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Optimization of Public Seat Functions to Assure a Comfortable Sitting Posture in Diverse Conditions

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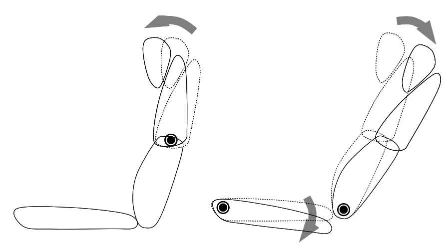
I. Introduction

To assure a comfortable sitting posture, some seat functions, such as the forward tilt of the seatback or seat swing function (Fig. 1), are included in public seats in railway vehicles and passenger airplanes [1] to [3]. However, it is unclear how these functions contribute to a comfortable sitting posture. Currently designers select seat functions based on their experience or sensory evaluation experiments [4]. Moreover, the conventional design assumes standard conditions in which all passengers have average physiques and standard sitting positions. Consequently, conventional design solutions are often poorly evaluated for non-standard conditions, including those with non-average physiques and varied postures (diverse conditions) [5] and [6].

The objectives of this study are to determine which seat functions assure a comfortable sitting posture and then optimize these seat functions for diverse conditions. To determine the relative importance of the seat functions, we conducted a sensory experiment using evaluation factors to elucidate factors for a comfortable sitting posture. We then analyzed the results of the sensory evaluation experiment via an analytic hierarchy process (AHP) and a fuzzy analytic hierarchy process (Fuzzy AHP) [7] and [8]. Second, we constructed a human-seat model for selected seats and performed simulations to optimize seat functions using the model. In this study, the signal-to-noise (SN) ratio from the Taguchi method [9] and [10] was used to consider variations in user physiques and the diversity of sitting postures. Finally, we conducted a sensory experiment to evaluate the optimized design solution.



1)forward tilt function 2)Seat swing function

Figure 1 : Structure of forward tilt function and seat-swing function

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Table 1 : Physique of examinees

Height (mm) / Weight (kg)	1637 ($\mu_h - \sqrt{1.5}\sigma_h$)	1714 (μ_h : Average)	1796 ($\mu_h + \sqrt{1.5}\sigma_h$)
53.2 ($\mu_w - \sqrt{1.5}\sigma_w$)	Physique 1 (Short physique)	Physique 6 (Corpulent physique)	
63.3 (μ_w : Average)	Physique 4 (Corpulent physique)	Physique 2 (Average physique)	Physique 5 (Slim physique)
73.4 ($\mu_w + \sqrt{1.5}\sigma_w$)		Physique 7 (Slim physique)	Physique 3 (Tall physique)

II. Seat Functions that Assure a Comfortable Sitting Posture

a) *Sensory Experiment*

i. *Experimental Conditions*

- Examinees: To incorporate passengers with various physiques, we evaluated passengers using combinations of three different heights and weights. Of the nine possible combinations, two are statistically rare, and consequently eliminated (Table 1). The height and weight levels are defined using their mean values μ_h and μ_w and standard deviations σ_h and σ_w.
- Sitting posture: Each examinee adjusted the seat to assume the most comfortable sitting posture.
- Evaluated seat functions: A sample seat was prepared with five different seat functions: adjustable head rest height, forward tilt, seat swing, seat cushion slide, and footrest. Figure 2 shows the seat functions of the experimental seat. The specifications of the sample seat are identical to an actual public transportation seat found in the Hatsukari express train in Japan.

ii. *Evaluation method*

Based on the results of a previous study [11], we chose two factors to evaluate seat functions: the fitness of the sitting posture and the amount of freedom for various sitting postures with a relative weighting of 7 to 3. The examinees evaluated each factor by answering the following questions using the semantic differential (SD) method on a five-point scale. “Is it possible to achieve a comfortable sitting posture?” and “Is it possible to achieve a variety of sitting postures?”

b) *Analysis of important seat functions for a comfortable sitting posture*

i. *Application of AHP and Fuzzy AHP*

To analyze the importance of seat functions in assuring a comfortable sitting posture, the results of the evaluation were analyzed using AHP and Fuzzy AHP.

AHP is a decision-making method that considers subjective human criteria. In AHP, a hierarchal model is initially created. The model consists of three components: the design object, evaluation factors, and alternatives. The factors in the decision-making problems are divided based on the hierarchy model. Then the degree of importance for each evaluation factor is determined using an evaluation matrix based on paired comparisons. Finally, the degree of importance of the alternatives based on the hierarchy model is numerically simulated using the degree of importance of the evaluation factors and the results of SD method.

