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Tailor-Made Modeling and Sway Control of Human Posture Riding on Electrical Wheelchair for Comfort Driving

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Abstract— **This paper gives an advanced driving control system that considers sway suppression of a passenger's posture in an electrical wheelchair. We proposed a passenger model that considers the passenger's physical frame and seating condition. The passenger's seating condition is classified as upright, standard, or round-shouldered posture. The sway of a passenger with round-shouldered posture is smaller than that of a passenger with upright posture, and they can be represented by the proposed model. To suppress the sway of a wheelchair passenger's posture, the wheelchair driving pattern is optimized using the proposed passenger's posture model. The comfort of the passenger with respect to the proposed wheelchair driving is evaluated through experiments.**

I. INTRODUCTION

Manual and electrical wheelchairs are the most useful vehicles for elderly and handicapped people. The number of people who use electrical wheelchairs increases year by year as the environment becomes more wheelchair accessible. Thus, the necessity for more comfortable and safe electrical wheelchairs increased. If the comfort and the safety of electrical wheelchairs can be improved, elderly and handicapped people can more easily go out, increasing their chances to take part in social or regional activities, and improving their quality of life(QOL).

There have been a lot of studies about comfort of wheelchair. For example, a passenger-wheelchair model was constructed, and the comfort was improved by suppressing the passenger's trunk behavior[1][2].The jarring motion of a wheel encountering a bump has been modeled by a human-wheelchair model[3]. In other studies, the relationship between comfort and handleability with a joystick[4][5], or between comfort and the passenger's vibration[6][7] have been examined. Comfort driving by suppressing passenger sway has been studied using a simple pendulum model by authors. A passenger model that considers the backrest was constructed, and a driving control system that suppresses the passenger's behavior was proposed[8], and passenger comfort has been evaluated based on several biological signals[9]. However, the passenger model includes parameters that must be identified from actual passenger's behavior. The passenger behavior must be thus measured. Taking such measurements gives strain for elderly and handicapped people. For this reason, a driving control system that requires measurement-free is desired.

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In this paper, a passenger model that considers the passenger's physical frame and posture is proposed. Then, we consider the relationship between the model parameters and the passenger's behavior. In addition, a driving control system that suppresses the passenger's behavior based on the proposed model is constructed. Finally, the effectiveness of the proposed control system is confirmed through experiment.

II. EXPERIMENT

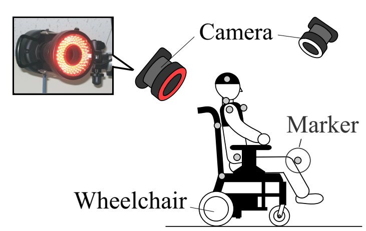
A. Experimental Methodology

The "Emu-S"(Wakogiken Co., Ltd.) electrical wheelchair, shown in Fig. 1(a), was used in this experiment. The wheelchair was accelerated by 2.0 m/s^2 to induce large passenger behavior. This acceleration pattern is a trapezoidal velocity pattern, with maximum velocity of 1 m/s and movement distance of 2 m. The passenger's behavior was measured by the motion capture system as shown in Fig. 1(b). Twelve markers were fixed on the passenger, and four markers were fixed on the wheelchair, as shown in Fig. 2, and the points of markers were measured by 12 cameras. Then, 12 trial subjects, all healthy males are tested. Table 1 shows the height and weight data of trial subjects.

B. Experimental Results

Figures 3 and 4 show the passenger's head and torso behavior as measured by the motion capture system. Then, the trial subjects are classified as having one of three postures: upright, standard, or round-shouldered, as shown in Fig. 5(a)∼(c). In Fig. 3 and Fig. 4, the upper graph shows the behavior of passengers with upright posture, the middle graph shows the behavior of passengers with standard posture and the lower graph shows the behavior of passengers with round-shouldered posture. The trial subjects are distinguished by line type. The passenger's posture is shown Table 2. In this classification, the passenger's torso behavior in the case

