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A LAYOUT DESIGN METHOD OF HUMAN-VEHICLE SYSTEMS BASED ON EQUIVALENT INERTIA INDICES

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ABSTRACT

This paper deals with a design method for layout of controls based on the equivalent inertia of human-vehicle systems. In this method, both the human and the object are modeled as articulated rigid bodies, and the posture of the human, the configuration of the vehicle, the contacts between the human and the vehicle, and the constraints on the human and on the vehicle are respectively defined prior to the analysis. The equivalent inertia of the human-machine system is then calculated at any prescribed points on the object taking the contacts and the constraints into consideration. Finally, optimization is carried out by choosing design variables and by employing the indices of equivalent inertia as the objective function. In this paper, layout designs of a steering wheel and an accelerator pedal optimized by using newly defined effective and ineffective equivalent inertia indices, are compared with subjective layout evaluated by human drivers. The results show the effectiveness of this method to design user-friendly layout for various physical sized drivers.

1. INTRODUCTION

Studies undertaken in order to design the layout for the system operator in human-machine systems have been conducted from an ergonomic perspective [1]. These studies evaluated movement and posture using computer generated models of the human body, focusing on the movable range and the angle of the joints [2]. However, the evaluation did not take account of interactions with the objects and, therefore, cannot be used to derive generic indices or design methods that can be applied in various situations in the same manner.

In addition, studies based on the manipulability, a well-known concept in robotic engineering, are also being undertaken. Tanaka *et al.* [3] proposed a manipulability ellipsoid based on the torque-exertion characteristics of the human body obtained from experiments. However, these studies are based on the human operation only, and do not consider the contact between the human and the object or the constraint conditions.

As is well known, the muscles, the only actuators in human body, contain muscle spindles and Golgi tendon organs that can detect changes in position, velocity and force of the muscle. It is also known that muscle possesses variable viscoelasticity [4]. Thus, in these studies it is important to consider the equivalent impedance characteristics of the human-machine system as well as the force-exertion characteristics.

In this paper, we propose a new method for designing the layout based on the equivalent impedance characteristics of a human-machine system. The authors previously proposed a method for deriving the equivalent inertia of a human-machine system taking the contact between the man and the machine and the constraints imposed by the system into consideration [5]. Furthermore, the authors have also developed a prototype system for analyzing the equivalent impedance characteristics taking into account the viscoelasticity of muscle [6]. Here we describe an optimization method for layout design of a human-machine system using equivalent inertia indices. Specifically, we conduct subjective judgements by drivers with regard to the layout of the steering wheel and the accelerator pedal, and then compare the results with calculations made using the objective function in order to verify the credibility of our objective function. Finally, it is shown how effective the method is for drivers of a range of physical sizes.

2. LAYOUT DESIGN METHOD

2.1. Modeling of the human and the object

Fig. 1 shows the framework of the proposed layout design method. First of all, a human-machine system model consisting of a human body and objects is configured using a computer. Here the human body and the objects are modeled together as a multibody system. Specifically, each part of the human body, such as the upper arms and the forearms, and each part of the object are dealt with as rigid bodies. The mass, center of gravity and the moment of inertia of each rigid body are then defined. Also, the positions of characteristic points (markers) on each rigid body are defined using coordinate systems to describe the center of the joints, and the contact and constraint positions. This paper deals with only holonomic constraints.

Fig.1(a) shows the coordinate systems used for modeling the human-machine system. A coordinate system, Σ_h, constitutes a generalized human coordinate system q_h, which describes the human's movements. Σ_e constitutes a contact point coordinate system, X_e, which describes the points on the human that make contact to the objects. k is the number of contact points. In a similar way, Σ_m constitutes a generalized coordinate system, q_m, describing the movement of the objects and Σ_c constitutes a contact point coordinate system, X_c, describing the positions on the objects at which contact is made to the human. Σ_{tr} describes the contact transmission virtual coordinate system between the human and the object with n_{tr} degrees of freedom [7]. When contact is made between the human and the object, the three coordinate systems, Σ_e, Σ_{tr}, and Σ_c are coincident with each other and no slipping occurs. The reference point, r_e, where the equivalent inertia is evaluated is in the Σ_r and can be defined at any point on the object. Σ_0 is a global coordinate system. Here neither the human nor the object