The degree of importance for AHP is an additive measure because the sum is equal to one. However, an additive measure cannot evaluate substitutability and complementarity of a sensory evaluation. Substitutability states that even if there is only one excellent evaluation among a number of evaluations, the overall evaluation is higher. In other words, substitutability emphasizes a

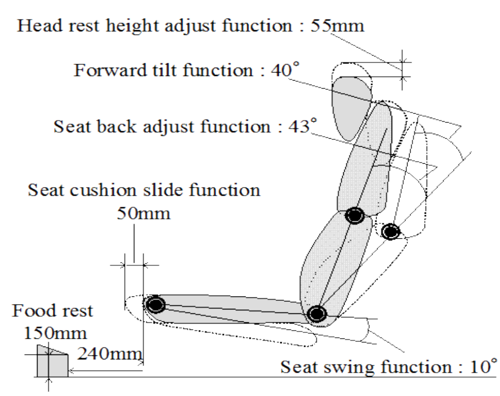

Figure 2 : Specification of the sample seat

good evaluation. In contrast, complementarity means that one inferior evaluation lowers the overall evaluation. Because AHP emphasizes overall balance, herein we employ Fuzzy AHP uses non-additive measures (possibility and necessity measures), which are described below.

First, we expressed the additive measure generally used in AHP, the degree of importance y of the alternatives as a weighted sum of the degrees of importance w_i ($0 \leq w_i \leq 1$) of the evaluation factors x_i, and the evaluation value $f_j(x_i)$ of j^{th} alternative of x_i. Then y can be expressed as where n is the number of

$$y = \max_j \sum_{i=1}^{n} w_i f_j(x_i) \quad (w_1 + \ldots + w_n = 1) \qquad (1)$$

evaluation factors. Fuzzy AHP normalizes the degrees of importance w_i ($0 \leq w_i \leq 1$) for cases where $w_i = 1$ for more than one i. For example, wi can be normalized by their maximum value. The classes A_l of the number of n is established using w_i' ($r_1 < r_2 < \ldots < r_n = 1$), which is the modified degree of importance, X is the class of

$$A_l = \{x_i \mid w_i' \_\ r_l\} \ , \quad l = 1, \ldots, n \ , \quad x \in X \qquad (2)$$

evaluation factors. The probability m of each class A_l is allocated as

$$m(A_l) = r_l - r_{l-1} \quad , \quad l = 1, \ldots, n \quad , \quad r_0 = 0 \qquad (3)$$

The possibility measure expectation E* (upper limited expectation), which adopts the maximum evaluation value f(x) for evaluation factors x included in each class A_l, while the necessity measure expectation E* (lower limited expectation), which adopts the minimum evaluation value, using probabilities m_l from

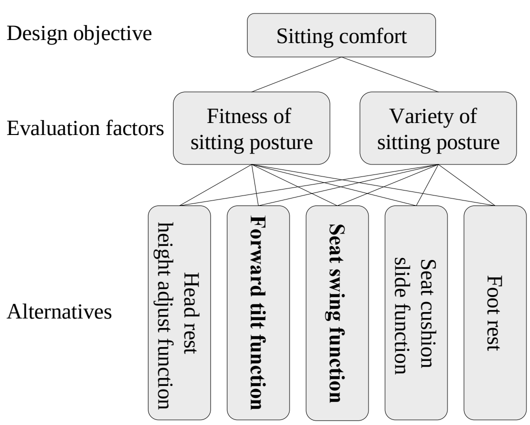

Figure 3 : Constructed hierarchy model

equation (3), are respectively expressed as

$$E^*(f) = \sum_{l=1}^{n} m(A_l) \max_{x \in A_l} f(x) = \sum_{l=1}^{n} (r_l - r_{l-1}) \max_{x \in A_l} f(x) \qquad (4)$$

$$E_*(f) = \sum_{l=1}^{n} m(A_l) \min_{x \in A_l} f(x) = \sum_{l=1}^{n} (r_l - r_{l-1}) \min_{x \in A_l} f(x) \qquad (5)$$

Thus, the most favorable degrees of importance of alternatives (y*, y*) in the possibility and necessity measures are expressed as

$$y^* = \max_j E^*(f_j) \qquad (6)$$

$$y_* = \max_j E_*(f_j) \qquad (7)$$

The seat functions were selected by applying these degrees of importance of the alternatives.

1.2.2. Data analysis and the selection of alternatives

Figure 3 shows the hierarchy model employed in this study. To determine the compound degree of importance of each measure and alternative, we applied three types of values: the degree of importance of the evaluation factors, the evaluation value assigned by each examinee, and the results of equations (1), (6), and (7).

Figure 4 shows the average of the compound degree of importance, as well as the measures for possibility, additivity, and necessity. The forward tilt and the seat swing functions are the most highly rated

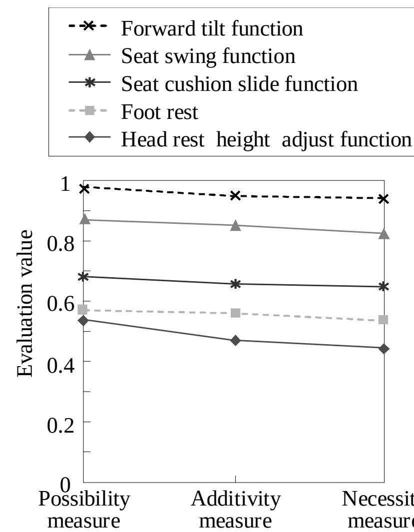

Figure 4 : Evaluations of the Alternatives

measures followed by the seat cushion slide, footrest, and headrest height adjustment functions, in that order. These findings can be explained by the body pressure distribution. In general, the lower the pressure on the body from the seat is thought to be more desirable [12].

