BEHAVIOR ANALYSIS OF PASSENGER'S POSTURE AND EVALUATION OF COMFORT CONCERNING OMNI-DIRECTIONAL DRIVING OF WHEELCHAIR

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Keywords: Wheelchair, Omni-directional drive, Passenger's posture behavior, Comfort sensation, Acceleration sensor.

Abstract: The purpose of this study is to analyze the relationship between passenger's posture behavior and comfort while riding omni-directional wheelchair. First, an algorithm to transform the obtained data in the sensor coordinates using acceleration sensor into the vehicle coordinates by means of proposed correction algorithm. Its effectiveness is demonstrated by experiments. Second, analysis on the relationship between acceleration of wheelchair movement, passenger's posture behavior and comfort sensation in the riding motion to forward, backward and lateral direction is studied. Posture behavior of passenger's head and chest is measured by acceleration sensors, and comfort sensation of passenger is evaluated by applying the Semantic Differential (SD) method and a Paired Comparison Test. Finally, through a lot of experiment, influence factors concerning comfort while riding to wheelchair are discussed.

1 INTRODUCTION

In today's aged society, a wheelchair is the most common vehicle to assist elderly and handicapped people. Wheelchairs can provide many profits to users, such as extending mobility, broadening community and social activities, and enhancing quality of life (QOL) of the users. Therefore, the user of electric powered wheelchair generally increases, and the development of wheelchair which is able to drive comfortably is highly required.

Various factors are largely related to the riding comfort of electric powered wheelchairs, such as seat comfort, ambient noise, and stability. The passenger's posture swing of body and the driving acceleration and deceleration are generally the main factors which influence on comfort.

In the international standard of ISO-2631-1, the riding comfort of a transportation vehicle is evaluated by the magnitude of the acceleration weighted by oscillation frequency (ISO-2631-1, 1997). Train's driving was often evaluated by this standard method and improved by suppressing the acceleration of uncomfortable frequency (C.H.Lee et al., 2005).

Passenger's comfort while riding wheelchair is also improved by suppressing the vibration with discomfort frequencies. Maeda described a wheelchair with passenger has three resonant frequencies; the first resonant frequency is 5$\sim$7[Hz], the second is 8[Hz], and third is 13$\sim$15[Hz]. And he addressed that the main point for improving a wheelchair passenger's comfort was to reduce the seat vibration of wheelchair at around 8[Hz] (S.Maeda et al., 2003).

The result described above is concerned with the vibration while driving over long time. On the other hand, a wheelchair is not the only steady-state operation, but also the transient state such as starting and stopping. Additionally, the high drive acceleration or deceleration causes passenger's discomfort. Yamagishi improved comfort while riding a car by reduction of acceleration and jerk (derivative of acceleration) (Y.Yamagishi and H.Inooka, 2005). However, up to the present, passenger's posture behavior of body which causes discomfort during riding has not been studied to own knowledge.

In the author's laboratory, comfort driving for wheelchair has been one of the main research subjects. Omni-directional Wheelchair (OMW) which can drive towards omni-direction is developed, and has a power assist system for helping fragile or elderly attendants (K.Terashima et al., 2006).

Passenger's comfort has been improved by sup-

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pressing the both of OMW and organ's vibration of passengers. Passenger's vibration can be estimated by the proposed two-dimensional passenger model. To suppress its vibration, the control system with two notch filters has been given. According to the simulation results, passenger's vibration is suppressed almost completely by the proposed controller in the case of forward and backward (H.Kitagawa et al., 2002), (J.Urbano et al., 2005). However, in the case of omni-direction such as lateral movements, it is only verified by simulation, not experiments. Therefore, it must be verified by experiments with measuring passenger's vibration. If lateral motion gives large discomfort, OMW is not appropriate as wheelchair for human being. It is necessary to investigate the posture behavior and comfort for the movements to any direction, whether or not OMW can be applied as a vehicle to carry people.

In most study about comfort driving, passenger's body posture is moved. However, passenger's posture behaviors while riding the wheelchair are not measured explicitly in actual experiments. The authors predict that passenger's behavior while riding is fairly related with the passenger's discomfort sensation.

