https://doi.org/10.20965/jrm.2013.p0959

Paper:

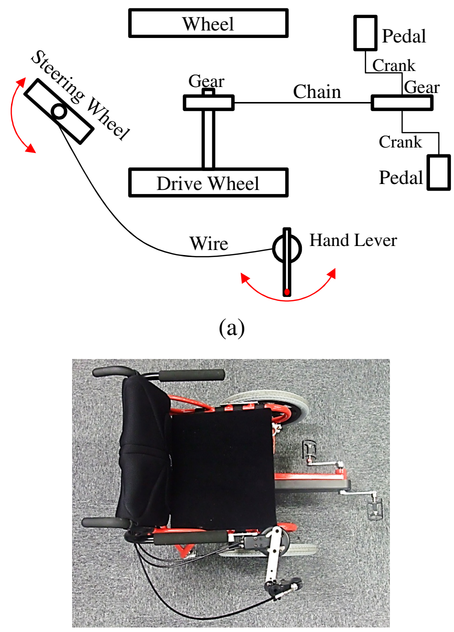
Investigation of User Load and Evaluation of Power Assistive Control on Cycling Wheelchair

Aya Kaisumi, Yasuhisa Hirata, and Kazuhiro Kosuge

Department of Bioengineering and Robotics, Tohoku University
6-6-01 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan
E-mail: kaisumi@irs.mech.tohoku.ac.jp

[Received May 10, 2013; accepted October 23, 2013]

Wheelchairs, walkers, and electric wheelchairs are well-known support devices for patients with lower-limb disabilities. However, disuse of lower limbs presents an ongoing barrier to rehabilitation, and can eventually lead to disuse syndrome. To overcome this situation, researchers have designed the cycling wheelchair. The cycling wheelchair is accessible to most patients who can bend their lower limbs. It is primarily used in rehabilitation facilities with planar floors and gentle slopes. To become practicable for everyday use, cycling wheelchairs require sufficient power to travel up steeper slopes or across bumpy surfaces. This paper aims to clarify the power consumed by users in everyday environments by measuring the tread force on the pedals. The investigation targets lower-limb disabled subjects and unimpaired subjects. It was observed that some of the users could not summon sufficient power for uphill travel. In addition, hemiplegic subjects with only one unimpaired leg placed large load on their healthy limb. As a first step to overcome this problem, we introduce traveling resistance compensation control into a cycling wheelchair and evaluate its efficacy.



(a)

(b)

Fig. 1. (a) Top view of mechanical configuration of cycling wheelchair. (b) Photographic top view.

Keywords: cycling wheelchair, power assist, hemiplegia

1. Introduction

Individuals with lower-limb disabilities can access a range of devices appropriate to their level of mobility such as canes, wheelchairs, and walkers. Wheelchairs are widely used by patients with severe walking disabilities. However, permanent wheelchair occupancy poses risks to the heart and upper limbs and interferes with blood circulation. Eventually, patients may become afflicted with disuse syndrome, which weakens muscles and bones.

The recently-introduced cycling wheelchair [1, 2] is an offshoot of functional electrical stimulation (FES) studies. In FES, human muscle movement is stimulated by functional electricity. FES has been utilized as a walking aid for paraplegic patients [3].

The original cycling wheelchair was supplemented with FES [4]; later, it was found that patients can pedal even without FES [5]. The cycling wheelchair is also expected to realize effective rehabilitation. Seki et al. reported increased muscle activity in hemiplegic patients using the cycling wheel chair [6]. The device may be purchased from TESS Co. Ltd., Sendai, Japan.

A top view of the cycling wheelchair and its mechanical configuration is shown in **Fig. 1**. The in-front pedal is connected to the right wheel by a chain. The device is a right wheel drive; the left wheel is passively driven. The travel direction is determined by the rear steering wheel, which the user controls by a hand lever. Steering by the hand lever is different from the typical steering of cars and bicycles, where the user uses both hands to control a center-front wheel. One-handed steering enables hemiplegic patients, who may not possess two functional hands, to control the device. The hand lever can be affixed either side of the cycling wheelchair.

