A Brake-based Assistive Wheelchair Considering a Seat Inclination

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Keywords: Manual Wheelchair Assistance, Passive Robotics, Servo Brake, Gravitation-Negating Control, Seat Inclination Control.

Abstract: Considering the road inclination conditions, we proposed an upper body posture adjustment system for a passive-type assistive wheelchair. On an inclined road, there is a high probability that a wheelchair will move in a direction that is different from that desired by its user. In our previous research, we proposed a system that estimated a wheelchair user's intentions and worked passively to complement their intentional force. This was accomplished by negating the wheel traction that was generated by the road's inclination using only the servo brakes on each wheel. However, in some cases, our system failed to assist the driving motion of the user because it negated only the gravitational force. Therefore, our wheelchair succeeded in avoiding the unintended movement, but its user was required to row the hand rims with a considerable amount of force to overcome these braking forces. Consequently, we proposed an upper body posture adjustment system that adapts to the inclined road conditions and reduces the wheel traction that is generated by gravity. The proposed system inclined the wheelchair seat and aligned the upper body posture of its user to the center position of the wheelchair. Using this method, the proposed system maintained the position of the user's center of gravity with respect to the center position of the wheelchair. Our experimental findings suggested that the proposed passive-type assistive wheelchair can complement the user's intentional force with smaller brake traction, indicating that the user can drive the wheelchair using less physical strength.

1 INTRODUCTION

Wheelchairs are widely used by mobility-impaired people in their daily activities. Recently, a number of serious wheelchair-related accidents have been reported in Japan. Interestingly, more than 80% of these accidents were caused by environmental hazards (National Consumer Affairs Center of Japan, 2002). For example, the inclination of a sidewalk poses a potentially high risk for wheelchair users. The Japanese government permits sidewalks to have an incline of up to 5° (Japan Institute of Construction Engineering, 2008). Such an inclination could potentially lead to a wheelchair deviating from the sidewalk and into the roadway, which could be catastrophic. Therefore, a wheelchair driving assistance system is important for use on an inclined sidewalk.

In previous research, many assistive technologies have been developed for wheelchairs. For example, many disabled people routinely use powered wheelchairs (Yamaha Motor Co., Ltd., 2014). Many previous researchers have attempted to develop assistance functions by adding wheels with actuators that were controlled using robotic technology, such as motion control (Miller and Slack, 1995), sensing, and artificial intelligence (Katevas et al., 1997) (Murakami et al., 2001). These intelligent wheelchairs provide several functions, such as suitable motion, obstacle avoidance, and navigation; thus, they provide a maneuverable system. However, many wheelchair users have the upper body strength and dexterity to operate a manual wheelchair. For these users, such systems may be considerably expensive and unnecessary.

Therefore, we developed a passive driving assistance system for a manual wheelchair, which

Chugo, D., Kohara, R., Iwaki, M., Muramatsu, S., Yokota, S. and Mashimoto, H.
A Brake-based Assistive Wheelchair Considering a Seat Inclination.
DOI: 10.5220/0006858001360143
In *Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2018) - Volume 2*, pages 136-143
ISBN: 978-989-758-321-6
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employs servo brakes (Chugo et al., 2013; Chugo et al., 2015; Chugo et al., 2016). This system incorporates the concept of passive robotics (Hirata et al, 2007). The proposed system passively operates on the basis of the external forces imposed by its user. No actuators are required in our system. Our wheelchair uses servo brakes that can control the braking torque to produce the desired motion according to the applied force and reference track. The system developed in our previous research estimated the intended direction of a manual wheelchair user by determining the characteristics of their hand motion and maintaining it as the reference track (Chugo et al., 2013). Using the estimated results, the system negated the effects of gravitational force on the wheelchair moving on the inclined road (Chugo et al., 2015) and enabled it to drive in a direction intended by its user (Chugo et al., 2016).

However, in some cases, our assistive wheelchair requires its user to use greater physical force to drive it. This is because the does not use actuators, only servo brakes, for assistance. On an inclined road, our wheelchair cancels the gravitational force by means of the braking torque; therefore, the wheelchair does not move in an unintended direction. However, the wheelchair does not provide any driving force, and the user is required to row its hand rims with greater force, which overcomes the braking traction. This problem makes it difficult for some users to operate our assistive wheelchair, especially an elderly person, who might have limited physical strength.