The purpose of this study is therefore to analyze the relationship between passenger's posture behavior and comfort while driving to the omni-direction. First, an algorithm to transform the obtained data in the sensor coordinates using acceleration sensor into the vehicle coordinates by the correction algorithm. Its effectiveness is demonstrated by experiments. Second, analysis on the relationship between acceleration of wheelchair movement, passenger's posture behavior and comfort sensation in the riding motion to the forward, backward and lateral direction is studied. Passenger's posture behavior is measured by acceleration sensors fixed at head and chest. Comfort sensation of passenger is evaluated by applying the Semantic Differential (SD) method. Thirdly, experimental analysis on the chest movement with comfort is done. Passenger's sensation is evaluated by a Paired Comparison Test.

Finally, through a lot of experiment, influence factors concerning comfort while riding to wheelchair are discussed.

2 EXPERIMENTAL SETUP

2.1 Experimental Wheelchair

To clearly analyze the relation between passenger's body behavior and comfort sensation while riding the wheelchair, high performance wheelchair "Emu-S" (Wakogiken Co., Ltd.) which can drive with high velocity and acceleration as shown in Figure 1 is used in experiments.

Figure 1: Wheelchair used in experiments.

This wheelchair was introduced for another's study, and also used for observing passenger's movement (S.Shimada et al., 2002). To observe the passenger's body behavior for omni-directional movement, wheelchair seat is set with 90 [deg] rotations as shown in Figure 2.

Figure 2: Seat allocation of a wheelchair in the case of observing a lateral motion.

Table 1 is a specification of this wheelchair. It has been made for a wheelchair football needed to move fast, and therefore it can drive with high velocity and high acceleration. The max velocity and acceleration are respectively 2.7[m/s] and 3.5[m/s^2]. This wheelchair's specification is enough from the viewpoint of practical wheelchair's use. However, it can largely induce passenger's posture movements and discomfort sensation while riding the wheelchair, and thus it is used to analyze in this experiments.

This wheelchair is driven by the reference signal of analog voltage -5 to +5[V]. And DSP is loaded for motor servo control and digital signal processing of brushless resolver signal.

2.2 Measurement of Passenger's Behavior

Acceleration sensor of ACA302 (Star Micronics Co., Ltd.) is used for measuring the passenger's behavior. This sensor can detect three-axes acceleration of X, Y and Z-axis, and the range of detection is $\pm$19.6[m/s^2]. Acceleration sensors are put at the passenger's head,

Table 1: Specification of wheelchair.

Size	800×630×900 [mm]
Weight	88 [kg]
Motor	AC Servo motor 232 [W] ×2
Rated torque	1.18 [N·m]
Max torque	4.5 [N·m]
Rated rotation	1880 [rpm]
Max rotation	3000 [rpm]
Location detect	Brushless resolver

chest and the wheelchair as shown in Figure 3 and Figure 4. Sensor signals can be amplified by circuit, because the signal voltage is very small ([mV] order). Acceleration data is obtained from AD board at the sampling times of 10[ms]. Reference of analog voltage for driving the wheelchair is provided from DA board.

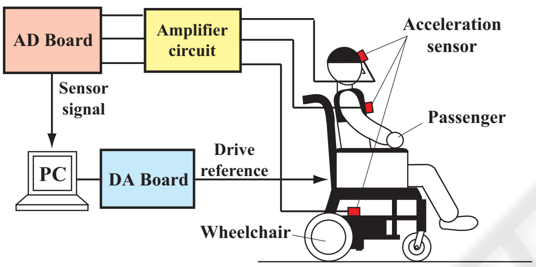

Figure 3: System for measuring passenger's behavior.

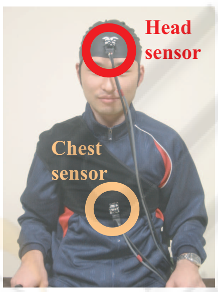

Figure 4: Acceleration sensor for measuring the motion of head and chest's point.

