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

Koumei Yamashita  Yoshiyuki Noda  Takanori Miyoshi  Kazuhiko Terashima

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/s² 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.

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. 2. Setting points of motion capture marker at the passenger’s body part](image)

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

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE PHYSICAL FRAME DATA OF PASSENGERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>height (cm)</td>
</tr>
<tr>
<td>subject1</td>
<td>187.5</td>
</tr>
<tr>
<td>subject2</td>
<td>164.4</td>
</tr>
<tr>
<td>subject3</td>
<td>178.0</td>
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<tr>
<td>subject4</td>
<td>172.5</td>
</tr>
<tr>
<td>subject5</td>
<td>169.6</td>
</tr>
<tr>
<td>subject6</td>
<td>173.0</td>
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<tr>
<td>subject7</td>
<td>161.0</td>
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<td>subject8</td>
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<tr>
<td>subject11</td>
<td>170.0</td>
</tr>
<tr>
<td>subject12</td>
<td>182.0</td>
</tr>
</tbody>
</table>

![Fig. 3. The head behavior of three posture passengers](image)

**Fig. 3. The head behavior of three posture passengers**

![Fig. 4. The torso behavior of three posture passengers](image)

**Fig. 4. The torso behavior of three posture passengers**

![Fig. 5. Passenger’s posture](image)

**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, $\theta_0$ is the initial angle of the body from upright, $\theta_1$ is the deflection angle of the body from the initial angle and $\theta_2$ 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 $\theta_1$ 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).

\[
\ddot{\theta}_1 = A_{11}\dot{\theta}_1^2 + A_{12}\dot{\theta}_1 + A_{13}\theta_1 + A_{14}\dot{\theta}_2^2 + A_{15}\dot{\theta}_2 + A_{16}\theta_2 + A_{17}\dot{\theta}_1\dot{\theta}_2 + A_{18}\theta_0 + B_1a_w + E_1 + \Lambda_1 \tag{1}
\]

\[
\ddot{\theta}_2 = A_{21}\dot{\theta}_1^2 + A_{22}\dot{\theta}_1 + A_{23}\theta_1 + A_{24}\dot{\theta}_2^2 + A_{25}\dot{\theta}_2 + A_{26}\theta_2 + A_{27}\dot{\theta}_1\dot{\theta}_2 + A_{28}\theta_0 + B_2a_w + E_2 + \Lambda_2 \tag{2}
\]

\[
y_1 = -L_{y_1}\sin(\theta_0 + \theta_1) \tag{3}
\]

\[
y_2 = -L_1\sin(\theta_0 + \theta_1) - L_{y_2}\sin(\theta_0 + \theta_1 + \theta_2) \tag{4}
\]

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

\[
A_{10} = Q^2 - PR \\
A_{11} = -Qm_2L_{m_2}\sin\theta_2/A_{10} \\
A_{12} = [R(c_A + c_B) - QC_B] / A_{10} \\
A_{13} = [R(k_A + k_B) - Qk_B] / A_{10} \\
A_{14} = -Rm_2L_{m_2}\sin\theta_2/A_{10} \\
A_{15} = (R - Q)c_B / A_{10} \\
A_{16} = (R - Q)k_B / A_{10} \\
A_{17} = -2Rm_2L_{m_2}\sin\theta_2/A_{10} \\
A_{18} = (R - Q)k_B / A_{10} \\
B_1 = -[(R - Q)m_2L_{m_2}\cos(\theta_0 + \theta_1 + \theta_2) + R(m_1L_{m_1} + m_2L_1)\cos(\theta_0 + \theta_1)] / A_{10} \\
E_1 = -[(R - Q)m_2gL_{m_2}\sin(\theta_0 + \theta_1 + \theta_2) + R(m_1L_{m_1} + m_2L_1)gL\sin(\theta_0 + \theta_1)] / A_{10} \\
\Lambda_1 = \begin{cases} R(k_S\theta_1 + c_S\dot{\theta}_1) / A_{10} & (\theta_1 \geq 0) \\ 0 & (\theta_1 < 0) \end{cases}
\]

<table>
<thead>
<tr>
<th>Posture</th>
<th>Subject No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>1,4,6,9,10</td>
</tr>
<tr>
<td>Standard</td>
<td>3,5,8,12</td>
</tr>
<tr>
<td>Round-shouldered</td>
<td>2,7,11</td>
</tr>
</tbody>
</table>