To resolve this problem, it is important to minimize the braking traction, which negates the gravitational force. On an inclined road, the upper body posture of the user tends to deviate from the center position of the wheelchair, and the position of their center of gravity (COG) moves in the direction of gravity. This causes a rotational force, which causes the unintended movement generated by the gravitational force increases. Therefore, an upper body posture adjustment is required to reduce the unnecessary braking force.

Therefore, this paper proposes an upper body posture adjustment system for wheelchair users. The proposed system inclines the wheelchair seat according to the inclination of the road. The proposed device measures the position of the user's COG and keeps it at the center position of the wheelchair. This paper is organized as follows: In Section 2, we introduce our assistive wheelchair and its problem specifications; In Section 3, we propose an upper body posture adjustment system; In Section 4, we show the results of experiments using our prototype; In Section 5, we present our conclusions.

2 ASSISTIVE WHEELCHAIR

2.1 System Configuration

Fig. 1(a) shows our prototype. The proposed wheelchair utilizes a powder brake, which is a type of servo brake. Powder brakes are widely used in industrial applications, and their cost is low compared with other servo brakes. The powder brake in Fig. 1(b) (ZKG-YN50, Mitsubishi Electric Corp.) generated enough braking torque to stop a wheelchair moving at 4 km/h, containing a 100-kg user, in one second.

Our prototype is based on a normal, manual wheelchair (BM22-42SB, Kawamura Cycle Co., Ltd.), and our system is compatible with an ordinary wheelchair that meets the ISO7193, 7176/5 standards. This means that a user can incorporate our system into their wheelchair without any special construction.

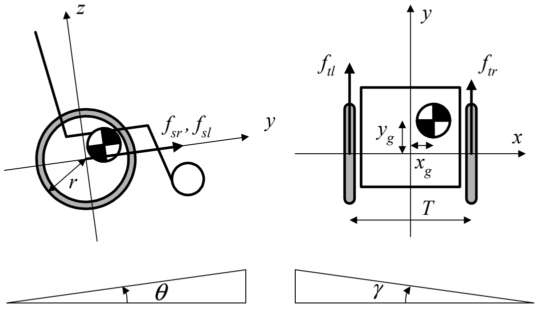
(a) Overview (b) Installed Servo Brake

Figure 1: Our Prototype.

For measuring the road inclination, our wheelchair has two tilt sensors: one for roll angle [Fig. 2(a)] and one for pitch angle [Fig. 2(b)]. These sensors are modularized and connected by USB cables to the control computer (PC). In this study, our prototype wheelchair has this module installed on its frame, under the seat.

2.2 Traction Required to Negate the Gravitational Force

Fig. 2 shows a wheelchair model on an inclined road. On a slope, the gravitational force pulls the wheelchair to a lower point on the incline.



(a) pitch angle (b) roll angle

Figure 2: Wheelchair model on an inclined road.

Kinematically, when the pitch angle is θ, the gravitational forces applied to the right wheel f_{sr} and left wheel f_{sl} are shown by

$$f_{sr} = f_{sl} = \frac{mg}{2}\sin\theta \tag{1}$$

where *m* is the mass of the wheelchair, including the user's body weight.

Furthermore, kinematically, when the roll angle is γ, the gravitational forces applied to the right wheel f_{tr} and left wheel f_{tl} are shown by

$$f_{tr} = -f_{tl} = \frac{y_g mg \sin\gamma}{\frac{T}{2} - x_g} \tag{2}$$

where (x_g, y_g) is the position of the center of gravity (COG), and *T* is the distance between the wheels.

Thus, the required braking traction on each wheel (τ_{cr}: right wheel, τ_{cl}: left wheel) to cancel the gravitational force is

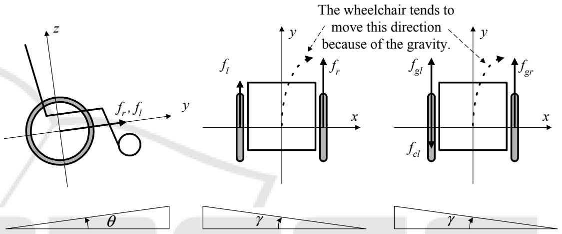
$$\tau_{cr} = \frac{f_{sr} + f_{tr}}{r} = \frac{1}{r}\left(\frac{mg}{2}\sin\theta + \frac{y_g mg \sin\gamma}{\frac{T}{2} - x_g} \right) \tag{3}$$

$$\tau_{cl} = \frac{f_{sl} + f_{tl}}{r} = \frac{1}{r}\left(\frac{mg}{2}\sin\theta - \frac{y_g mg \sin\gamma}{\frac{T}{2} - x_g} \right) \tag{4}$$