(a) Electrical wheelchair



(b) Motion capture system

Fig. 1. Experimental setup for measuring the passenger's posture behavior using motion capture

of upright posture is big, while the behavior of passengers with round-shouldered posture is small, as shown in Fig. 4. It would appear that this difference in behavior is caused by the difference in the effect of gravity on passengers. The gravity effect is the force pushing passengers backward, as shown in Fig. 6. In the case of upright posture, the gravity effect is small as shown in Fig. 7, and the passenger's body swing is large when the wheelchair stops, because of the small resistance against the forward swing. Then, the weak support of the backrest is thought to be the cause of the big torso behavior. Passengers who have upright posture tend to not lean against the backrest, and when there is acceleration, the torso behavior is big as they sink against on the backrest. On the other hand, gravity has a large effect on the passengers with round-shouldered posture, as shown in Fig. 8. It would appear that the passenger's body swing is small because of the big resistance against the forward swing. Furthermore, these passengers tend to strongly lean against the backrest, so their torso behavior with acceleration is small. Besides, the passenger's head behavior hardly changes with the passenger's posture. The cause of this behavior seems to be that the head has no support like the backrest for the body, and it balances upright at any posture as shown in Fig. 9.

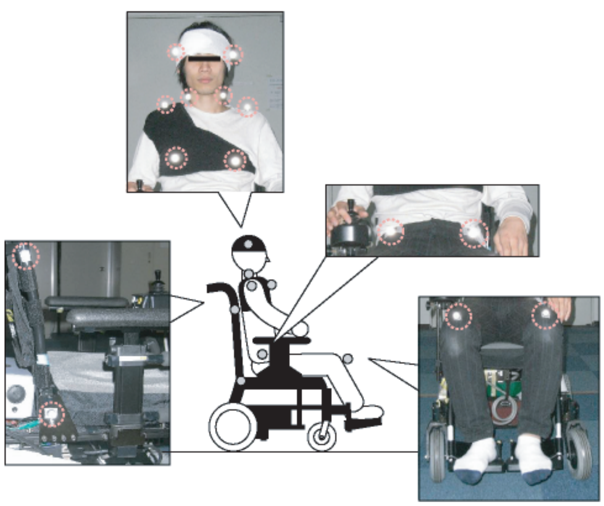


Fig. 2. Setting points of motion capture marker at the passenger's body part

TABLE I

THE PHYSICAL FRAME DATA OF PASSENGERS

	height (cm)	weight (kg)
subject1	187.5	72.9
subject2	164.4	55.8
subject3	178.0	64.5
subject4	172.5	68.8
subject5	169.6	75.7
subject6	173.0	69.0
subject7	161.0	51.5
subject8	169.5	59.9
subject9	173.0	51.4
subject10	171.0	62.4
subject11	170.0	64.3
subject12	182.0	62.7

Consequently, the passenger's posture affects the passenger's behavior, but in past researches[8], passenger's initial posture has not been considered. In the conventional model, every passengers have been represented as the upright posture, but actually, the passengers sit on the seat at the various initial posture, and after swaying during driving, the final posture is the initial posture. Thus, a passenger model that considers both of initial passenger posture and equilibrium(balancing) point is required to get more precise simulation behavior. In the following section, a novel passenger model is proposed.