3 DATA CORRECTION OF ACCELERATION SENSOR

3.1 Correction Algorithm

It seems extremely difficult in the usual experiments that acceleration sensors must be horizontally placed at the exact accuracy. Therefore, the acceleration data obtained in the sensor coordinates by experiments should be converted in the drive coordinates by a correction algorithm. Acceleration sensor coordinates are x, y and z, and drive coordinates are u, v and w as shown in Figure 5. This study deals the drive toward one direction of forward, backward, rightward or leftward at once, and then the corrected acceleration must be appeared only in the drive direction acceleration of u-axis by the proposed algorithm.

With the proposed correction algorithm, acceleration sensor can be placed at any point of passenger's body part without considering sensor mount angle.

First, sensor coordinates are rotated through an angle ϕ around x-axis. Next, its coordinates are rotated through an angle θ around y-axis. With these rotation, z-axis is matched with w-axis. The coordinates after rotation are x', y' and z' as shown in Figure 6. Accelerations after the rotation represented as $a_{x'}$, $a_{y'}$ and $a_{z'}$, are calculated by Eq.(1), where a_x, a_y and a_z are the accelerations before the rotation. Notation of S and C denotes sinusoidal and cosine function respectively.

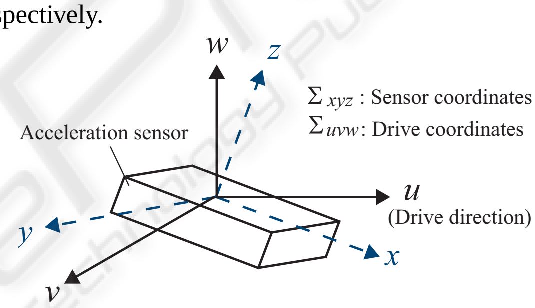

Figure 5: Sensor and drive coordinates.

$$\begin{pmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{pmatrix} = \begin{pmatrix} C\theta & S\theta S\phi & -S\theta C\phi \\ 0 & C\phi & S\phi \\ S\theta & -C\theta S\phi & C\theta C\phi \end{pmatrix} \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \qquad (1)$$

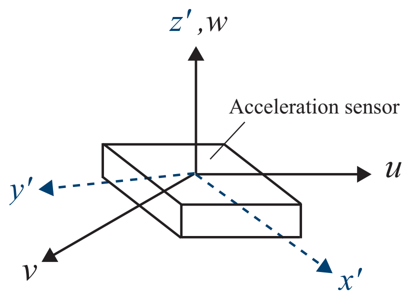

Figure 6: Coordinates after rotation through angles ϕ and θ.

The values of $a_{x'}$, $a_{y'}$ and $a_{z'}$ at initial state are described by Eq.(2). Acceleration is appeared only in z' axis, and gravity acceleration is g =9.8[m/s^2].

$$\begin{pmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \qquad (2)$$

By using the second row equation on Eq.(1), ϕ is calculated as Eq.(3), where $\bar{a_y}$ and $\bar{a_z}$ are the average of a_y and a_z at initial state, respectively.

$$\phi = \tan^{-1}\left(-\frac{\bar{a_y}}{\bar{a_z}}\right) \quad (3)$$

Then, θ is given in Eq.(4). ϕ is obtained by previous calculation, and $\bar{a_x}$, $\bar{a_y}$ and $\bar{a_z}$ are the average of acceleration at initial state.

$$\bar{a_x}\cos\theta + \bar{a_y}\sin\theta\sin\phi - \bar{a_z}\sin\theta\cos\phi = 0 \quad (4)$$

At the last, sensor coordinates are rotated through an angle ψ around z' axis. With this rotation, x' axis is matched with a drive direction of u axis. The relation between(a_u,a_v,a_w) and ($a_{x'}$,$a_{y'}$,$a_{z'}$) is expressed by the following equation.

$$\begin{pmatrix} a_u \\ a_v \\ a_w \end{pmatrix} = \begin{pmatrix} C\psi & S\psi & 0 \\ -S\psi & C\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{pmatrix} \quad (5)$$

The rotation angle ψ can be defined as Eq.(6). The passenger and wheelchair are transferred towards one direction of forward, backward or lateral at once. Then, the acceleration a_v of v axis expressed by Eq.(7) which is the direction perpendicular to u-axis, is small. Therefore, ψ is chosen so as to minimize the following cost function J.

$$J = \min_{\psi} \int_0^T a_v(\psi,t)^2 dt \quad (6)$$

$$a_v(\psi,t) = -a_{x'}(t)\sin\psi + a_{y'}(t)\cos\psi \quad (7)$$

In off-line process, three rotation angles of ϕ, θ and ψ can be estimated automatically, and made the sensor coordinates transformed in order to correct the installation error.