2.3 Problem Specifications in the Uphill Condition

Our assistive wheelchair on an inclined road negates the gravitational forces on the road, as in Eqs. (3) and (4). Our wheelchair does not have actuators and can only use braking traction. Therefore, especially in an uphill condition, our assistive wheelchair requires the user to use more physical strength to drive it.

For example, when the user goes uphill on a road, as in Fig. 3, the wheelchair moves to a lower position because of the gravitational forces on the road. In this condition, without an assistance system, a manual wheelchair user should drive the left wheel hard so that $f_l > f_r$, as in Fig. 3(b) (where f_r is the driving force on the right wheel and f_l is the driving force on the left wheel). To negate the gravitational force, our assistive wheelchair controls the servo brake according to Eqs. (5) and (6). In this condition, the wheelchair negates only the rotational moment generated by the gravitational force because the servo brake cannot generate a driving force.



(a) side view (b) top view (w/o assist) (b) top view (w/ assist)

Figure 3: Braking tractions on an inclined road.

$$f_{cr} = r(\tau_{cr} - \tau_{cl}) \quad \left(if\ |f_{cr}| > |f_{cl}|\right), \quad f_{cr} = 0\,(else) \tag{5}$$

$$f_{cl} = r(\tau_{cr} - \tau_{cl}) \quad \left(if\ |f_{cr}| < |f_{cl}|\right), \quad f_{cl} = 0\,(else) \tag{6}$$

In the case of Fig. 3(c), our system generates the braking traction f_{cl} on the left wheel to negate the gravitational force pulling the wheelchair to a lower position (in the right direction). In this case, our wheelchair user should drive each wheel equally so that $f_{gl} = f_{gr}$ (where f_{gr} is the driving force on the right wheel and $f_{gl}\,(= f_l + f_{cl})$ is the driving force on the left wheel with our assistance force). This means that the user can row the wheelchair as if on a flat road. However, the passive system does not assist the driving force and the required driving force increases with the braking force f_{cl} on the left wheel. Therefore, the user may feel that the wheelchair is too heavy, especially in this uphill situation.

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To reduce the user's load, the braking traction f_{cl} to negate the gravitational force should be minimized. From Eqs. (3) and (4), the position of the COG, $\left(x_g, y_g\right)$ increases the difference between the right and left braking tractions. This means that if the position of the COG locates at the center position of the wheelchair, the user's load will decrease. On an inclined road, the upper body posture of the user tends to deviate from the center position of the wheelchair. Therefore, it is important to adjust the upper body posture to reduce the user's load.

3 UPPER BODY ADJUSTMENT SYSTEM

3.1 Proposed Device

Fig. 4 shows an overview of the proposed assistance system. The system consists of a lifting device with a urethane cushion designed for the wheelchair and its controller. We designed the lifting device to be as thin as possible for easy implementation. Generally, the distance between the seat position and foot support is important for increasing usability (Defloor et al., 1999). The thickness of our lifting device is only 18 mm, and a user can install it without having to reconfigure the wheelchair.

To realize a thin design for our lifting device, we developed a tilt mechanism that is based on the elasticity of acrylic resin, as shown in Fig. 5. Also, to realize a thin mechanism, there is no sensor in the lifting device. The controller uses only pressure sensors to estimate the position of the COG of the user's upper body. The four air cells, each of which has an air compressor, lift or incline the aluminum base, as shown in Fig. 4(b). The acrylic resin also prevents the base from shifting. The cells can be cycled more than 20,000 times, according to the manufacturer's specifications.

(a) normal position (b) inclined position

Figure 4: Proposed upper body posture adjustment system.