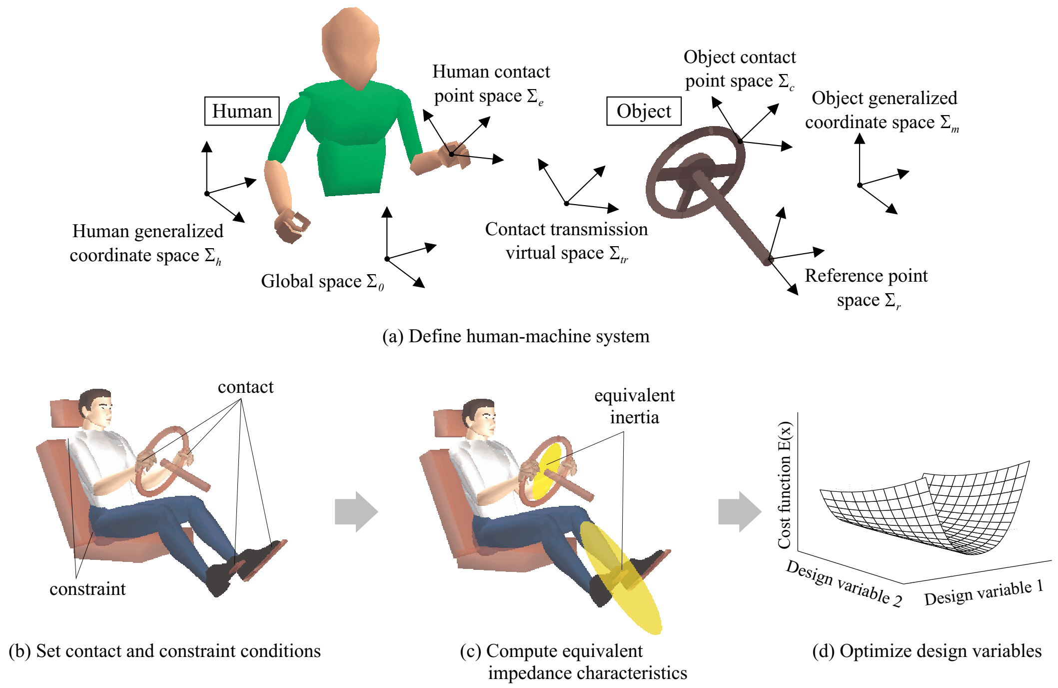

Figure 1: *Framework of the proposed layout design method based on equivalent inertia of human-machine systems.*

is singular postures and $n_h \geq 6,\ n_e = n_c \geq n_{tr}, n_m \geq 6$.

2.2. Setting contact and constraint conditions

Next, configurations and constraint conditions are defined. The posture of the human-machine system can be expressed by $q = [q_{h0}^T, {q_h}^T, q_{m0}^T, {q_m}^T]^T \in \Re^n, n = n_h + n_m + 12$. $q_{h0} \in \Re^6$ and $q_{m0} \in \Re^6$ are variables to transform from Σ_0 to Σ_h and to Σ_m, respectively. Because the contact points between the human and the object, $X_e \in \Re^{n_e}$ and $X_c \in \Re^{n_c}$ always coincident with each other, the following equation holds true.

$$J_e \dot{q_h} - J_c \dot{q_m} = 0, \tag{1}$$

where $J_e \in \Re^{n_e \times n_h}$ is the Jacobian matrix from Σ_h to Σ_e, and $J_c \in \Re^{n_c \times n_m}$ is the Jacobian matrix from Σ_m to Σ_c. Please note that $rank(J_e) = rank(J_c) = r_e \leq n_e = n_c = 6k$.