Table II: Classified list of subject into three posture

Fig. 6. The effect of gravity

Fig. 7. Gravity effect of Upright posture

Fig. 8. Gravity effect of Round-shouldered posture

Fig. 9. The posture of head and neck region
\[ A_{20} = PR - Q^2 \]
\[ A_{21} = -Pm_2L_1lm_2 \sin \theta_2/A_{20} \]
\[ A_{22} = \{Q(c_A + c_B) - PC_B\}/A_{20} \]
\[ A_{23} = \{Q(k_A + k_B) - Pk_B\}/A_{20} \]
\[ A_{24} = -Qm_2L_1lm_2 \sin \theta_2/A_{20} \]
\[ A_{25} = (Q - P)c_B/A_{20} \]
\[ A_{26} = (Q - P)k_B/A_{20} \]
\[ A_{27} = -2Qm_2L_1lm_2 \sin \theta_2/A_{20} \]
\[ A_{28} = (Q - P)k_B/A_{20} \]
\[ B_2 = -\{(Q - P)m_2l_m \cos(\theta_0 + \theta_1 + \theta_2) + Q(m_1l_m + m_2L_1) \cos(\theta_0 + \theta_1)\}/A_{10} \]
\[ E_2 = -\{(Q - P)m_2gl_m \sin(\theta_0 + \theta_1 + \theta_2) + Q(m_1l_m + m_2L_1)g \sin(\theta_0 + \theta_1)\}/A_{10} \]
\[ A_2 = \begin{cases} (Q(k_2\theta_1 + c_2\theta_1))/A_{20} & (\theta_1 \geq 0) \\ 0 & (\theta_1 < 0) \end{cases} \]
\[ P = m_1L_1^2 + I_1 + m_2L_1^2 + I_2 + 2m_2L_1l_m \cos \theta_2 + m_2L_m^2 \]
\[ Q = m_2L_1L_m \cos \theta_2 + I_2 + m_2L_m^2 \]
\[ R = m_2L_2^2 + I_2 \]

\[ \min_{\mathbf{x}} J(\mathbf{x}) = \min_{\mathbf{x}} \{w_1J_1(\mathbf{x}) + w_2J_2(\mathbf{x})\} \quad (5) \]

where

\[ J_1(\mathbf{x}) = \frac{1}{T} \int_{0}^{T} (y_{Texp} - y_{Tsim})^2 \, dt + \epsilon_T \quad (6) \]

and

\[ J_2(\mathbf{x}) = \frac{1}{T} \int_{0}^{T} (y_{Hexp} - y_{Hsim})^2 \, dt + \epsilon_H \quad (7) \]

where, \( x = (k_A, c_A, k_B, c_B, k_S, c_S) \), \( y_{Texp} \) and \( y_{Tsim} \) 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. \( \epsilon_T \) and \( \epsilon_H \) are respectively the square value of the difference between the maximum value of measured behavior and simulated behavior. \( \epsilon_T \) and \( \epsilon_H \) are expressed by (8) and (9). And, \( y_{Texp}, y_{Tsim}, y_{Hexp}, y_{Hsim}, y_{Tsim} \) and \( y_{Hsim} \) 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.

\[ \epsilon_T = \left\{ (y_{Texp} - y_{Tsim})^2 \right\} \quad (8) \]

\[ \epsilon_H = \left\{ (y_{Hexp} - y_{Hsim})^2 \right\} \quad (9) \]

We decided that the initial angle \( \theta_0 \) 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.

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;
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 the backrest and a small constant of the waist. 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.

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 \( \Delta T \) 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, \( \theta_1 \), and the value that evaluates the driving time, \( J_d \), by the weighting coefficients \( w_1, w_2, w_3, w_4, w_5 \) and \( w_6 \) 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.

\[
\min_x J(x) = \min_x \left\{ \int_0^{T_i} \theta_1^2 dt + \int_0^{T_i} \theta_2^2 dt + w_1 J_d \right\} \quad (10)
\]

\[
J_d = -\int_0^{T_i} \int_0^{T_i} a_{wi} dt \quad (11)
\]

where

\[
x = a_{wi} = (a_{w1}, a_{w2}, \cdots, a_{wn}) \quad (i = acc, dec) \quad (12)
\]

![Fig. 12. Identification result of subject 10](image1)

![Fig. 13. Identification result of subject 11](image2)
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/s² 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.

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.

REFERENCES