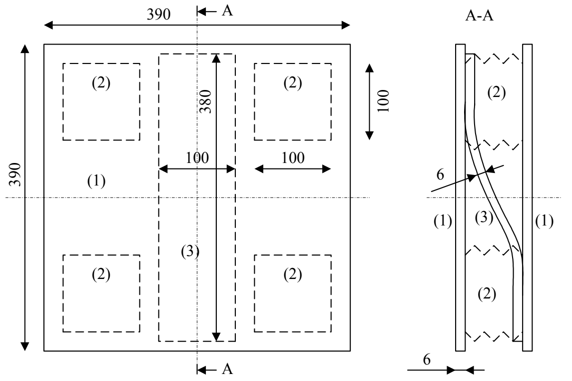


Figure 5: Design of a lifting device. (1) aluminium base, (2) air cell, and (3) acrylic resin.

Fig. 6 shows the controller for our posture adjustment system. It consists of a control box, which contains interface modules connected to a control PC by USB cables and an air compressor module, which contains air compressors, solenoid-operated valves, and pressure sensors. Both parts are small and can be installed within a wheelchair body. The controller requires a 12-V, 2.8-A power supply in order to lift a 100-kg user, and the standard batteries in the servo brake system can supply it. Therefore, the proposed posture adjustment system does not require additional batteries for the controller.

Our posture adjustment system has four air cells, each of which has an air compressor, solenoid-operated valve, and pressure sensor. To lift the seat cushion, the system drives the air compressors. To lower it, the system stops the compressors and opens the solenoid-operated valves. The elasticity of the acrylic resin helps the air cells shrink in the case where no user is seated in the chair. A sensor on each air cell measures pressure in real time, and the controller uses the measured data to position the COG of the user.

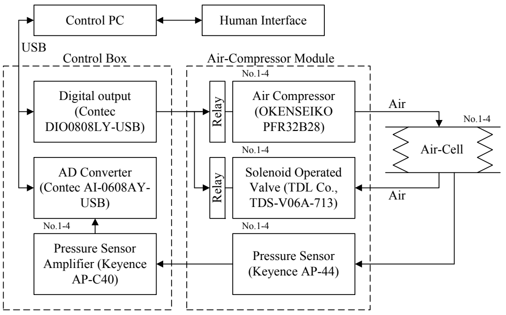


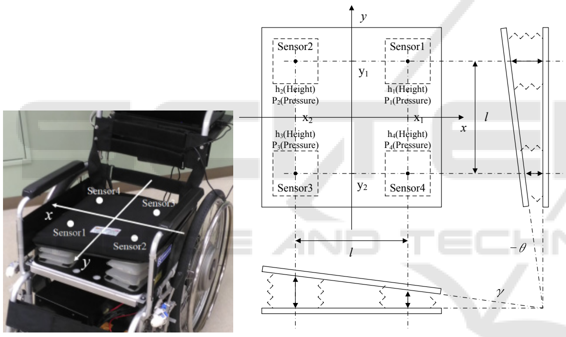
Figure 6: Overview of our controller for a posture adjustment system.

3.2 Position Estimation of the Center of Gravity

The distribution of pressure on the sitting surface inflects the posture of the user's upper body (Rader et al., 1999). Therefore, we use the position of the user's COG on the wheelchair seat as an index to estimate their upper body posture.

To estimate the position of the COG on the wheelchair seat, we use the pressure sensor on each air cell. This position (x_c, y_c) is derived from (7). The position and coordination of pressure sensors are shown in Fig. 7. The pressure values $p_i (i=1,\cdots,4)$ are measured by the sensor on each air cell.

$$\begin{cases} x_c = \left\{(p_1+p_4)x_1+(p_2+p_3)x_2\right\} \Big/ \sum_{i=1}^{4} p_i \\ y_c = \left\{(p_1+p_2)y_1+(p_3+p_4)y_2\right\} \Big/ \sum_{i=1}^{4} p_i \end{cases} \tag{7}$$



(a) sensor position (b) kinematical relationship

Figure 7: Kinematics of proposed upper body posture adjustment system.

3.3 Control Algorithm for the Proposed Device

The proposed device inclines the wheelchair seat according to the position of the user's COG. However, to realize its thin profile, there are no sensors in the lifting device, and the control box contains only the air pressure sensors. Therefore, the system cannot measure the seat inclination directly. Instead, the controller estimates the seat inclination using only its pressure sensors and realizes the reference inclination, which aligns the position of the user's COG to the center position of the wheelchair. The proposed scheme calculates the volume of the air cells by integrating the airflow during lifting.