3.2 Verification of Proposed Algorithm

Figure 7 indicates that acceleration sensor signals of a_x, a_y and a_z are converted to the data signal of a_u, a_v and a_w, and the corrected data has only in the drive direction of u-axis by the proposed algorithm described in the previous section. Through these results, the proposed algorithm can provide the exact value of acceleration using acceleration sensor.

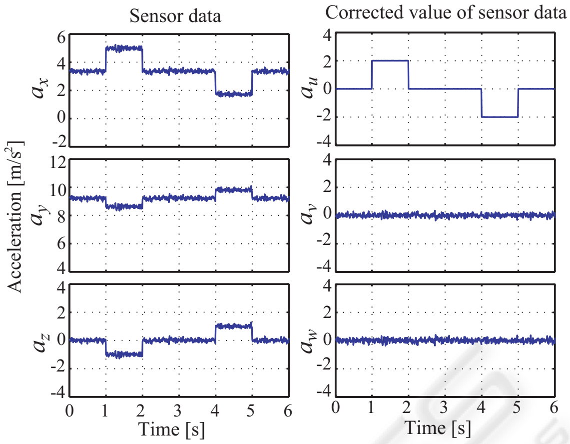

Figure 7: Result of the corrected values of sensor data by the proposed algorithm.

4 RELATIONSHIP BETWEEN PASSENGER'S POSTURE BEHAVIOR AND COMFORT

4.1 Passenger's Posture Behavior and Comfort in Omni-directional Drive

In order to discuss the relationship between passenger's posture behavior of body and comfort feeling, a lot of experiments are executed as follows.

4.1.1 Experimental Description

At experiments, the wheelchair is driven by three patterns with various acceleration of 0.5, 1.0 and 2.0[m/s^2]. These patterns are the trapezoidal velocity one with maximum velocity of 1[m/s] and movement distance of 2[m]. And it is respectively driven towards four-direction of forward, backward, rightward and leftward. The group of healthy and standard proportions comprised of 6 people (average: 170[cm], 60[kg]) is tested. All of them have never ridden on this wheelchair before.

Furthermore, the wheelchair is driven particularly in patterns with various acceleration of 1.0, 1.3, 1.7, 2.0 [m/s^2] with the same maximum velocity of 1[m/s] and distance of 2[m]. Drive directions are forward direction where 3 passengers are tested.

The passengers were given the information about the movement distance and the direction in experiments before start, and given a start sign when the wheelchair's movement starts. SD method is used for the investigation of passenger's comfort.

4.1.2 Experiment in Forward-backward Direction Drive

Passenger's posture acceleration of *u*-axis for the forward drive experiment with acceleration of 2[m/s^2] is shown in Figure 8. Numbers in the above side of Figure 8 corresponds to the passenger's posture shown in the bottom side.

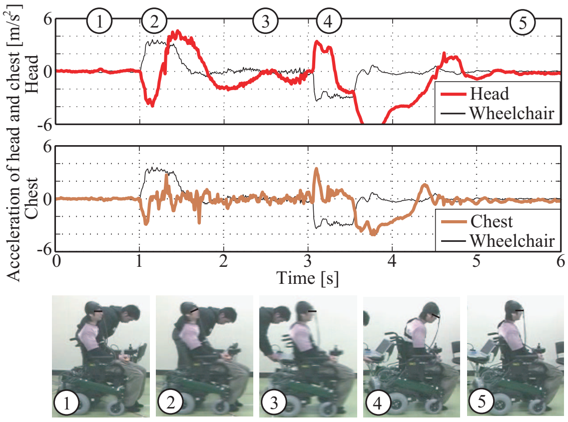

Figure 8: Acceleration of head and chest in the case of forward transfer with acceleration of 2.0 [m/s^2].

