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Basic Study on Optimization of Seat Angles for Lower Limb Blood Flow

[Saori SONE, Daisuke SANNAN, Takeo KATO, Yoshiyuki MATSUOKA and Hiromu HASHIMOTO]

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 seat angles. For this aim, the changes in lower limb blood flow causing these symptoms were measured to each combination of the seat angles. As a result, it was confirmed that the shear and compressive forces between the buttock and the seat fluctuated by the seat angle strongly influence lower limb blood flow. And the possibility to optimize the seat angles using these forces was indicated.**

Keywords—**ergonomic design, lower limb blood flow, seat, shear force**

I. 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 or 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 clarify the relationship between the lower limb blood flow causing the above symptoms and the seat angles (cushion angle and back angle) in order to optimize the seat angles (the cushion and back angles) for preventing lower limb blood flow decline.

Saori SONE, Takeo KATO and Hiromu HASHIMOTO
Tokai University
JAPAN

Daisuke SANNAN and Yoshiyuki MATSUOKA
Keio University
JAPAN

II. Blood flow measurement with change in seat angles

A. 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 volume in skin microcirculation related to the congestion and swelling of lower limbs (Table1).

The subjects are three males in their 20s, whose height and weight are (1.75m, 75kg), (1.68m, 58kg) and (1.69m, 60kg). These values are ±0.04m and ±12kg from the average values of Japanese male (1.71m, 63.3kg). 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:

Table 1 Comparison of measurement method of blood flow

Measurement method	Measurement objectives	Features of measurement
Ultrasonic doppler method	Blood flow rate in blood vessel (femoral artery, portal vein, etc) [ml/min・kg]	・Possible to evaluate extent of stenosis/occlusion of blood vessel ・Cavitation by long-term measurement put burden on body
Laser doppler method	Blood flow rate in microcirculation (arteriole, capillary vessel, venule, etc) [ml/min・kg] (measurable area blood flow is 0.6～1.5mm)	Precision data without noise
Near-infrared spectroscopy (NIRS)	・Oxygenated hemoglobin concentration amount [mmol/l・mm] ・Blood rate but not bloof flow rate	Measurableness of multicomponent simultaneously

1) The room air temperature is set at 26±1℃ and the humidity at 60% (for decreasing the measurement error of blood flow volume 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 [10] before the measurement.
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 [5] is excluded.
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 volume when the subjects lie down on the air bed in the supine position is measured (Fig. 1).
2) The blood flow volume when they sit down on the chair in the standard sitting posture is measured (Fig. 1).
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 seat 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°, 40° and cushion angle: θ_C = 8°, 14°, 20°) and all combinations are conducted.
5) The trimmed mean of the blood flow rates is calculated.

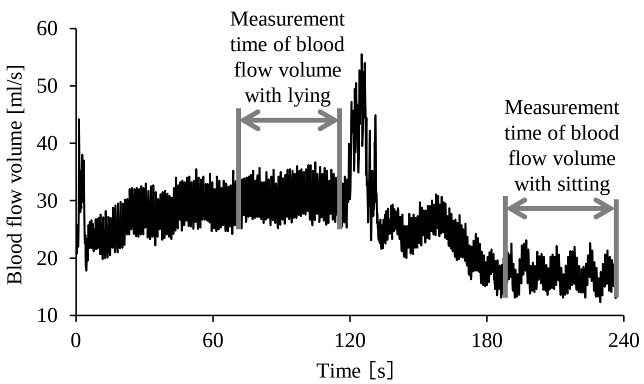


Figure 1 Waveform of blood flow rate

B. *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 2 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 2 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 Fig. 2 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 volume, and conducted the measurement of the blood flow volume regarding these force, shown in the next chapter.

III. Blood flow measurement with change in shear force and compressive force

A. *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

Table 2 ANOVA table for back angle and cushion angle

Factor	Sum of square	D.F.	Mean of square	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
$\theta_B \times \theta_C$	0.00314	4	0.000786	1.586	2.92
Repeatability error	0.00892	18	0.000495		
Total	0.0394	26			