It is possible that the forward tilt and the seat swing functions distribute the pressure to large regions of the body by increasing the pressure on the back. Thus, we expect these functions to be highly rated. In summary, we selected the forward tilt and the seat swing functions, which were highly rated in the three measures — possibility, additivity, and necessity — as the necessary seat functions to assure a comfortable sitting posture for varied conditions.

III. Optimization of Seat Functions for a Comfortable Sitting Posture

Here we focus on the forward tilt and seat swing functions as the functions necessary to realize a comfortable sitting posture. Because we optimized the forward tilt function in a previous study [13], we briefly summarize the optimization. Then we clarified the optimization of a seat swing function with and without a

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forward tilt function in diverse conditions. Finally, a sensory experiment confirmed the effectiveness of the seat swing function with a forward tilt function.

a) Optimization of the forward tilt function

The forward tilt function is the function that bends the seatback between the thorax and the lumbar regions. This function contributes to fitness of the

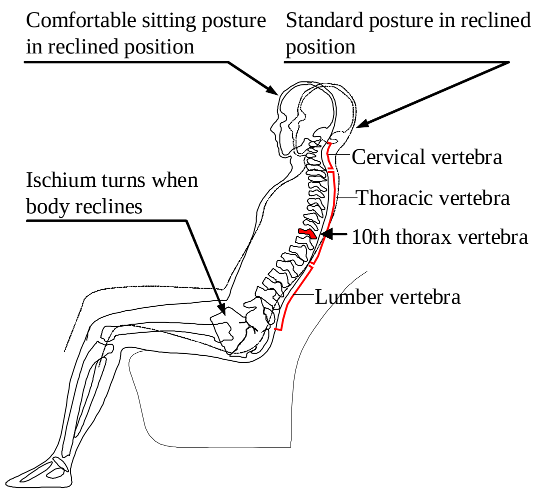

Figure 5 : Forward tilt pivot position

seatback for assuming a comfortable sitting posture. We have determined the optimal pivot point of the forward tilt and the movement range of the forward tilt angle (FA) based on a sensory experiment with diverse users in a previous study. These results are summarized below.

i. *Optimization of the forward tilt position*

Previously a sensory experiment involving 16 Japanese participants (8 male and 8 female) with varying physiques (height percentile from 10% to 99%) determined the optimal forward tilt position for diverse users. The pivot point of forward tilt function is behind the 10th vertebra (Fig. 5) because the point of largest movement in the spine (except the thorax) is between the 10th and 11th vertebrae.

ii. *Optimization of the movement range of the forward title angle*

A sensory experiment evaluated the comfort of a sitting posture and determined the optimum movement range of FA using the same conditions as above. Figure 6 shows the acceptable comfort range of FA for each examinee. Based on the results, we selected an FA movement range between 0 and 30 degrees.

iii. *Relationship between the forward tilt function and the seat swing function*

The previous section demonstrates that the forward tilt function can assure a comfortable sitting posture by tilting the seatback at a pivot point behind the 10th thorax vertebra and a 0 to 30 degree movement range. Moreover, the design solution of the seat swing

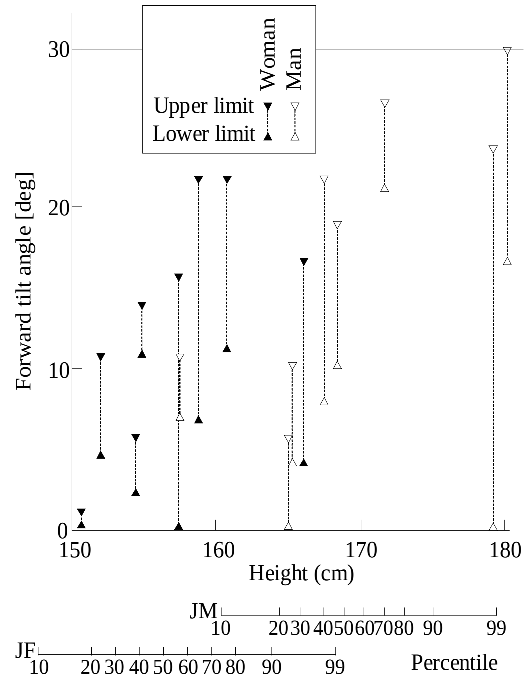

Figure 6 : Suitable forward tilt angle range for different builds

function is related to FA because the seat swing function sinks the back end of the seat cushion on the axis of the front edge of the seat cushion in tandem when adjusting the seatback to prevent the hip sliding force. The force is usually generated on the buttocks in an anterior direction from the human body dynamics varied from the seat angles. The hip sliding force is one cause of uncomfortable sitting [14], and varies as a function of the back angle (BA), which is the angle between the seatback and the vertical direction, and the cushion angle (CA), which is the angle between the seat cushion and the horizontal. BA and CA are adjusted by the seat swing function. In addition, the hip sliding force varies with FA as adjusted by the forward tilt function.