The head and chest acceleration can be obtained by subtracting the acceleration of the wheelchair from the measured acceleration of the head and chest.

When the forward transfer is started, a head moves in the opposite direction and a chest doesn't move due to the backrest as shown at the number 2 of Figure 8. During constant velocity drive, the head movement is suppressed by passenger's adjustment in number 3. The deceleration triggered a head swing. Then, a chest swing also appears, because there is not barrier of preventing a chest movement like the backrest in number 4. When a deceleration time is ended, the passenger intentionally suppresses the body movement, and there is no residual vibration at the end of driving in number 5.

The passenger's behavior in forward transfer of 0.5 and 1.0 [m/s^2] is shown in Figure 9. The head acceleration becomes bigger with increasing the drive acceleration. The average values of 6 passenger's maximum head acceleration in the driving acceleration of 0.5, 1.0 and 2.0 [m/s^2] are respectively 1.95 (standard variation σ=0.57), 2.84 (σ=0.96) and 6.64 (σ=1.41) [m/s^2]. The distinguished movement of chest doesn't appear at starting and stopping time in driving of 0.5 and 1.0 [m/s^2]. It seems that the chest movements appear between the drive acceleration of 1.0 and 2.0 [m/s^2].

During the backward drive, the passenger behaves in the same way as shown in Figure 10. The amplitude of head swing is similar to that of forward drive.

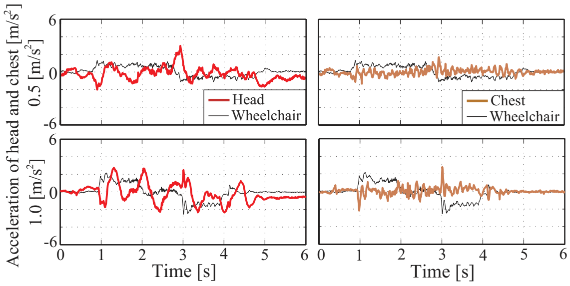

Figure 9: Acceleration of head and chest in the forward transfer of 0.5 and 1.0 [m/s^2].

The average of 6 passenger's maximum head accelerations in driving with 0.5, 1.0 and 2.0 [m/s^2] are respectively 2.29 (σ=0.59), 3.35 (σ=0.05) and 6.11 (σ=1.39) [m/s^2]. However, the chest swing is not appeared in the deceleration interval, and the swing is appeared in the acceleration interval, because of the backrest. The wheelchair's acceleration is opposite to that of forward, because the wheelchair is driven toward the reverse direction.

Questionnaires using SD method with forward and backward driving is shown in Figure 11 and 12 respectively. The right side in figure is a positive side, and left side is a negative side for all items of assessment. These results are total assessments about 6 passengers. Assessment of all items such as "Good Ride or Bad Ride", "Comfortable or Uncomfortable", "No-Swing or Swing", "Defensive or Aggressive" and "Bland or Pungent" are the significant difference with changing the drive acceleration by the analysis of variance was detected. Through this result, it is determined that the passenger's assessment becomes worse while increasing the drive acceleration during forward-backward direction drive.

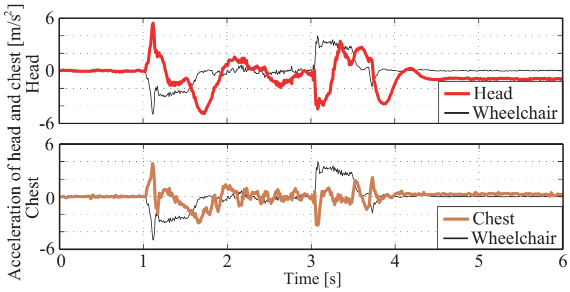

Figure 10: Acceleration of head and chest in the backward transfer of 2.0 [m/s^2].