A set of m $(m \leq n - 2\,r_e)$ components out of n elements of q is defined as a variable $x \in \Re^m$ for determining a layout, and an appropriate initial value is substituted for this variable x. Therefore, by formulating the following equation, consisting of independent conditional expressions, the number of which is expressed as $n - m - 2r_e$, it is possible to calculate a unique posture, q, for the human-machine system.

$$\Phi_L(q) = 0 \tag{2}$$

Concerning contact points between the human and the object, the number of which is expressed as k, the contact constraint matrix [8] $H \in \Re^{n_{tr} \times 6k}$, $n_{tr} = r_e = \sum_{i=1}^{k} n_{tr_i}$is defined as follows:

$$H = block\ diag.\{H_i\}. \tag{3}$$

$H_i \in \Re^{n_{tr_i} \times 6}$, $(i = 1, 2, ..., k)$ is the contact constraint matrix at each contact point under the condition that $1 \leq n_{tr_i} \leq 6$. If the constraints on the human the vehicle are expressed by Φ_h and Φ_m respectively, the following equations can be established as

$$G_h \dot{q}_h = 0, \tag{4}$$
$$G_m \dot{q}_m = 0, \tag{5}$$

where $G_h \in \Re^{c_h \times n_h}$ and $G_m \in \Re^{c_m \times n_m}$ are Jacobian matrices of Φ_h and Φ_m respectively.

2.3. Calculating equivalent inertia [5]

Fig.2 illustrates a relationships between force and acceleration in a human-machine system. The inertia tensor of the human $M_h \in \Re^{n_h \times n_h}$ in Σ_h can be defined by configuration, mass, center of mass, and moment of inertia in each body segment. Here, by using $P_h \in \Re^{n_h \times n_h}$, orthogonal complementary projection of G_h, $P_h {G_h}^T = 0$, the constrained inertia matrix [9] $M_h' \in \Re^{n_h \times n_h}$ and the constrained Jacobian $\bar{J}_e \in \Re^{n_e \times n_h}$ can be obtained as follows:

$$M_h' = M_h + P_h M_h - (P_h M_h)^T, \tag{6}$$
$$\bar{J}_e = J_e P_h. \tag{7}$$

Based on coordinate transformation of tensors, the equivalent inertia ${}^hM_m' \in \Re^{n_m \times n_m}$ in Σ_m can be obtained as

$${}^hM_m' = J_c^T H^T (H\ {}^hM_e'^{-1} H^T)^{-1} H J_c, \tag{8}$$
$${}^hM_e' = (\bar{J}_e M_h'^{-1} \bar{J}_e^T)^{-1}. \tag{9}$$

In the same manner as be done with equations (6) and (7), by using orthogonal complementary projection of G_m, $P_m {G_m}^T = 0$, we

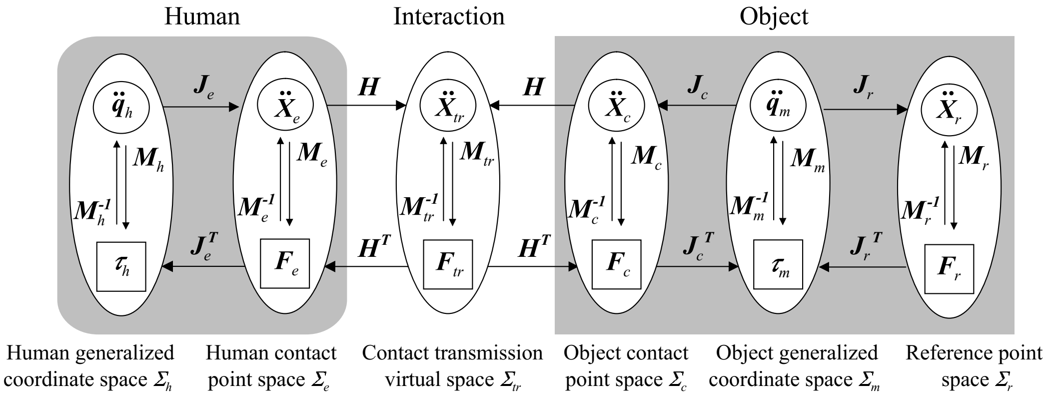

Figure 2: *Force/acceleration relationships in a human-machine system* [5]