b) Optimization of the seat swing function

The optimal combination between BA and CA minimizes the hip sliding force and optimizes the seat swing function. In this study, the seat swing functions with and without the forward tilt function were optimized. Here users adjusted FA to a certain value.

i. *Design method*

The seat swing function was optimized using the SN ratio, which is the measure from the Taguchi method to evaluate the stability of the functional value of a design objective with respect to the variance of a variety of factors. When data is divided into a functional characteristic value S (signal) and variance N (noise), the ratio of these values is the SN ratio [15], and indicates the stability of a functional value. Maximizing the SN ratio improves the performance of the design objective; thus, selecting a design solution that

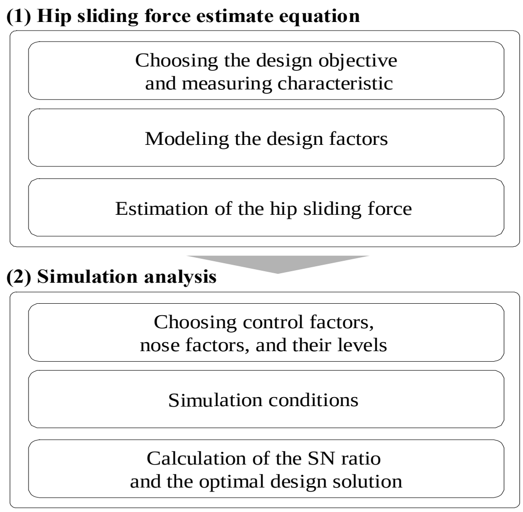

Figure 7 : Flow of seat swing function optimization

maximizes the SN ratio minimizes the influence of noise factors, which can destabilize a function.

ii. *Optimization Steps*

Figure 7 shows the procedure to optimize the seat swing function. First the hip sliding force is estimated, and then simulations analyze the results. There are three steps to construct the hip sliding force estimation equation: (1) select the design objective and measure its characteristics, (2) model the design factor, and (3) estimate the hip sliding force.

- *Select the design objective and measure its characteristics*

The seat swing function reduces the hip sliding force. Therefore, the design objective is for the hip sliding force to be 0 N.

- *Model the design factors*

To model the factors that influence the hip sliding force, initially a human model and seat model must be separately constructed. Then a human-seat model, which depicts their relationship, is constructed.

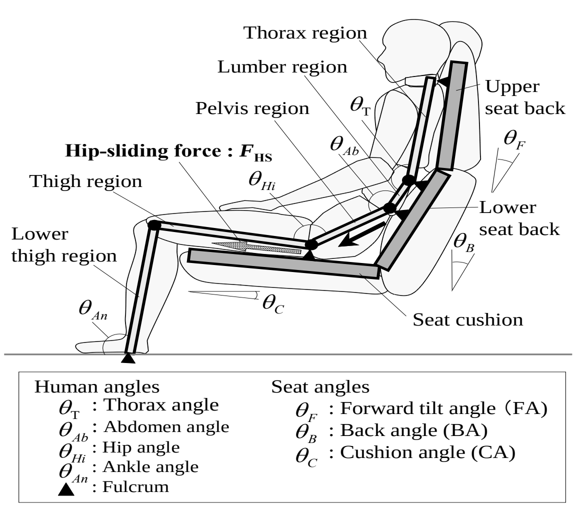

Figure 8 : Human-seat model

Because the human model needs to be split into parts, we selected division points based on both human anatomy and sitting posture [16]. Our two-dimensional model includes the thoracic, lumbar, and pelvic regions as well as the thigh and lower thigh regions. For each body region measurement, we used the statistical average of the human body measurements [17].

For each body region weight, we renormalized the weights from an earlier study to match the models used in this study [18]. We considered three types of sitting postures: the standard one and two types of hip sliding postures (stretched waist and bent waist) [19]. In the standard sitting posture, a passenger sits such that the buttocks are positioned deep on the seat cushion and the waist is in contact with the seatback. In the hip sliding posture, the passenger sits with the buttocks slid forward and the pelvis rotated such that waist does not come into contact with the seatback. The stretched waist sitting posture stretches both the pelvis and the waist, while the bent waist posture bends both the pelvis and the waist. The greater trochanter point of the hip sliding sitting posture is set 100 mm forward from the standard sitting posture, based on an earlier study [19].

The two-dimensional seat model consists of three parts: upper seatback, lower seatback, and seat cushion, which are rigid-body link structure. As shown in Section 2.1.1, the forward tilt function rotates around a pivot point behind the 10th thorax vertebrae. The size and adjustability of the sample seat are based on a real-life Hatsukari public seat (Section 1.1.1).