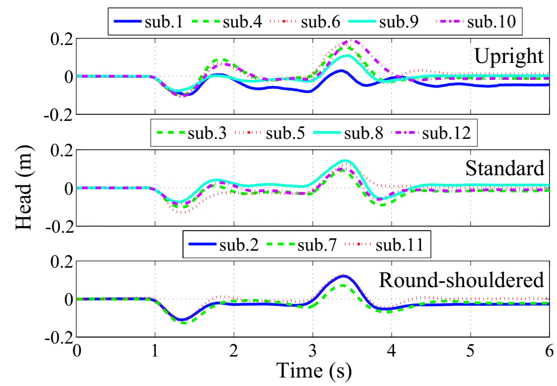


Fig. 3. The head behavior of three posture passengers

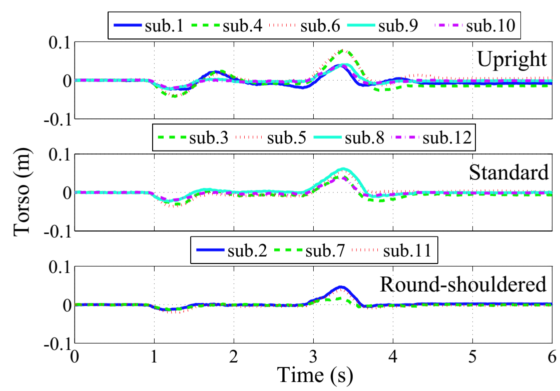
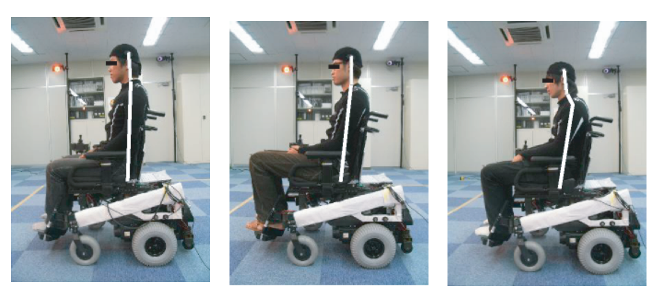


Fig. 4. The torso behavior of three posture passengers



(a) Upright posture (b) Standard posture (c) Round-shouldered posture

Fig. 5. Passenger's posture

III. Passenger Model Considering Passenger Posture

The passenger model that considers passenger physical frame and posture is shown in Fig. 10. The proposed model is a double inverted pendulum of a lumped mass system. There are springs and dampers(k_A,c_A,k_B,c_B) as the muscle at the joint of the model. In the proposed model, θ_0 is the initial angle of the body from upright, θ_1 is the deflection angle of the body from the initial angle and θ_2 is the angle formed by the trunk and the head. The resistance force of the backrest is represented by the spring and the damper(k_S,c_S), and it is available when θ_1 is over 0 deg. To simplify an expression, the resistance force of the backrest is assumed to act on only one point of the body. The parameters representing the spring and damper of the waist joint, neck joint and backrest(k_A,c_A,k_B,c_B,k_S and c_S, respectively) require identification. m_1 and m_2 are the mass of the body and head, L_1 and L_2 are the length of the body and head, and L_{m_1} and L_{m_2} are the distance of the mass point from the waist and neck joint. L_{y_1} and L_{y_2} are the distance of the marker of the motion capture system from the waist and neck joint, and y_1 and y_2 are the passenger's torso and head position relative to the wheelchair. The input of the model a_w is the driving acceleration of the wheelchair. The length of the body and head, L_1 and L_2, and the distance of the marker from the waist and neck joint, L_{y_1} and L_{y_2}, are actually measured by tape measure. The mass m_1 and m_2 of the body and head are respectively identified as 48.9% and 6.9% of the passenger's weight, and the distance L_{m_1} and L_{m_2} of the mass point from the waist and neck joint are respectively identified as 50% of L_1 and 80% of L_2[10]. The state equation of the proposed model is represented by (1) and (2), and the output equation y_1 and y_2 of the passenger's torso and head behavior, is represented by (3) and (4).

$$\begin{aligned}\ddot{\theta}_1 = {} & A_{11}\dot{\theta}_1{}^2 + A_{12}\dot{\theta}_1 + A_{13}\theta_1 + A_{14}\dot{\theta}_2{}^2 \\ & + A_{15}\dot{\theta}_2 + A_{16}\theta_2 + A_{17}\dot{\theta}_1\dot{\theta}_2 + A_{18}\theta_0 \\ & + B_1 a_w + E_1 + \Lambda_1 \end{aligned} \quad (1)$$