have

$$\bar{J}_r = J_r P_m, \tag{10}$$

$${}^{hm}M''_m = {}^{hm}M'_m + {}^{hm}\overline{M}'_m, \tag{11}$$

$${}^{hm}\overline{M}'_m = P_m {}^{hm}M'_m - (P_m {}^{hm}M'_m)^T, \tag{12}$$

$${}^{hm}M'_m = {}^{h}M'_m + M_m. \tag{13}$$

Therefore, the equivalent inertia of the human-machine system ${}^{hm}M''_r \in \Re^{6\times 6}$ taking the constraints on both the human and the object into consideration can be expressed by

$${}^{hm}M''_r = (\bar{J}_r {}^{hm}M''^{-1}_m \bar{J}_r^{\,T})^{-1}. \tag{14}$$

2.4. Optimizing the layout

Using x as design variables and $\mathcal{J}(x)$ as an objective function, an optimal design problem is formulated as follows.

$$minimize \;\; \mathcal{J}(x) \tag{15}$$

$$subject\ to \;\; q_{h_{min}} \leq q_h \leq q_{h_{max}} \tag{16}$$

$$q_{m_{min}} \leq q_m \leq q_{m_{max}} \tag{17}$$

Here, $q_{h_{min}} \in \Re^n_h$ and $q_{h_{max}} \in \Re^n_h$ are the limit values of human joint movements, and $q_{m_{min}} \in \Re^n_m$ and $q_{m_{max}} \in \Re^n_m$ are minimum and maximum values of posture, q_m, of the object.

The objective function $\mathcal{J}(x)$ described in equation (15) needs to be defined to meet the actual layout design it is applied to. In the next section, determination of the objective function, $\mathcal{J}(x)$, using the equivalent inertia is discussed.

3. APPLICATION TO HUMAN-VEHICLE SYSTEMS

In this section, we propose an objective function based on the concepts of both the effective and ineffective equivalent inertia. The successful utilization of this function, when applied to the layout of the steering wheel and accelerator pedal, is then verified.

3.1. Effective and ineffective inertia

For simplicity, let us consider the case that the degree of freedom in the reference point r is confined to the x-y plane in Σ_r. Here, using the upper left 2x2 sub matrix of ${}^{hm}M''_r$, an inertia ellipse can be drawn as shown in Fig.3. Assuming the acceleration at point r is a, the inertial force F is given by

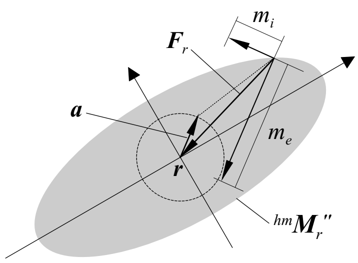

Figure 3: *Effective and ineffective equivalent inertia*

$$F_r = {}^{hm}M''_r a. \tag{18}$$

Except for the case where a is in the same direction as either of the major axes of the inertia ellipse, F_r is in a different direction to a. Thus, F_r can be separated into components parallel and perpendicular to a. The component in the same direction as a is defined as the effective equivalent inertia, m_e, and the component orthogonal to the direction of a is defined as the ineffective equivalent inertia, m_i. The effective equivalent inertia, m_e, can be obtained using the Rayleigh quotient:

$$m_e = \frac{a^T \, {}^{hm}M''_r a}{a^T a}. \tag{19}$$

The ineffective equivalent inertia m_i can be calculated as follows:

$$m_i = |{}^{hm}M''_r a - m_e a|. \tag{20}$$

m_e has its maximum value when the vector a is in the same direction as the eigenvector corresponding to the maximum eigenvalue of the equivalent inertia ${}^{hm}M''_r$ and is a minimum when a is in the same direction as the eigenvector corresponding to the minimum eigenvalue of ${}^{hm}M''_r$. Conversely, m_i is 0 when a is in the same direction as either of the eigenvectors of ${}^{hm}M''_r$.