We constructed the human-seat model using the above human and seat models (Fig. 8). Because the hip sliding force estimate and the features of the sitting position can be viewed from the sagittal plane of the human body, the human-seat model in this study is constructed in the sagittal plane. Forces include friction between the human body and the seat, where the vertical component of force from each seat part (the upper seatback, the lower seatback, and the seat cushion) is multiplied by the friction coefficient, which is assumed to be 0.3 [20].

- *Estimate the hip sliding force*

Then we constructed human-seat models with respect to varied sitting postures to estimate the hip sliding equation for all postures (Figs. 9–11, equations 8–10). Table 2 explains the variables in these equations [21].

Similar to the estimation of the hip sliding force, the simulation analysis consists of three parts: (1) select the control and noise factors as well as their levels, (2) determine the simulation conditions, and (3) calculate the SN ratio and optimal design solution.

- *Select the control and noise factors as well as their levels*

  First, we defined the factors influencing the design objective. Then these factors are

Table 2 : Sign on formulation of hip sliding force estimation

Sign	Meaning	Sign	Meaning	Sign	Meaning
F_{HS}	Hip sliding force	H	Height of seat cushion	i=1	Thorax region
F_{h}	Horizontal force on trochanter major	M	Body weight	i=2	Lumber region
F_{v}	Vertical force on trochanter major	M_i	Weight of i th body section	i=3	Pelvis region
F_i	Force on i th human body section	l_{ia}	Ratio of L_i and the length from i th body section upper-edge to gravity-center	i=4	Thigh region
L	Body height	l_{ib}	1 - l_{ia}	i=5	Lower thigh region
L_i	Length of i th body section	l_{ma}	Composite ratio of 3rd and 4th body section in stretched waist sitting posture	k	Coefficient of frictional resistance
L_{h}	Buttock-trochanterion length	$l_{m'a}$	l_{ma} in bent waist sitting posture.		

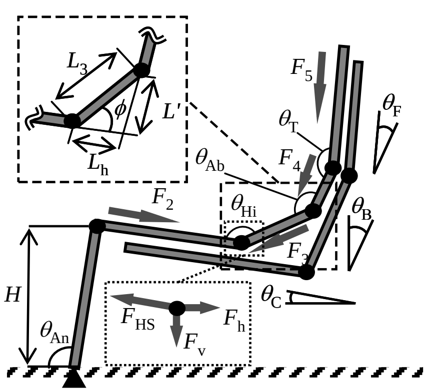

Figure 9 : Standard sitting posture

$$
F_{\mathrm{HS1}} = -F_{\mathrm{h}} \cos\theta_{\mathrm{C}} - F_{\mathrm{v}} \sin\theta_{\mathrm{C}} - \kappa\left(-F_{\mathrm{h}} \sin\theta_{\mathrm{C}} + F_{\mathrm{v}} \cos\theta_{\mathrm{C}}\right)
$$

$$
\left(\begin{array}{l}
F_{\mathrm{h}} = F_2 \cos\theta_{\mathrm{C}} - F_3 \sin\left(\theta_{\mathrm{Hi}} + \theta_{\mathrm{C}}\right) \\
F_{\mathrm{v}} = F_2 \sin\theta_{\mathrm{C}} + F_3 \sin\left(\theta_{\mathrm{Hi}} - \theta_{\mathrm{C}}\right) + M_2 l_{2\mathrm{b}} g + M_3 l_{3\mathrm{a}} g \\
F_2 = \dfrac{M_1 l_{1\mathrm{b}} g + M_2 l_{2\mathrm{a}} g}{\sin\theta_{\mathrm{C}} - \cos\theta_{\mathrm{C}} \tan\theta_{\mathrm{An}}} \\
F_3 = \dfrac{F_{4-5} + \left(M_4 l_{4\mathrm{a}} g + M_3 l_{3\mathrm{b}} g\right)\left(\cos\theta_{\mathrm{B}} - \kappa \sin\theta_{\mathrm{B}}\right)}{-\cos\theta_{\mathrm{Ab}} - \kappa \sin\theta_{\mathrm{Ab}}} \\
F_4 = \left(M_5 l_{5\mathrm{a}} g + M_4 l_{4\mathrm{b}} g\right)\left(\cos\theta_{\mathrm{B}} - \kappa \sin\theta_{\mathrm{B}}\right) + F_5\left(\cos\theta_{\mathrm{F}} - \kappa \sin\theta_{\mathrm{F}}\right), \\
F_5 = M_5 l_{5\mathrm{b}} g \left\{\cos\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right) - \kappa \sin\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right)\right\} \\
\theta_{\mathrm{An}} = \sin^{-1}\left(H/L_1\right),\ \theta_{\mathrm{Hi}} = 180^\circ - \phi,\ \ \theta_{\mathrm{Ab}} = \phi + 90^\circ - \theta_{\mathrm{C}} + \theta_{\mathrm{B}} - \theta_{\mathrm{F}}, \\
\phi = \sin^{-1}\left\{\left(L'/L_3\right)\sin\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right)\right\} \\
L' = L_{\mathrm{h}} \cos\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right) + \sqrt{L_3^{\,2} - L_{\mathrm{h}}^{\,2} \sin^2\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right)}
\end{array}\right) \tag{8}
$$