$$\begin{aligned}\ddot{\theta}_2 = {} & A_{21}\dot{\theta}_1{}^2 + A_{22}\dot{\theta}_1 + A_{23}\theta_1 + A_{24}\dot{\theta}_2{}^2 \\ & + A_{25}\dot{\theta}_2 + A_{26}\theta_2 + A_{27}\dot{\theta}_1\dot{\theta}_2 + A_{28}\theta_0 \\ & + B_2 a_w + E_2 + \Lambda_2 \end{aligned} \quad (2)$$

$$y_1 = -L_{y_1}\sin(\theta_0 + \theta_1) \quad (3)$$

$$y_2 = -L_1 \sin(\theta_0 + \theta_1) - L_{y_2}\sin(\theta_0 + \theta_1 + \theta_2) \quad (4)$$

$A_{11} \sim A_{28}$,B_1,B_2,E_1,E_2,B_1,B_1,Λ_1,Λ_2 in (1) and (2) are represented below.

$$\begin{aligned}
A_{10} &= Q^2 - PR \\
A_{11} &= -Qm_2L_1l_{m_2}\sin\theta_2/A_{10} \\
A_{12} &= \{R(c_A + c_B) - Qc_B\}/A_{10} \\
A_{13} &= \{R(k_A + k_B) - Qk_B\}/A_{10} \\
A_{14} &= -Rm_2L_1l_{m_2}\sin\theta_2/A_{10} \\
A_{15} &= (R - Q)c_B/A_{10} \\
A_{16} &= (R - Q)k_B/A_{10} \\
A_{17} &= -2Rm_2L_1l_{m_2}\sin\theta_2/A_{10} \\
A_{18} &= (R - Q)k_B/A_{10} \\
B_1 &= -\{(R - Q)m_2l_{m_2}\cos(\theta_0 + \theta_1 + \theta_2) \\
&\quad + R(m_1l_{m_1} + m_2L_1)\cos(\theta_0 + \theta_1)\}/A_{10} \\
E_1 &= -\{(R - Q)m_2gl_{m_2}\sin(\theta_0 + \theta_1 + \theta_2) \\
&\quad + R(m_1l_{m_1} + m_2L_1)g\sin(\theta_0 + \theta_1)\}/A_{10} \\
\Lambda_1 &= \begin{cases} R(k_S\theta_1 + c_S\dot{\theta}_1)/A_{10} & (\theta_1 \geq 0) \\ 0 & (\theta_1 < 0) \end{cases}
\end{aligned}$$

TABLE II

CLASSIFIED LIST OF SUBJECT INTO THREE POSTURE

Posture	Subject No.
Upright	1,4,6,9,10
Standard	3,5,8,12
Round-shouldered	2,7,11

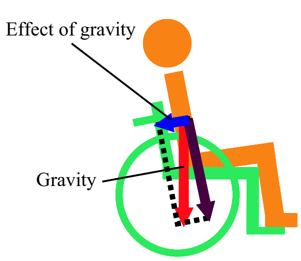


Fig. 6. The effect of gravity

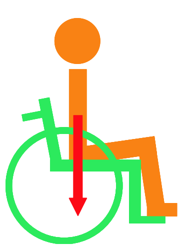


Fig. 7. Gravity effect of Upright posture

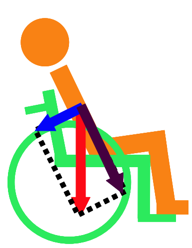
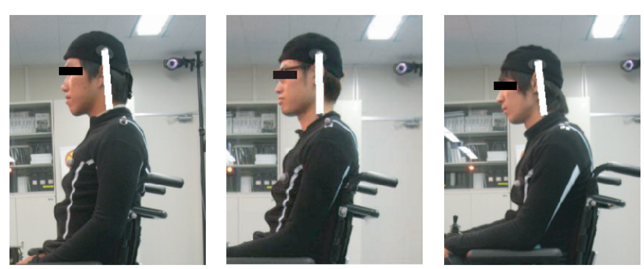