For the layout of a human-vehicle system, we assume that the direction in which the driver operates on the objects (the steering wheel or accelerator pedal) is the direction of a. As the value of m_e (the effective equivalent inertia) gets larger, the acceleration due to the external force applied to the driver at contact point with

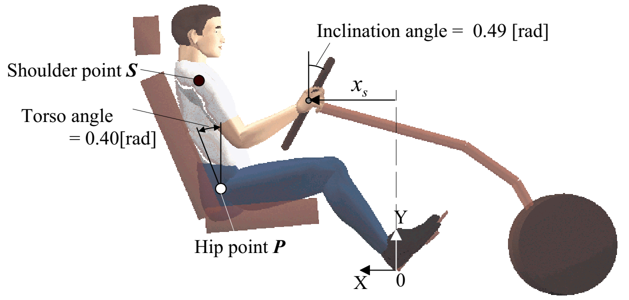

Figure 4: *Experimental condition*

Table 1: *Statue of the subjects*

Subject	A	B	C	D	E
height (m)	1.61	1.67	1.68	1.72	1.80
weight (kg)	50.0	60.0	65.0	62.0	70.0

Table 2: *Driving position parameters and appropriate longitudinal position of the steering wheel.*

Subject		A	B	C	D	E
hip point (m)	x	0.715	0.711	0.741	0.738	0.794
	y	0.255	0.255	0.252	0.252	0.247
	z	0.134	0.128	0.127	0.123	0.115
right shoulder point (m)	x	0.854	0.851	0.881	0.879	0.935
	y	0.685	0.704	0.705	0.717	0.737
	z	-0.052	-0.065	-0.067	-0.075	-0.093
wheel center (m)	y	0.616	0.616	0.616	0.616	0.616
	z	0.134	0.128	0.127	0.123	0.115
x_s (m)		0.429	0.415	0.428	0.417	0.439

the object becomes smaller. On the other hand, if m_i is small, the driver's operational force can be transmitted effectively to the acceleration vector at point r on the object. Following these discussions, we propose an objective function as

$$\mathcal{J}(x) = w_e \frac{1}{m_e} + w_i m_i + w_j \sum_{i=1}^{n_h} K_i(q_{h_i}), \quad (21)$$

$$K_i(q_{h_i}) = k_{1_i} e^{k_{1_i}(k_{2_i} - q_{h_i})} + k_{3_i} e^{k_{3_i}(q_{h_i} - k_{4_i})}, \quad (22)$$

where w_e, w_i, w_j are weighting factors. Equation (22) describes the passive stiffness of the human joint i, which is introduced to realize natural operational postures. The parameters, $k_{ji}(j = 1, 2, 3, 4)$, have the following relationship: $k_{1i} > 0, k_{3i} > 0$, and $k_{2i} < k_{4i}$. For the details, please refer to [10].

3.2. Application to steering wheel position

In the layout shown in Fig.4, five male subjects (aged 25 to 40), as shown in Table 1, were seated facing the steering wheel. The hip point, right shoulder point and the position of the steering wheel except for longitudinal position of each subject are shown in Table 2. They were asked to set the right hand at a three o'clock position and the left hand at a nine o'clock position, and to grip the steering wheel. The steering wheel was then moved only back and forth, and position, x_s, where each subject felt the most comfortable to steer was verified through subjective judgement. Table 2 also shows x_s values obtained for each subject.