4.1.3 Experiment in Lateral Direction Drive

Passenger's behavior in the rightward drive is shown in Figure 13 and Figure 14. When the wheelchair drives toward the right direction, the passenger's behavior is almost the same as that of forward or back-

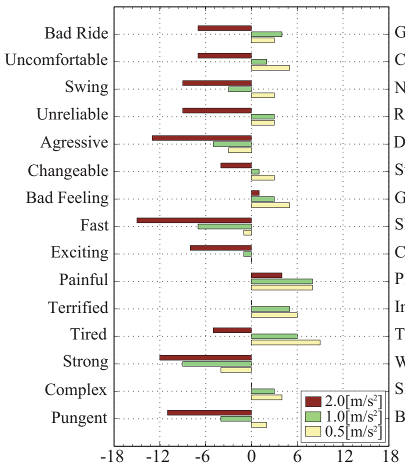

Figure 11: SD questionnaire result in the forward transfer.

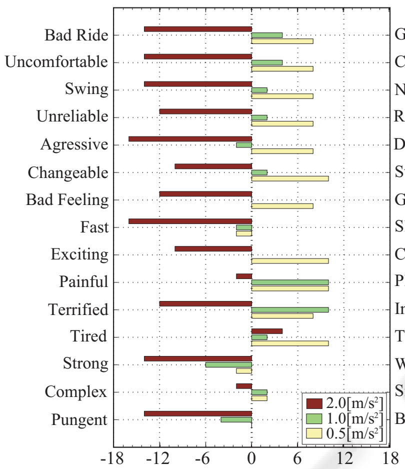

Figure 12: SD questionnaire result in the backward transfer.

ward drive. However, the head swing amplitude is bigger than that of forward drive. The average of maximum acceleration in 0.5, 1.0 and 2.0 [m/s^2] are respectively 4.4 (σ=1.18), 4.52 (σ=0.87) and 6.8 (σ=1.02) [m/s^2]. The distinguished chest swing only appears in driving of 2.0 [m/s^2] at the stopping and starting, and its amplitude is as the same level as the forward drive.

In the driving toward the left direction, the passenger behaves is similar to that of rightward drive as shown in Figure 15. The average of maximum acceleration in 0.5, 1.0 and 2.0 [m/s^2] are respectively 2.59 (σ=0.56), 3.59 (σ=0.37) and 7.85 (σ=1.46) [m/s^2]. The chest movements only appears in the driving of 2.0 [m/s^2].

Questionnaires using SD method in rightward and leftward driving is shown in Figure 16 and 17 respectively. The results show that the passenger's assessment becomes worse with increasing the drive acceleration during lateral direction drive. Furthermore, the lateral direction movements making the head swing bigger are more comfortable than the backward of the forward-backward direction movements. The backward driving is the most uncomfortable direction in four one. The leftward and rightward direction driving which often thought to be uncomfortable, are as comfortable as the case of the forward movements.

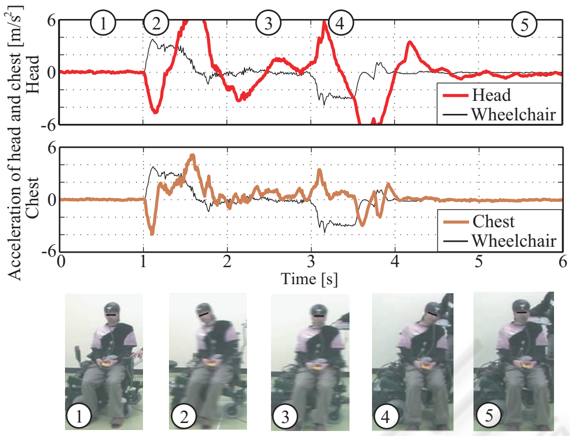

Figure 13: Acceleration of head and chest in the rightward transfer of 2.0 [m/s^2].

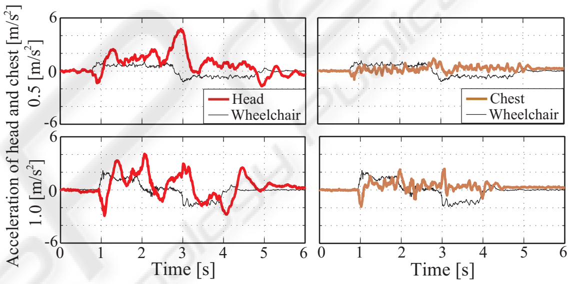

Figure 14: Acceleration of head and chest in the rightward transfer of 0.5 and 1.0 [m/s^2].