Fig. 8. Gravity effect of Round-shouldered posture



(a) Upright posture (b) Standard posture (c) Round-shouldered posture

Fig. 9. The posture of head and neck region

$$
\begin{aligned}
A_{20} &= PR - Q^2 \\
A_{21} &= -Pm_2L_1l_{m_2}\sin\theta_2/A_{20} \\
A_{22} &= \{Q(c_A + c_B) - Pc_B\}/A_{20} \\
A_{23} &= \{Q(k_A + k_B) - Pk_B\}/A_{20} \\
A_{24} &= -Qm_2L_1l_{m_2}\sin\theta_2/A_{20} \\
A_{25} &= (Q - P)c_B/A_{20} \\
A_{26} &= (Q - P)k_B/A_{20} \\
A_{27} &= -2Qm_2L_1l_{m_2}\sin\theta_2/A_{20} \\
A_{28} &= (Q - P)k_B/A_{20} \\
B_2 &= -\{(Q - P)m_2l_{m_2}\cos(\theta_0 + \theta_1 + \theta_2) \\
&\quad +Q(m_1l_{m_1} + m_2L_1)\cos(\theta_0 + \theta_1)\}/A_{10} \\
E_2 &= -\{(Q - P)m_2gl_{m_2}\sin(\theta_0 + \theta_1 + \theta_2) \\
&\quad +Q(m_1l_{m_1} + m_2L_1)g\sin(\theta_0 + \theta_1)\}/A_{10} \\
\Lambda_2 &= \begin{cases} Q(k_S\theta_1 + c_S\dot{\theta}_1)/A_{20} & (\theta_1 \geq 0) \\ 0 & (\theta_1 < 0) \end{cases}
\end{aligned}
$$

$$
\begin{aligned}
P &= m_1L_{m_1}^2 + I_1 + m_2L_1^2 + I_2 \\
&\quad +2m_2L_1L_{m_2}\cos\theta_2 + m_2{L_{m_2}}^2 \\
Q &= m_2L_1L_{m_2}\cos\theta_2 + I_2 + m_2{L_{m_2}}^2 \\
R &= m_2L_{m_2}^2 + I_2
\end{aligned}
$$

IV. Parameter Identification

A. Identification Methodology

The spring and damper parameters k_A,c_A,k_B,c_B,k_S,c_S of the proposed model must be identified. The optimization problem is represented by (5). J_1 and J_2 in (5) are the assessment function of the torso and the head respectively, and they are represented by (6) and (7). The identification method of a genetic algorithm is applied, and the parameters that minimize (5) are decided;

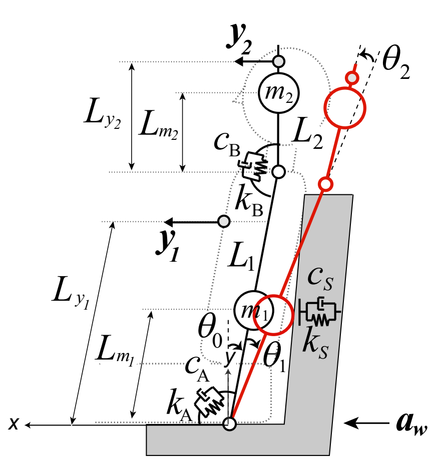


Fig. 10. Mathematical model of passenger's behavior considering the posture

$$
\min_{\mathbf{x}} \; J(\mathbf{x}) = \min_{\mathbf{x}} \{w_1J_1(\mathbf{x}) + w_2J_2(\mathbf{x})\} \tag{5}
$$

where

$$
J_1(\mathbf{x}) = \frac{1}{T}\int_0^T (y_{Texp} - y_{Tsim})^2 dt + e_T \tag{6}
$$

and

$$
J_2(\mathbf{x}) = \frac{1}{T}\int_0^T (y_{Hexp} - y_{Hsim})^2 dt + e_H \tag{7}
$$