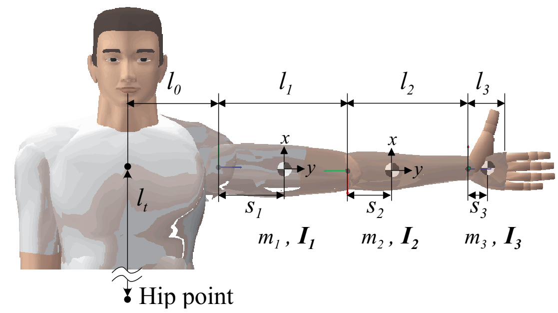

Figure 5: *A multibody human model of upper extremity.*

Table 3: *Inertial parameters of upper extremity.*

Subject		A	B	C	D	E
l_t (m)		0.524	0.543	0.546	0.559	0.584
l_0 (m)		0.206	0.214	0.215	0.220	0.229
l_1 (m)		0.251	0.265	0.267	0.277	0.296
l_2 (m)		0.230	0.247	0.250	0.261	0.283
l_3 (m)		0.053	0.055	0.056	0.057	0.060
s_1 (m)		0.128	0.135	0.137	0.141	0.151
s_2 (m)		0.085	0.091	0.092	0.096	0.041
s_3 (m)		0.038	0.039	0.040	0.041	0.043
m_1 (kg)		1.15	1.38	1.50	1.43	1.61
m_2 (kg)		0.75	0.90	0.98	0.93	1.05
m_3 (kg)		0.35	0.420	0.46	0.43	0.49
I_1 ($\times 10^{-3}$ kg.m^2)	x	5.109	6.846	7.549	7.724	9.967
	y	0.659	0.882	0.973	0.996	1.285
	z	5.153	6.904	7.613	7.790	10.05
I_2 ($\times 10^{-3}$ kg.m^2)	x	2.705	3.733	4.135	4.307	5.735
	y	0.492	0.680	0.753	0.784	1.044
	z	2.550	3.519	3.898	4.060	5.406
I_3 ($\times 10^{-3}$ kg.m^2)	x	0.129	0.167	0.183	0.183	0.226
	y	0.031	0.041	0.045	0.045	0.055
	z	0.113	0.198	0.159	0.159	0.197

Next, multibody driver models were scaled to the subjects with three degrees of rotational freedom for the shoulder and wrist joints and one degree of rotational freedom for the elbow joint. Inertia properties are determined as shown in Table 3. The models were seated so as to correspond the hip and shoulder point and grasping points of both hands as in the experiment. Rigid contact was set between the hands and the steering wheel. Please note that the posture of the upper extremity was determined with Tolani's method [11] so that splay angle of the elbow becomes 0.15 rad based on Schneider's research on driving posture [12]. Setting reference point r as the center of the steering wheel and tangential direction as a, the effective equivalent inertia m_{es} and the ineffective equivalent inertia m_{is} were calculated using lower right 3×3 sub matrix of the equivalent inertia ${}^{hm}M_r''$. The objective function $\mathcal{J}_s(x)$ is

$$\mathcal{J}_s(x) = w_{es} \frac{1}{m_{es}} + w_{is} m_{is} + w_{js} K_e(q_e) \quad (23)$$

$$K_e(q_e) = k_{1_e} e^{k_{1_e}(k_{2_e} - q_e)} + k_{3_e} e^{k_{3_e}(q_e - k_{4_e})} \quad (24)$$

where $w_{es} = 0.01$, $w_{is} = 1.0$, $w_{js} = 0.5$ and the elbow joint passive stiffness characteristic were used in the equation (24) (see Fig.6). Ten different back and forth wheel positions were set as