The lifting height *h(T)* when the air compressor works for *T* seconds is derived by

$$h(T) = {v(T)} \Big/ {s} \tag{8}$$

where *v(T)* is the volume of an air cell and *s* is its cross-sectional area. Also, *v(T)* is the integration of the airflow, and the volume of the air cell is changed according to its pressure. The relationship between the cell's volume and pressure is inversely proportional according to Boyle's law. Therefore, *v(T)* is defined by (9) when its pressure is *p(T)*:

$$v(T)\cdot p(T) = \int_0^T u(p(t))\cdot p(t)\,dt \tag{9}$$

where *u* is the airflow of the compressor in the case of an inflow ($u>0$) or the solenoid-operated valve in the case of an outflow ($u<0$). Also, *u* is a function of the pressure *p* in the air cell that the pressure sensor can measure. Meanwhile, *T* is the operating time of the air compressor or valve. The parameters of *u* are derived based on the manufacturer's specifications. In this case, we set *u* as in (10):

$$u = \begin{cases} -a_i p + b_i & (u>0) \\ -a_o p - b_o & (u<0) \end{cases} \tag{10}$$

where $a_i = 6.7\times10^{-5}$, $a_o = 12.5\times10^{-5}\left[m^3/\mathrm{sec}\cdot kPa\right]$, $b_i = 7.66\times10^{-5}$, and $b_o = 3.2\times10^{-5}[m^3/\mathrm{sec}]$ are constants. From Eqs. (8) to (10), the estimated lifting height is derived from (11). Our system integrates the instantaneous height from the start time to *T* and can estimate the lifting height through odometry. We assume that the temperature is constant.

$$h(T) = \frac{1}{s\cdot p(T)}\int_0^T \left(ap(t)+b\right)\cdot p(t)\,dt \tag{11}$$

Using the height estimation scheme, we can estimate the inclination of the lifting device from (12). The estimated height h_i of each air cell ($i=1,\cdots,4$) is given by (12), and *l* (=250 mm) is the distance between them, as shown in Fig. 7(b). The inclination value is small, and we use approximate equations, as in (13):

$$\begin{cases} \gamma = \dfrac{-\left\{(h_1+h_2)/2\right\}+\left\{(h_3+h_4)/2\right\}}{l} \\ \theta = \dfrac{-\left\{(h_1+h_4)/2\right\}+\left\{(h_2+h_3)/2\right\}}{l} \end{cases} \tag{12}$$

$$\sin\gamma \approx \gamma, \quad \sin\theta \approx \theta \tag{13}$$

Our system realizes the pitch γ and roll θ inclinations as follows. From the kinematic relationship, the height of each air cell should be fulfilled as follows:

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$$\begin{cases} h_2 > h_1 \\ h_3 > h_4 \end{cases} (if\ \gamma > 0), \quad \begin{cases} h_3 > h_2 \\ h_4 > h_1 \end{cases} (if\ \theta > 0) \qquad (14)$$

Using (14), our controller sets the minimum height of an air cell h_0 from the reference inclination. If $\gamma > 0$ and $\theta > 0$, our controller sets $h_1 = h_0$ and derives h_2 to h_4 using (12) and considering the restraint condition that the all air cells are all connected to the same plane. Because the outflow is larger than the inflow, we set $h_0 = 10[mm]$ to improve the response time of our device. If the controller discharges all the air from the cell, the charging time will be long. Using these principles, the controller of the proposed device can realize the reference inclinations.

The proposed system inclines the wheelchair seat when the position of the user's COG does not align with the center position of the chair: it tries to return the user to their original position. The inclination references $(\gamma_{ref}, \theta_{ref})$ are generated by the simple PID controller as in (15). Considering the individual differences, as in (16), the proposed controller uses the position of the user's COG when they sit on the seat in a natural sitting posture as a position control reference. In many cases, this reference (x_{org}, y_{org}) is almost the center position of the wheelchair seat $(x_{org} \approx 0, y_{org} \approx 0)$, which means the proposed system adjusts the position of the COG to the center position of the chair.