,where, $\mathbf{x} = (k_A,\ c_A,\ k_B,\ c_B,\ k_S,\ c_S)$, y_{1exp} and y_{2exp} in the equation are the measured passenger's head and torso behavior, and y_{1sim} and y_{2sim} are the simulated behavior of the passenger model. e_T and e_H are respectively the square value of the difference between the maximum value of measured behavior and simulated behavior. e_T and e_H are expressed by (8) and (9). And, y_{Texpf}, y_{Texpb}, y_{Hexpf}, y_{Hexpb}, y_{Tsimf}, y_{Tsimb}, y_{Hsimf} and y_{Hsimb}, are shown in Fig. 11. In (5), w_1 and w_2 are the weighting coefficients, and they are respectively decided as the mean square of measured head behavior and torso behavior.

$$
e_T = \left\{(y_{Texpf} - y_{Tsimf})^2 + (y_{Texpb} - y_{Tsimb})^2\right\} \tag{8}
$$

$$
e_H = \left\{(y_{Hexpf} - y_{Hsimf})^2 + (y_{Hexpb} - y_{Hsimb})^2\right\} \tag{9}
$$

We decided that the initial angle θ_0 of the body at the upright posture is 0 deg, at the standard posture is 5 deg and at the round-shouldered posture is 10 deg, respectively.

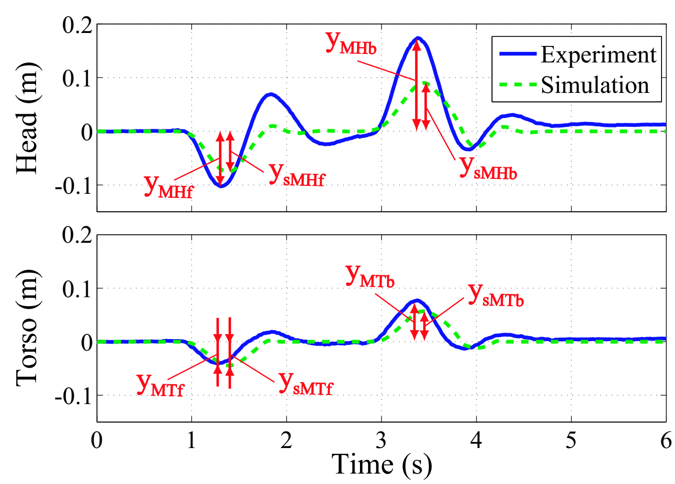


Fig. 11. The peak of passenger's measured behavior and simulation behavior

B. Identification Result

The identification results of the parameters in the proposed model are shown in Table 3. For example, the simulated results of trial subject 10(upright posture) and 11(round-shouldered posture) are shown in Fig. 12 and Fig. 13, respectively. In the figures, the upper graph shows the passenger's head behavior and the lower graph shows the passenger's torso behavior. The measured behavior is represented by a solid line, and the simulated behavior is represented by a broken line. These figures show that the simulated behavior followed the measured behavior well, and the proposed model can represent the measured passenger's behavior with high accuracy for passengers with any posture.

Then, we considered the identified parameters of the passenger model. First, it is confirmed that the passengers who have a long head or a heavy weight tend to have a large spring constant of neck. The cause appears to be that the head behavior is not very different among trial subjects. If two people have the same head behavior, it is a matter of course that a person who has a long head or a heavy head has a large spring constant. Second, the spring constants of the waist and backrest are considered with the passenger's posture. The passengers who have upright posture tend to have a small spring constant of the backrest, and a large spring constant of the waist. This is probably the case because passengers who have upright posture tend not to lean against the backrest, and have a small constant of the backrest and a large constant of the waist. On the other hand, the passengers who have round-shouldered posture tend to have a large spring constant of the backrest and a small spring constant of the waist. They tend to lean hard against the backrest and have a large spring constant of the backrest and a small constant of the waist. Consequently, it was confirmed that the model parameters have a trend that depends on passenger's physical features or posture. Moreover, it could be possible that we guess the model parameters to carry out more experiment, and examine the trend in detail.