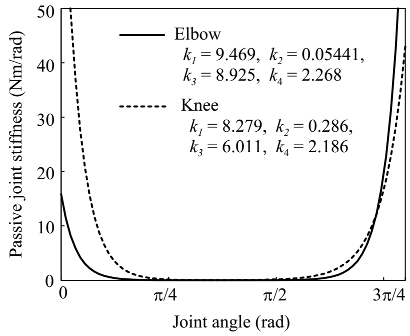

Figure 6: *Joint passive stiffness of elbow and knee joint.*

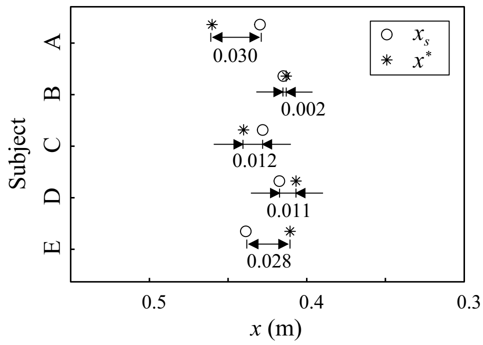

Figure 7: *Comparison between optimized and ergonomically comfort longitudinal position of the steering wheel.*

initial values, and the steepest descent method was used to get optimized position x^*.

Fig.7 shows x_s and x^* values for each subject. It is apparent that the most appropriate position in the back and forth direction can be estimated with an accuracy of about 0.03 m at the maximum, if equation (21) is used as the objective function.

3.3. Application to accelerator pedal

The accelerator pedal that controls the speed of a vehicle should accurately and effectively reflect the driver's intention. Thus the ineffective equivalent inertia when the accelerator pedal is pushed in the direction a (m_{ia}) should be as small as possible. Furthermore, to maintain the desired speed against disturbance while driving, the value of m_{ea} should be large. The effective equivalent inertia angle α is defined as the angle between the characteristic vector corresponding to the calculated maximum value of the equivalent inertia and the level surface (see Fig.8). The angle α and an appropriate range obtained from subjective tests were compared with each other.

Based on a multibody model of each test subject and the layout determined as in the previous section, the equivalent inertia at the point of contact of the right foot and the accelerator pedal was calculated for different heights of the hip point. As shown in Fig.9, the multibody model was configured with 3 degrees of rotational freedom for the hip and ankle joints and one degree of rotational freedom for the knee joint. The length, the center of mass, the mass and the moment of inertia of the lower extremities of each subject were set as well as those of the upper extremities, based on previously calculated values and a method described in

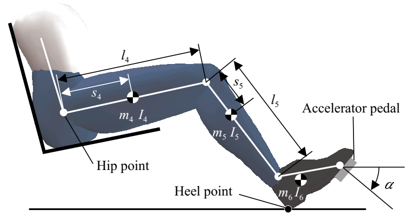

Figure 8: *A multibody model of lower extremity.*

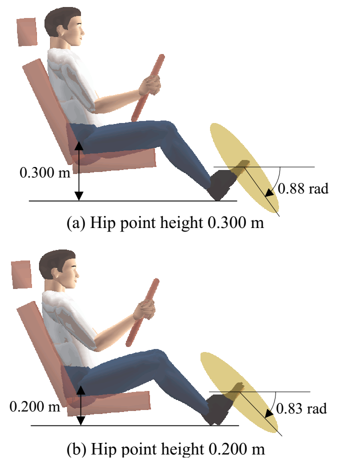

Figure 9: *Examples of effective equivalent inertia angle.*

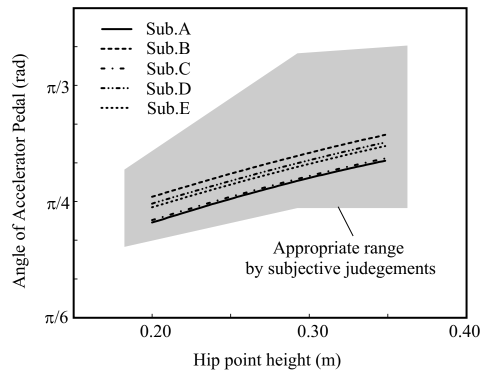

Figure 10: *Effective equivalent inertia angle and appropriate range of accelerator angle.*

the literature [10]. The posture of each segment of the lower extremities were determined at the same time that the contact points of the knee joint, the heel point, and the accelerator pedal were determined using a method described in the literature [12].