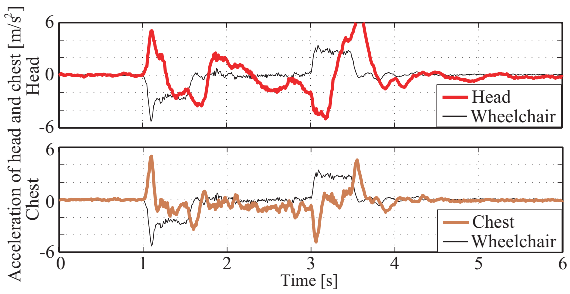

Figure 15: Acceleration of head and chest in leftward transfer of 2.0 [m/s^2].

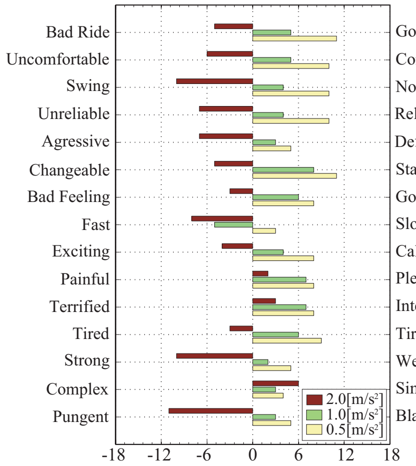

Figure 16: SD questionnaire result in the rightward transfer.

Figure 17: SD questionnaire result in the leftward transfer.

4.1.4 Experiment for Detecting Threshold Acceleration of the Chest Movements

The passenger's posture behavior at 1.0, 1.3, 1.7 and 2.0 [m/s^2] in the case of the forward drive are shown in Figure 18. Head and chest behavior at 1.0 and 1.3 [m/s^2] is alike as shown in Figure 18. The head movement becomes bigger while increasing the drive acceleration, and that is as the same as the previous experimental results. The distinguished chest movement appears in the case of 1.7 and 2.0 [m/s^2]. Threshold of the chest movement is estimated to be the value between 1.3 and 1.7 [m/s^2]. By the results using SD method, the passenger's comfort sensation becomes worse while increasing the drive acceleration. Then, the passenger says that they feel discomfort sensation when the chest is moved. The similar results were obtained in other passenger's experiments.

Through these results, it seems that the chest movements induce the passenger's uncomfortable, and uncomfortable feelings can be reduced by controlling of chest movements.

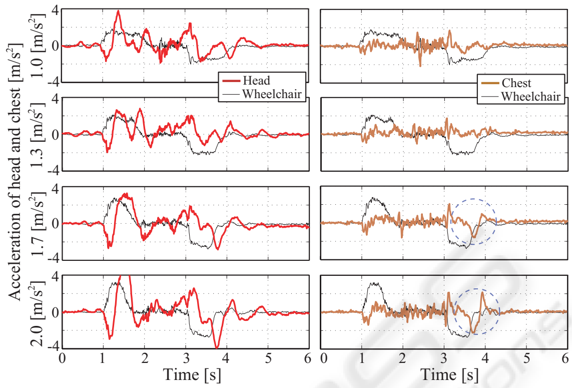

Figure 18: Acceleration of head and chest in case of forward transfer using various driving acceleration.

4.2 Comfort Sensation Focused on the Swing of Chest Part

Through the previous experiments, the passenger's comfort may be influenced by the chest movement. Therefore, the effect of chest movement on the comfort is investigated in details.

4.2.1 Experimental Description

In this section by using various patterns of the wheelchair is moved that acceleration and deceleration as shown in Table 2. The maximum velocity, distance and other condition are the same with the previous experiments.

Pattern I has a big deceleration such that induces the chest movement, because there is no backrest in the front part as shown in Figure 19. Pattern IV has a big acceleration such that induces the chest movement by the same reason. Drives by these two patterns are thought to be uncomfortable.

Table 2: Driving patterns.