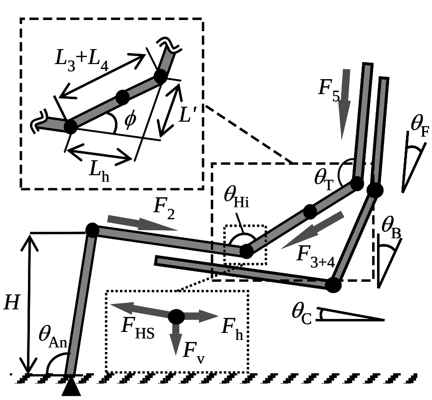

Figure 10 : Hip-sliding sitting posture(Stretched waist)

$$
F_{\mathrm{HS2}} = -F_{\mathrm{h}} \cos\theta_{\mathrm{C}} - F_{\mathrm{v}} \sin\theta_{\mathrm{C}} - \kappa\left(-F_{\mathrm{h}} \sin\theta_{\mathrm{C}} + F_{\mathrm{v}} \cos\theta_{\mathrm{C}}\right)
$$

$$
\left(\begin{array}{l}
F_h = F_2 \cos\theta_{\mathrm{C}} + F_{3+4} \cos\left(\theta_{\mathrm{Hi}} + \theta_{\mathrm{C}}\right), \\
F_{\mathrm{v}} = F_2 \sin\theta_{\mathrm{C}} + F_{3+4} \sin\left(\theta_{\mathrm{Hi}} + \theta_{\mathrm{C}}\right) + M_2 l_{2\mathrm{b}} g + \left(M_3 + M_4\right) l_{\mathrm{ma}} g \\
F_2 = \dfrac{M_1 l_{1\mathrm{b}} g + M_2 l_{2\mathrm{a}} g}{\sin\theta_{\mathrm{C}} - \cos\theta_{\mathrm{C}} \tan\theta_{\mathrm{An}}} \\
F_{3+4} = \dfrac{F_5 + \left(M_5 l_{5\mathrm{a}} g + \left(M_3 + M_4\right) l_{\mathrm{mb}} g\right)\left(\cos\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right) - \kappa \sin\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right)\right)}{-\cos\theta_{\mathrm{T}} + \kappa \sin\theta_{\mathrm{T}}} \\
F_5 = M_5 l_{5\mathrm{b}} g \left(\cos\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right) - \kappa \sin\left(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}\right)\right), \\
\theta_{\mathrm{An}} = \sin^{-1}\left(H/L_1\right),\ \ \theta_{\mathrm{Hi}} = 180^\circ - \phi,\ \ \theta_{\mathrm{T}} = \phi + 90^\circ - \theta_{\mathrm{C}} + \theta_{\mathrm{B}} - \theta_{\mathrm{F}}, \\
\phi = \sin^{-1}\left[\left\{L'/\left(L_3 + L_4\right)\right\}\sin\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right)\right] \\
L' = L_{\mathrm{h}} \cos\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right) + \sqrt{\left(L_3 + L_4\right)^2 - L_{\mathrm{h}}^{\,2} \sin^2\left(90^\circ + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}\right)}
\end{array}\right)
$$

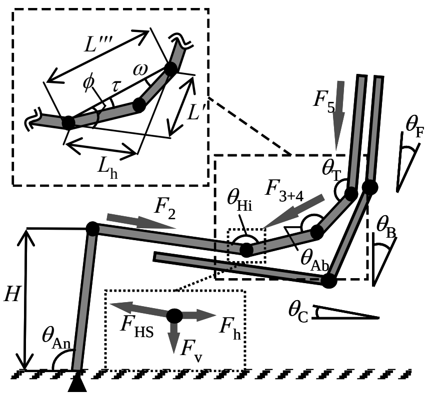

Figure 11 : Hip-sliding sitting posture (Bent waist)