TABLE III

IDENTIFIED PARAMETERS OF PASSENGERS WITH PROPOSED MODEL

subject	1	2	3	4	5
k_A	912.41	50.70	433.56	299.04	330.71
c_A	80.43	21.95	49.21	28.68	58.22
k_B	12.63	8.87	16.97	20.68	12.35
c_B	6.06	0.61	0.88	1.55	1.48
k_s	142.41	840.36	321.69	249.82	189.35
c_s	0.94	0.31	1.69	0.03	12.48
subject	6	7	8	9	10
k_A	364.31	459.84	202.42	410.65	253.35
c_A	28.41	47.80	17.28	33.95	50.68
k_B	15.22	10.00	15.90	11.45	12.81
c_B	0.86	0.54	0.89	1.11	0.66
k_s	350.01	292.03	450.49	307.10	379.16
c_s	0.07	13.53	0.00	0.02	0.00
subject	11	12			
k_A	220.92	531.55			
c_A	36.13	29.17			
k_B	11.92	16.53			
c_B	0.55	0.96			
k_s	621.60	244.55			
c_s	0.88	0.01			

Unit: k (kgf/m), c (kgf·s/m)

V. COMFORTABLE DRIVING CONTROL OF AN ELECTRICAL WHEELCHAIR

We designed a comfortable driving pattern which suppresses the passenger's behavior based on the proposed model. The driving pattern was designed using the optimization problem represented by (10), and its decision variable is represented by (12). Then, acc and dec in (12) mean the case of acceleration and deceleration, respectively. The decision variable **x** is the pattern of driving acceleration, and sampling period ΔT is 0.01 s. The relationship between the time, t, and the number of sampling, n, is $t = n\Delta T$. The assessment function involves multiplying the angle of the head, $\theta_T(= \theta_0 + \theta_1 + \theta_2)$, the integral square value of the body angle, θ_1, and the value that evaluates the driving time, J_d, by the weighting coefficients w_1, w_2 and w_3. w_1, w_2 and w_3 are set as 1, 40, and 220 respectively. J_d is represented by (11). The acceleration and deceleration driving time, T_i, is limited, and thus the double integration value of acceleration is large in the case of high-speed driving, and the negative value of it, J_d, is small.

$$\min_{\mathbf{x}} J(\mathbf{x}) = \min_{\mathbf{x}} \left\{ w_1 \int_0^{T_i} \theta_1^2 dt + w_2 \int_0^{T_i} \theta_T^2 dt + w_3 J_d \right\} \quad (10)$$

$$J_d = -\int_0^{T_i} \int_0^{T_i} a_{w_i} dt dt \quad (11)$$

where

$$\mathbf{x} = a_{w_i} = (a_{0_i},\ a_{1_i},\ \cdots,\ a_{n_i}) \qquad (i = acc, dec) \quad (12)$$