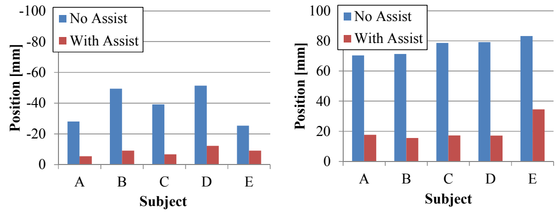
$$\begin{cases} \gamma_{ref} = -\left(k_p x_e + k_i \int_0^T x_e dt + k_d \dfrac{dx_e}{dt} \right) \\ \theta_{ref} = -\left(k_p y_e + k_i \int_0^T y_e dt + k_d \dfrac{dy_e}{dt} \right) \end{cases} \qquad (15)$$

$$x_e = x_c - x_{org}, \quad y_e = y_c - y_{org} \qquad (16)$$

3.4 Preliminary Experiment with the Proposed Device

In this experiment, we set the proposed wheelchair on two inclined roads ($\gamma = -4, 8$ °; $\theta = 0$ °). On these roads, our wheelchair could be stopped using the handbrake. Each of five subjects (subjects A–E in Table 1) sat in our prototype, which adjusted the positions of their COGs. To verify the effectiveness, the subjects tried each tried to navigate the inclined road without the proposed device.

Fig. 8 shows the experimental results. In each case, using the proposed device, the positions of the COGs were located around the center position compared with the results without the device. Therefore, the proposed device is effective for adjusting the position of the COG on the wheelchair seat.



(a) $\gamma = -4$ °   (b) $\gamma = 8$ °

Figure 8: Position of COG (x-direction) on an inclined road.

4 EXPERIMENTS

4.1 Experimental Setup

In this experiment, the 14 subjects listed in Table 1 tested our prototype. The subjects moved from side to side in a figure of eight on a test road with an 8° incline using our prototype wheelchair with upper body posture adjustment assistance, as shown in Fig. 9. This course had the typical characteristics of an inclined sidewalk environment: (A) is a straight uphill path; (B) is curved uphill path; (C) is a straight downhill path; and (D) is curved downhill path. To compare the effectiveness of the proposed assistance system, the subjects repeated these trials in wheelchairs without the system. Furthermore, for accurate verification, the subjects did not know how the proposed assistive system worked and whether the trials were with or without the system.

Table 1: Subjects.

Subject	**Weight [kg]**	**Height [m]**	**Gender**	**Age**	**Handedness**
A	50	1.66	male	23	left
B	52	1.64	female	22	right
C	42	1.60	female	23	right
D	61	1.74	male	24	right
E	53	1.70	male	21	right
F	67	1.84	male	23	both
G	55	1.65	male	24	right
H	60	1.74	male	24	right
I	57	1.67	male	23	left
J	56	1.72	male	21	right
K	65	1.77	male	24	right
L	60	1.75	male	21	right
M	50	1.54	female	23	left
N	50	1.54	female	22	right

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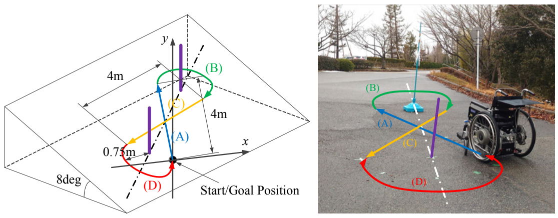


(a) overview of a test course (b) real environment

Figure 9: Test course on an inclined road.

4.2 Experimental Results

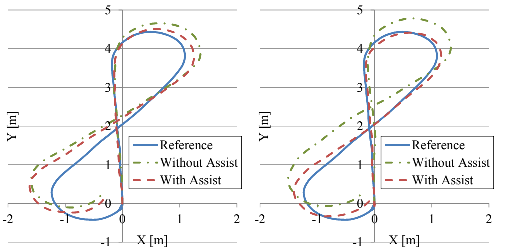
The results show that the subjects could drive in an intended direction when using our system (Fig. 10). Fig. 11 shows the running tracks of the wheelchair. With the proposed assistance system, the subjects could drive the wheelchair according to the reference path, compared with the running tracks without the system. This tendency was the same for left- and right-handed subjects.

Fig. 12 shows the inclination of the seat surface as the wheelchair passed section C. From Fig. 12(b), it can be seen that our assistive system inclined the seat surface according to the inclination angle of the road and succeeded in adjusting the upper body posture of the subject. While adjusting the upper body posture, the maximum braking traction, which negates the gravitational force, decreased, as shown in Fig. 13. Especially in a straight uphill path (section A), the proposed system reduced the braking traction by more than 50%, and this means that the subject could drive the wheelchair using less physical strength. As a result, the driving velocity increased and, as shown in Fig. 14, the time required to pass through each section decreased.