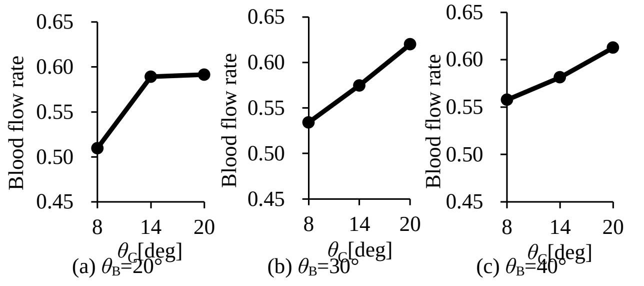
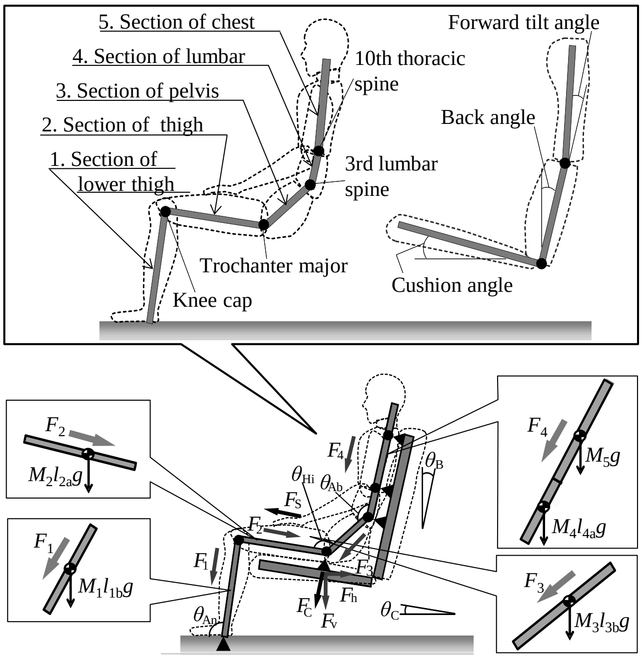


Figure 2 Blood flow rate regarding cushion angle

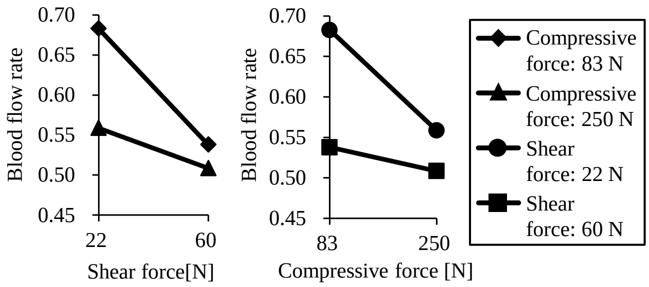


θ_C: seat cushion angle, θ_B: seat back angle, θ_{Hi}: hip angle, θ_{Ab}: abdomen angle, θ_{An}: ankle angle, M_1: weight of lower thigh, l_{1b}: length from lower thigh lower-edge to gravity center, M_2: weight of thigh, l_{2a}: length from thigh upper-edge to gravity center, M_3: weight of pelvis, 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

Figure 3 Rigid link model of human body and seat

Table 3 ANOVA table for shear force and compressive force

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× Compressive	0.00674	1	0.00674	8.19**	5.31	9.90%
Repeatability error	0.00658	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

Figure 4 Blood flow rate regarding shear force and compressive force

angles by the following procedures:

1) The shear and compressive forces are estimated by the rigid link model of human body and seat (Fig. 3) [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:

$$F_1 = \frac{-F_2 \cos\theta_C}{\cos\theta_{An}} \quad (1)$$

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 3rd 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 10th 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 methods of 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 one of the combinatorial optimization problem requiring the huge amount of calculation. Therefore, GA that each 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 is conducted in each combination.

B. *Result 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 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 4 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 interaction is confirmed from that each blood flow rate decreases at the different rate in each graph. Moreover, each contributing rate 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.

IV. Conclusion

This study clarified the followings by measuring the blood flow with change in seat angles.

1) The cushion angle is significant with 99% confidence to the blood flow rate.
2) The influence of the shear and compressive forces to the blood flow rate are assumed.

Moreover, to assume the influence of the forces to the blood flow rate, this study also measured the blood flow and clarified the followings.

1) The blood flow rate decreases with the increase in the shear and compressive forces.
2) The influence of the shear force to the blood flow rate is larger than that of the compressive force. The contributing rate of the shear and compressive forces are 46.6% and 28.3%, respectively.

