boxplot of normalized blood flow rate in two groups of the angles: \((q_{C1}, q_{B1})\) \((q_{C2}, q_{B2})\) and \((q_{C3}, q_{B3})\); \((q_{C3}, q_{B3}), (q_{C4}, q_{B4})\) and \((q_{C5}, q_{B5})\), respectively. Figure 8 shows the normalized blood flow rate decreases with increasing the weighted sums. Therefore, the normalized blood flow rate of the minimum (optimized) weighted sum \(W_{min}: (q_{C1}, q_{B1})\) is the highest. On the other hand, Figure 9 indicates the normalized blood flow rate does not vary with the change of the cushion and back angles in the constant weighted sums.

Figure 10 shows the scatterplots of the weighted sums and the normalized blood flow rate and the result of the correlation analysis. The scatterplots indicates the blood flow rate decreases with increasing the weighted sum. Meanwhile, the correlation coefficient of the weighted sums and the normalized blood flow rate is \(-0.801\) and is significant with 99% confidence by the test for no correlation.

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

Table 4. Subject’s height and weight

<table>
<thead>
<tr>
<th>No.1</th>
<th>No.2</th>
<th>No.3</th>
<th>No.4</th>
<th>No.5</th>
<th>No.6</th>
<th>No.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height[m]</td>
<td>1.70</td>
<td>1.69</td>
<td>1.67</td>
<td>1.70</td>
<td>1.72</td>
<td>1.70</td>
</tr>
<tr>
<td>Weight[kg]</td>
<td>60</td>
<td>60</td>
<td>59</td>
<td>58</td>
<td>55</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 5. ANOVA table for weighted sum and subjects

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sum of square</th>
<th>D.F.</th>
<th>Mean of square</th>
<th>F0</th>
<th>F-value</th>
<th>Contribution ratio</th>
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</thead>
<tbody>
<tr>
<td>Weighted sum</td>
<td>0.567</td>
<td>4</td>
<td>0.141</td>
<td>98.4**</td>
<td>3.56</td>
<td>23.4%</td>
</tr>
<tr>
<td>Subjects</td>
<td>1.56</td>
<td>7</td>
<td>0.223</td>
<td>155**</td>
<td>2.87</td>
<td>65.0%</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.143</td>
<td>28</td>
<td>0.00512</td>
<td>3.55**</td>
<td>1.96</td>
<td>4.30%</td>
</tr>
<tr>
<td>Repeatability error</td>
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<td>80</td>
<td>0.00144</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.39</td>
<td>119</td>
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</tr>
</tbody>
</table>

Figure 8. Normalized blood flow rate of maximum, minimum and intermediate weighted sums
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 ($\theta_c=25^\circ$ and $\theta_b=35^\circ$) were derived using the weighting factor method because these contribution ratios can be used as the weighting factors.

The experiment in order to confirm the validity of the contribution ratios of the shear and compressive forces and the optimal angles clarified the followings:

1) The blood flow rate decreases with increasing the weighted sums; it has little change with the constant weighted sums;
2) The lower limb blood flow measured using the seat with the derived optimal angles is the highest.
3) There is the proportional relationship between the weighted sum and the blood flow rate (correlation coefficient: $-0.801$).

The obtained knowledge in this study (the influence of the shear and compressive forces on the lower limb blood flow) can be effective for designing the chair to relieve the symptoms: deep venous thrombosis, pressure ulcer, swelling of lower limbs and etc.

Acknowledgement

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