[m/s^2]	Forward		Backward	
Driving pattern	Ⅰ	Ⅱ	Ⅲ	Ⅳ
Acceleration	1.0	2.0	1.0	2.0
Deceleration	2.0	1.0	2.0	1.0

In the present experiments, to evaluate discomfort sensation more clearly, a Paired Comparison Test is used. After forward drive (or backward drive) two pattern of Ⅰ and Ⅱ (or Ⅲ and Ⅳ), it was asked which pattern induces you discomfort feeling. 10 people with healthy and standard proportion were selected as subjects.

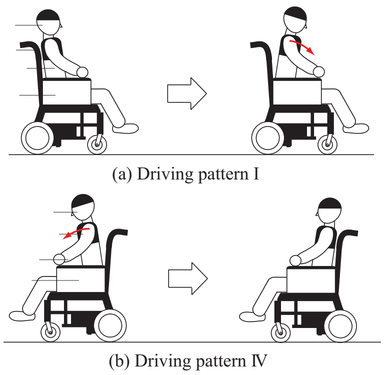

Figure 19: Drive patterns cause the chest swing.

4.2.2 Experimental Result and Discussion

Experimental results are shown in Figure 20. With respect to the pattern I and Ⅳ, the chest movement is observed at the anticipated point, because there is not backrest for the direction such that acceleration value is big. On the other hand, in the case of pattern Ⅱ and Ⅲ, the chest is not largely moved, because backrest exists for the direction in which the acceleration is big.

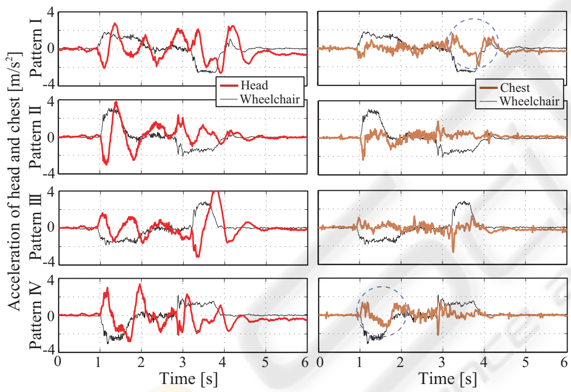

Figure 20: Acceleration of head and chest in the drive pattern I, Ⅱ, Ⅲ and Ⅳ.

According to the result of a paired comparison test as shown in Table 3, the discomfort sensations were almost same. The swing amplitude of I and Ⅳ is almost same. Here, that of Ⅱ and Ⅲ is almost same, where, the swing amplitude of I and Ⅳ is bigger than that of Ⅱ and Ⅲ. Therefore, the remarkable relationship between passenger's chest movement and discomfort could not be detected through this experiment conditions as seen from Table 2. However, comfort is almost same in each pattern. This may be the influence of the pressure from the backrest as a main factor.

Through these experiments, it becomes clearly that the passenger's body behavior is one of the factor that affects passenger's behavior. However, passenger's comfort is not depending on only passenger's behavior, and it is possible that there is another factor. For example, velocity or distance of wheelchair driving, and the chest pressure with backrest. These analyses are the near future problems to be solved.

Table 3: Number of passenger with discomfort feeling. (Total number ; N=10)

	Forward		Backward	
Driving pattern	I	Ⅱ	Ⅲ	Ⅳ
Discomfort passenger	4	6	6	4

5 CONCLUSION

The results obtained in this paper were as follows.

1. The transformed value of acceleration into the movements coordinates of wheelchair at the various body parts from the sensor data of sensor coordinates could be calculated by the proposed algorithm, and its effectiveness was verified.
2. Amplitude of passenger's head swing became bigger while increasing the drive acceleration.
3. The chest movement was largely appeared from the certain value of the drive acceleration between 1.3 and 1.7 [m/s^2]
4. From SD questionnaires, high acceleration drive caused passenger's discomfort.
5. Ride comfort for the movements to vehicles, backward direction is the most uncomfortable in four kinds of movements, and forward, leftward and rightward directions are almost same level with respect to comfort. Further, we showed the possibility that OMW will be able to apply as the transfer wheelchair without particular discomfort in the same level with conventional wheelchair with the ability of only forward and backward movements.

In the future, to find another factor, experimental condition such as the driving pattern, the ambient environment, and the evaluating method for passenger's comfort should be studied. Further, motion of slant and rotation should be studied for investigating the comfort driving.

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