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References

[1] Masanori SANJYO, Ai NAKAYAMA, Tomokazu KAWAMURA, Toshihiko OHASHI, Shingo IKEDA, Hiroyuki ONO, Hiroaki SHITABA, Toshihiro ENDO, Mayuki NAKAJIMA, Mihoko SUGIHARA, Mikiya ENDO, Hisae TAMURA, Satoshi SAKURAGAWA, Kenji IKEDA, Katsuro OKAMOTO, Kiyoyuki YAMAZAKI, Naoaki KANAI: The Effects of Massage by Air Boots on Peripheral Circulation, Annals of Tokai University, 6 (2000), 227.

[2] Yuzuru SAKUTA, Makoto TAKAHASHI: The Interaction between Pressure and Shear Force as a Factor of Pressure Ulcers by Assessing Blood Flow Measurement, Japan Society for Medical and Biological Engineering, 44, 1 (2006), 101.

[3] Masaki TAMAGUCHI, Takuzou IWATSUBO: Analysis of Pathogenic of Pressure Ulcer by Using Cellular Automaton, The Japan Society of Mechanical Engineers annual meeting, 2010, 6 (2010), 147.

[4] Takeshi NISHIYASU, Kang Hi SUNG, Haruo IKEGAMI: Effect of Muscle Pump on Hemodynamics (Paer2), The Japan Society of Physical Fitness and Sport Medicine, 34, 5 (1985), 284.

[5] Keiji IMADO, Kengo OHNISHI, Atsuyoshi MIURA, Masuji NAGATOSHI, Fumie YUFU, Yoshimasa GOTO: Development of Auto Stretching Device for Lower Limbs, The Japan Society of Mechanical Engineers, 2006 (2006), 285.

[6] Yukio OBITSU: Anatomy of the Peripheral Venous System, The Journal of Japanese College of Angiology, 49, 3 (2009), 200.

[7] Hideko KAWA, Harumi MOROOKA, Kiyokazu KITAMURA, Hideo MOROOKA: The Influence of Localized Pressure of Lower Body on the Amount of Skin Blood Flow. An Assumption to Establish a Design Guide to Support Panty Hose, Journal of the Japan Research Association for textile end-uses, 36, 7 (1995), 491.

[8] Motomu MINAMIYAMA, Ishio NINOMIYA: Edema of legs. Circulatory dynamics of legs. Veins of lower extremity, Current Therapy, 12, 2 (1994), 201.

[9] Narihiko KONDO: Thermoregulatory Responses in Humans, Kobe University Repository, 5, 2 (1998), 341.

[10] Maya TANAKA, Mimako YOSHIDA, Kozo HIRATA: Effect of the Peripheral Pressure at Groin Region Immediately After the Wear of Girdle on the Rate of Blood Flow in the Skin at the Bottom of Feet and Surface Humidity on the Skin, Journal of the Japan Research Association for textile end-uses, 40, 3 (1999), 175.

[11] Yoshiro FUJII, Noritaka ISOGAI, Nozomu KUROZUMI, Hiroshi KAMIISHI, Takeshi KUYAMA: Measurement of Peripheral Circulation with Laser-Doppler Flowmeter and Its Application in Plastic Surgery, Medical Journal Kinki University, 11, 3 (1986), 367.

[12] Toyoki KUGUMIYA, Ryoichi KAWATE, Masaki NAGASE, Yutaka INADA: Measurement of Changes in Peripheral Circulation at Sevoflurane Anesthesia Induction with Laser-Doppler Capillary Perfusion Monitor, Japanese Society of Medical Instrumentation, 56, 12 (1986), 562.

[13] Yoshiyuki MATSUOKA, Atsuya NIWANO, Atsushi MORITA: Design of Swing-seat Function Using Simulation of Hip-sliding Force, 143 (2001), 65.

About Authors

Saori SONE
She is a first year master's degree student in the graduate school of engineering at Tokai University, Japan. Her research focuses on the optimization methods for ergonomic design.

Daisuke SANNAN
He is a second year master's degree student in the graduate school of science and technology at Keio University, Japan. His research focuses on robust design method, and Quality Function Deployment (QFD).

Takeo KATO
He is a junior associate professor at Tokai University, Japan. His research focuses on design methodology to improve the quality and efficiency of the design activities. Recent researches include robust design method, Quality Function Deployment (QFD), Design Structure Matrix (DSM), and so on.

Yoshiyuki MATSUOKA
He is a professor at Keio University, Japan. His major research interests are design science. Based on the design theory and methodology he proposes, he has designed and created various products and systems.

Hiromu HASHIMOTO
He is a professor and a vice chancellor of Tokai University. His major researches are tribology, web handling and biomimetics. He received a total of 13 academic awards.