$$
\begin{gathered}
F_{\mathrm{HS3}} = -F_{\mathrm{h}} \cos\theta_{\mathrm{C}} - F_{\mathrm{v}} \sin\theta_{\mathrm{C}} - \kappa\left(-F_{\mathrm{h}} \sin\theta_{\mathrm{C}} + F_{\mathrm{v}} \cos\theta_{\mathrm{C}}\right) \\
\left(\begin{aligned}
& F_{\mathrm{h}} = F_2 \cos\theta_{\mathrm{C}} + F_{3+4} \cos(\theta_{\mathrm{Hi}} + \theta_{\mathrm{C}} - \tau), \\
& F_{\mathrm{v}} = F_2 \sin\theta_{\mathrm{C}} + F_{3+4} \sin(\theta_{\mathrm{Hi}} + \theta_{\mathrm{C}} - \tau) + M_2 l_{2\mathrm{b}} g + (M_3 + M_4) l_{\mathrm{m'a}} g \\
& F_2 = \frac{M_1 l_{1\mathrm{b}} g + M_2 l_{2\mathrm{a}} g}{\sin\theta_{\mathrm{C}} - \cos\theta_{\mathrm{C}} \tan\theta_{\mathrm{An}}} \\
& F_{3+4} = \frac{F_5 + \left(M_5 l_{5\mathrm{a}} g + (M_3 + M_4) l_{\mathrm{m'b}} g\right)\left(\cos(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}) - \kappa \sin(\theta_{\mathrm{B}} - \theta_{\mathrm{F}})\right)}{-\cos(\theta_{\mathrm{T}} - \omega) + \kappa \sin(\theta_{\mathrm{T}} - \omega)} \\
& F_5 = M_5 l_{5\mathrm{b}} g\left(\cos(\theta_{\mathrm{B}} - \theta_{\mathrm{F}}) - \kappa \sin(\theta_{\mathrm{B}} - \theta_{\mathrm{F}})\right), \\
& \theta_{\mathrm{An}} = \sin^{-1}(H/L_1),\ \theta_{\mathrm{Hi}} = 180° - \phi + \tau,\quad \theta_{\mathrm{T}} = \phi + 90° - \theta_{\mathrm{C}} + \theta_{\mathrm{B}} - \theta_{\mathrm{F}} + \omega, \\
& \phi = \sin^{-1}\left\{(L'/L''')\sin(90° + \theta_{\mathrm{B}} - \theta_{\mathrm{C}})\right\} \\
& L' = L_{\mathrm{h}} \cos(90° + \theta_{\mathrm{B}} - \theta_{\mathrm{C}}) + \sqrt{(L''')^2 - L_{\mathrm{h}}^{\ 2} \sin^2(90° + \theta_{\mathrm{B}} - \theta_{\mathrm{C}})}\ , \\
& L''' = \sqrt{L_3^2 + L_4^2 - 2L_3 L_4 \cos(180° - 24°)}
\end{aligned}\right)
\end{gathered}
\tag{10}
$$

Table 3 : Conditions of Each Simulation

Simulation No.	Control factor	Noise factor		
		Physique	Sitting Posture	FA
Simulation 1 : Optimization of seat swing function considering standard condition	BA, CA	1 level (standard)	1 level (standard)	1 level (0 deg)
Simulation 2 : Optimization of seat swing function considering diverse condition	BA, CA	7 levels	3 levels	1 level (0 deg)
Simulation 3 : Optimization of seat swing function with forward tilt function considering standard condition	BA, CA	7 levels	3 levels	3 levels

divided into control and noise factors. A designer can determine the level of influence of a control factor, but not that of a noise factor. We identified the following factors:

a. CA (control factor)
b. BA (control factor)
c. FA (noise factor)
d. Physiques (noise factor)
e. Sitting postures (noise factor)

The level of each factor was determined, as described below. CA has 51 different values from 0 to 50 degrees in one-degree increments. In this study, physique, sitting posture, and FA, are noise factors with seven, three, and three levels, respectively. FA is set to 0, 15, or 30 degrees.

iii. *Determine the simulation conditions*

We used three different conditions in the simulation analysis (Table 3).

- Simulation 1: The seat swing function is optimized for the standard condition. In particular, CA minimizes the hip sliding force Y (equation 8) for each BA value.
- Simulation 2: The single seat swing function is optimized by determining the levels of physique and sitting posture.
- Simulation 3: The seat swing function with the forward tilt function is optimized by determining the levels of physique, sitting posture, and FA.

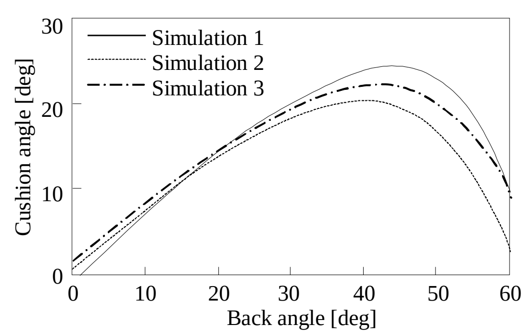

Figure 12 : Specification of the sample seat

In the simulations, the SN ratios of the hip sliding force are estimated for each combination of BA and CA. The SN ratio is the ratio of the signal factor to the noise factor. Then the optimal design solution is selected by the combination of BA and CA that maximized the SN ratio against each BA.

iv. *Calculate the SN ratio and Optimal Design Solution*

The equation for the SN ratio differs according to the type of measurement characteristic. In this study, the target value of hip sliding force is 0 N. When the SN ratio is minimized, it is defined as where FHSi is the hip sliding force and n is the number of the measurement

$$\eta = -10 \log \frac{1}{n} \sum_{i=1}^{n} F_{HSi}^{2} \qquad (11)$$

characteristics (Yi). If the mean of the hip sliding force is *μ*, and its variance is *σ2*, then the expected value of the SN ratio (*η*) is

$$E(\eta) = -10 \log\left[\mu^2 + \sigma^2\right] \qquad (12)$$

Therefore, the true value of the SN ratio includes both the mean value of the hip sliding force and variance due to the noise factor.