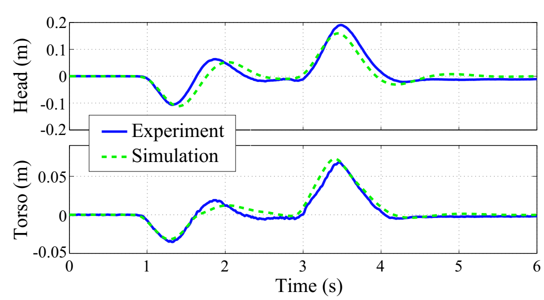


Fig. 12. Identification result of subject 10

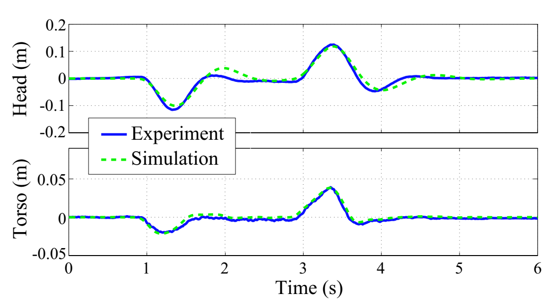


Fig. 13. Identification result of subject 11

VI. Experimental Results

Figures 14 and 15 show the driving pattern designed for trial subjects 10 and 11, respectively. In the figures, the upper graph shows the acceleration pattern of the electrical wheelchair, the middle graph shows the passenger's head behavior and the lower graph shows the passenger's torso behavior. The designed driving pattern is represented with a solid line, and the trapezoidal velocity pattern of acceleration 2.0 m/s^2 is represented with a broken line. Figures 14 and 15 show that the designed driving pattern can suppress both the head behavior and the torso behavior to about half of the maximum behavior of the trapezoidal velocity pattern. The designed driving pattern has longer acceleration and deceleration time than the trapezoidal velocity pattern; however, the time it takes for the passenger to come to a complete stop is subequal in both driving patterns. Furthermore, both trial subjects evaluated the designed driving pattern as a more comfortable driving pattern than the trapezoidal velocity pattern, as shown in Fig. 16. Figure 16 shows the comparison of comfort between the designed driving pattern(1st Drive) and the trapezoidal velocity pattern(2nd Drive). The data is obtained by hearing. By using the proposed passenger model, it was confirmed that the driving pattern that suppresses the passenger's behavior can be designed for passengers with any type of posture. Moreover, it is confirmed that the driving pattern that suppresses the passenger's behavior can improve the comfort of driving an electrical wheelchair.

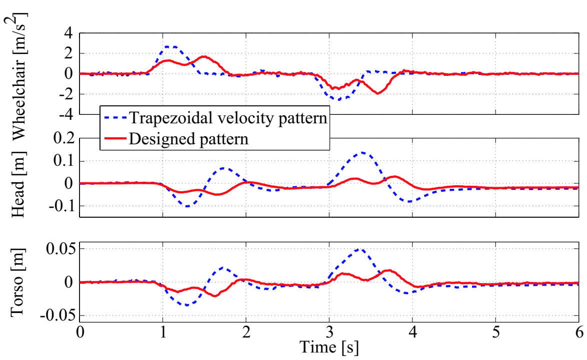


Fig. 14. The behaviors on driving with designed acceleration pattern of subject 10

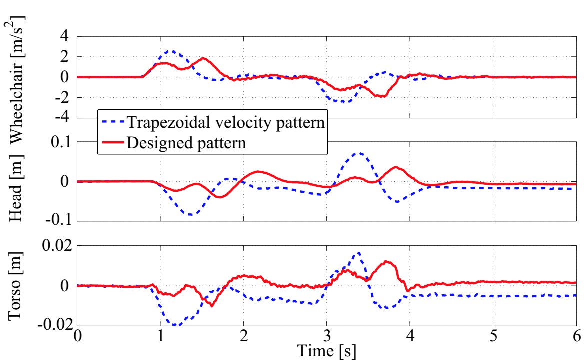


Fig. 15. The behaviors on driving with designed acceleration pattern of subject 11

Which drive did you feel ..... ?	1st Drive	2nd Drive
Uncomfort		×
Body movement		×

Fig. 16. Comparison about comfort between 1st Drive and 2nd Drive

VII. Conclusions

In this paper, a driving control system that considers the passenger's posture in an electrical wheelchair is presented. First, the behavior of passengers riding on an electrical wheelchair is measured by using a motion capture system. The passengers of several heights, weights, and posture types were selected. As a result of the measuring, the passengers were classified as having upright, standard or round-shouldered posture, and it was confirmed that there is a relationship between a passenger's posture and behavior. Second, to get more precise simulation behavior and model parameters, a passenger model that considered the passenger's posture is constructed. As a result, it was confirmed that the proposed model can represent the measured passenger's behavior with high accuracy for passengers with any posture. Finally, using the proposed model and identified model parameters, a comfortable driving pattern that suppresses the passenger's behavior is designed for 2 trial subjects, one with upright posture and one with round-shouldered posture. The findings confirmed that the designed driving pattern can suppress the passenger's behavior and improve the comfort of driving an electrical wheelchair.

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