To investigate how the proposed system feels to its users, we conducted the questionnaire survey in Table 2. Typically, such a questionnaire has scales of 1–5 or 1–7. In this experiment, to avoid a concentration of “neither” responses, as is the Japanese habit (Takahashi et al., 2013), we used a scale of 1–6.

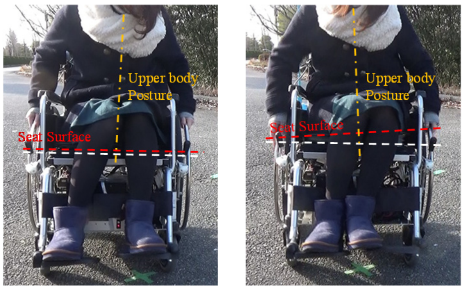
(a) passing (A) (b) passing (C)

Figure 10: Test run by subject A with the proposed controller.



(a) subject A (left handed) (b) subject B (right handed)

Figure 11: Running tracks.



(a) without assistance (b) with assistance

Figure 12: Inclination of seat surface and upper body posture at passing (C) (subject C).

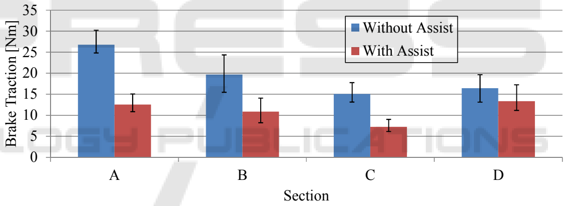


Figure 13: Maximum braking traction in each section.

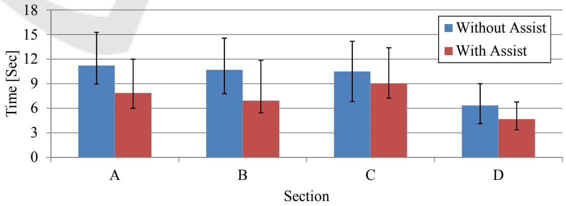


Figure 14: Passing time for each section.

Fig. 15 shows the questionnaire results. In the results from Q1 to Q3, the subject feels that the driving force is light with our assistance system. Furthermore, the results from Q4 and Q5 indicate that the subject felt that it was easy to drive on the reference path with our system. We can verify this result from the running tracks in Fig. 11. The results from Q6 and Q7 indicate that the subject felt that the driving assistance was better with the proposed device. The assistance algorithm with the servo brake was the same; therefore, by adjusting the upper body posture, the subjects felt that the assistance effectiveness was better.

Table 2: Questionnaire.

	Higher Score (Maximum is 6)	**Lower Score (Minimum is 1)**
Q1	I do not feel fatigue in this trial.	A feel fatigue in this trial.
Q2	A hand rim is light.	A hand rim is heavy.
Q3	It is easy to strain my arm.	It is hard to strain my arm.
Q4	It is easy to drive on the straight path.	It is difficult to drive on the straight path.
Q5	It is easy to drive on the curved path.	It is difficult to drive on the curved path.
Q6	The assistance is smooth.	The assistance is awkward.
Q7	The assistance is quick.	The assistance is slow.

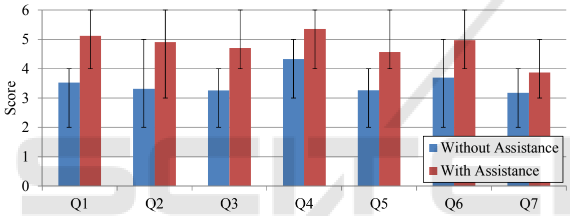


Figure 15: Questionnaire results.

5 CONCLUSIONS

This paper proposed an upper body posture adjustment system for wheelchair users on an inclined road. Our system succeeded in maintaining the user's body balance. As a result, the gravitational force caused by road inclination was reduced, and the required braking traction for wheel driving assistance was also reduced. Consequently, the user could use less force with the proposed system.

ACKNOWLEDGEMENTS

This work is supported in part by Hyogo Foundation for Science and Technology, Kawanishi Memorial ShinMaywa Education Foundation and Exploratory Research on Feasibility Study (FS) Stage (AS242Z00295K) by Adaptable and Seamless Technology Transfer Program through Target-driven R&D, Japan Science and Technology Agency (JST).

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