This simulation yields the optimal CA with the maximum SN ratio for each BA, which prevents the hip sliding force (the hip sliding prevention curve).

- *Simulation results and analyses*

Figure 12 shows the results of simulations 1, 2, and 3 (the hip sliding prevention curves). The curve of simulation 3 lies between those of simulation 1 and simulation 2. This observation can be explained by the interplay of two forces: a decrease in the hip sliding force with the hip sliding posture (calculated from eq. 9), and an increase in the hip sliding force with the forward tilt (calculated from eq. 8).

IV. Sensory Experiment

To confirm the effectiveness of the optimized design solution for the seat swing function with a forward tilt (simulation 3), we performed a sensory experiment to compare the optimal design solution (simulation 3) and the standard solution (simulation 1).

a) Sensory experiment

i. *Conditions*

The sensory experiment included seven different physiques, two types of sitting postures, and the seat described in Section 1.1.1. BA and CA were selected such that CA clearly affected the hip sliding force prevention curves; that is, the experiment included simulations 1 and 3. For each BA (30, 35, and 40 degrees), simulation 1 used CA = 20, 23, and 25 degrees, while simulation 3 used CA = 19, 21, and 23 degrees respectively.

ii. *Method*

Examinees sat in two different sitting postures (standard and hip sliding sitting posture) on the seat using the previously mentioned combinations of CA and BA, and then evaluated the extent to which they “did not feel the hip sliding force” using the SD method on a five-point scale.

b) Analysis of the effectiveness of the optimal design solution

i. *Estimate of the SN ratio*

The SN ratios of the design solutions from simulations 1 and 3 were estimated using the ratings from the sensory experiment on a five-

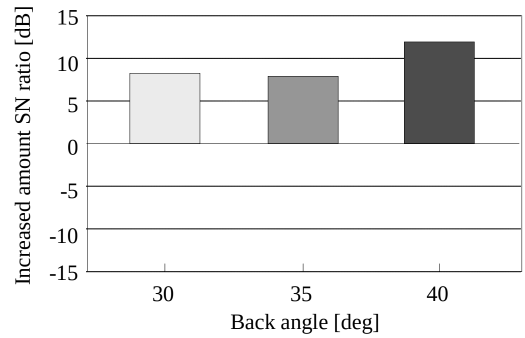

Figure 13 : Increment in SN ratio from conventional solutions (simulation 1) to the proposed solution (simulation 3)

point scale. The SN ratio η is then calculated as

$$\eta = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \qquad (13)$$

where yi is the rating from a given experiment, and n is the number of combinations of CA and BA. The total number of ratings is 14 because examinees evaluated two different sitting postures.

ii. *Analysis of the Sensory Experiment*

Figure 13 indicates that simulation 3 has a larger SN ratio than simulation 1 for all BAs. The solution for simulation 3 prevents the hip sliding force for diverse physiques, sitting postures, and FAs. Thus, the sensory experiment confirms the effectiveness of our optimized solution using diverse conditions (simulation 3).

V. Conclusion

Two seat functions, forward tilt function and seat swing function, are necessary to assure a comfortable sitting posture. Thus, we optimized these functions using the SN ratio, which was obtained by the Taguchi method by considering users’ diverse physiques and sitting postures. Moreover, we conducted a sensory experiment to confirm the effectiveness of the optimal design solution. The key findings are summarized below.

1. AHP and Fuzzy AHP analyses reveal that the forward tilt and seat swing functions are most highly rated to assure a comfortable sitting position for diverse conditions, physiques, and sitting postures. Thus, these are the key functions to assure a comfortable sitting posture.
2. A comparison of the design solutions for standard conditions (standard physique, sitting posture, and

FA = 0 degrees) and the seat swing function with a forward tilt (varied physiques, sitting postures, and FAs) reveals that the CA for each BA is lower for the seat swing function with a forward tilt than the standard condition. Although the hip sliding force increases as FA increases, the hip sliding posture decreases the overall force.

3. To compare the optimal design solution of the seat swing function with the forward tilt function to standard solution, we conducted a sensory experiment for varied physiques and sitting postures. The SN ratio of the optimal design solution is higher than that of the standard one, confirming the effectiveness of the design solution in assuring a comfortable sitting posture under diverse conditions.

Herein we have designed a public seat that combines the seat swing function with a forward tilt to assure a comfortable sitting posture. In the future, we plan to optimize public seats based not only on pressure minimization, but also on other aspects of human physiology, such as muscle activity and blood flow.

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