Fig. 9 shows the ellipsoids created using the upper right 3×3 matrix of the equivalent inertia for two different heights of the hip point for Subject D. It can be seen that the angle α is larger for the higher hip point. Fig 10 shows both the change in α and the appropriate range obtained from the subjective judgments of five different subjects of varying height. The effective equivalent inertia angle α of all the subjects are within the appropriate range. Based on these results, it is considered that when the appropriate layout for the accelerator pedal is determined, an evaluation using equation (21) can be effective.

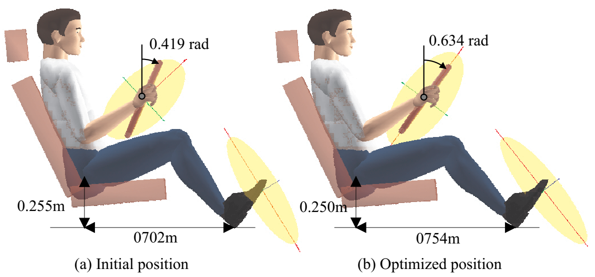

Figure 11: *Initial and optimized driving position (Subject E, Case II)*

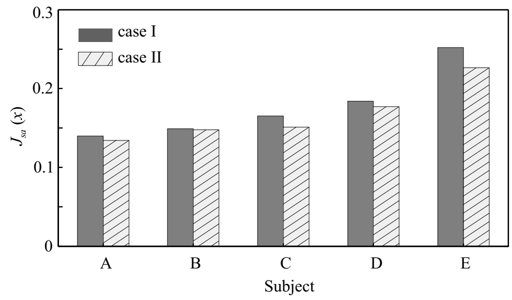

Figure 12: *Comparison of converged values of* $\mathcal{J}_{sa}(x)$

3.4. Driving position

In the previous sections, we verified the effectiveness of the equivalent inertia indices in determining the positions for the steering wheel and the accelerator pedal. The optimized layouts for five subjects were analyzed using the objective function $\mathcal{J}_{sa}(x)$.

$$\mathcal{J}_{sa}(x) = \mathcal{J}_s(x) + \mathcal{J}_a x \tag{25}$$

$$\mathcal{J}_a(x) = w_{ea}\frac{1}{m_{ea}} + w_{ia}m_{ia} + w_{ja}K_k(q_k) \tag{26}$$

$$K_k(q_k) = k_{1_k}e^{k_{1_k}(k_{2_k}-q_k)} + k_{3_k}e^{k_{3_k}(q_k-k_{4_k})} \tag{27}$$

where the weighting factor in equation (26) is the same as in equation (23) and the joint passive stiffness of the knee joint is described by equation (27) (see Fig. 6). The initial parameters for all the subjects were set to those calculated in section 3.2 for the layout for Subject A. Optimization was done for two different conditions; (I) the seat tilted at a fixed angle, $\pi/36$, but able to be slid forwards and backwards (II) the seat could be slid forwards and backwards and the angle of the steering wheel could be tilted. Fig. 11 shows the initial and optimized driving positions of Subject E under condition ID, and the converged values of each subject, $\mathcal{J}_{sa}(x)$, are shown in Fig. 12. It can be seen that the operability improves with increasing $\mathcal{J}_{sa}(x)$ for all the subjects by adjusting the angle of the steering wheel and the position of the seat. Although the solutions obtained require verification for global optimization, it is considered that the use of the equivalent inertia indices of human-machine systems can be effective in designing easy to operate layouts for drivers of various physical sizes.

4. CONCLUSIONS

This paper proposes a new method based on equivalent inertia indices for designing the layout for the system operator in a human-machine system. It also discusses the application of the method to a human-vehicle system. Furthermore, objective functions calculated using both the effective and ineffective equivalent inertias for the steering wheel and the accelerator pedal in the layout of a vehicle were examined. These objective functions were compared with subjective test results in order to verify the effectiveness of the method.

In large number of design variables case, our optimization method needs further improvements to avoid local optimized results. To expand to impedance characteristics, it would be important to determine an objective function including viscoelasticity of musculoskeletal system.

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