Because it is right-wheel driven, the device characteristics differ between left and right turning. In particular, the

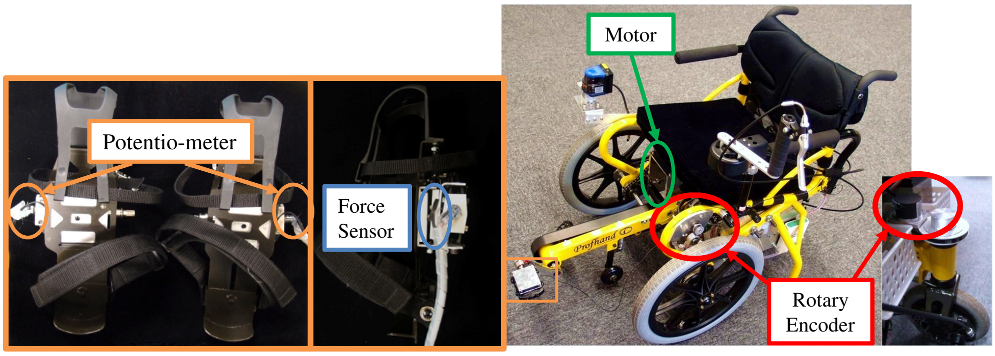


Fig. 2. System for measurement and experiment.

distance from the center of rotation to the actuating wheel is shorter on the right side than on the left, rendering right turning more difficult.

Research on cycling wheelchairs has recently extended from the FES field into virtual reality and robotics [7, 8]. The device is primarily used in rehabilitation facilities and indoors. While very easy to drive, even by patients with moderate to severe lower-limb disabilities, uphill travel presents a major challenge, while downhill travel is dangerous. Furthermore, uneven surfaces and narrow corners may be difficult to travel even by unimpaired users. A promising solution to these problems is power assistance. When introducing power assistive control to cycling wheelchairs, we must preserve the beneficial effect of rehabilitation. Therefore, we must first clarify the specific load cost in different environments. Though cycling wheelchairs have attracted a fair share of research attention, the required user load in difficult everyday environments has yet to be investigated.

This paper focuses on the load required by cycling wheelchair users in everyday tasks such as traveling uphill, traversing uneven surfaces, turning left and right, and crossing rough roads. The trials are undertaken by both lower-limb disabled subjects and unimpaired subjects. The latter part of the paper introduces power assistance control. Since everyday users will encounter a range of environments, the control needs to adapt to each environment. The proposed control is based on travel resistance compensation.

Section 2 describes the system for the measurement and the power assistive experiment. Section 3 investigates user load in a range of daily environments. Power assistive control is introduced to the cycling wheelchair in Section 4. In addition, in this section, the efficacy of the control is validated by an experiment on unimpaired subjects. Section 5 discusses the main findings, and Section 6 concludes the paper.

2. System for Measurement and Experiment

Figure 2 shows the sensors, computers, and actuators affixed to the TESS cycling wheelchair Profhand for user load investigations and for evaluating the proposed power assistance control. Since the cycling wheelchair is a right wheel drive, the motor with rotary encoder is utilized on the driving axis. The position and orientation of the system is detected by rotary encoders on the rear steering wheel and passive left wheel.

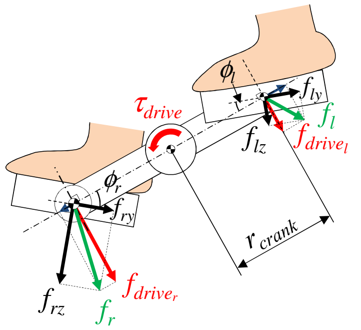


Fig. 3. Torque calculation from tread force on pedals.

The tread forces are measured by two force sensors, each with three degrees of freedom (DOF), located on the pedal to measure the tread force. From these tread forces, the driving torque τ_{drive} generated by the user at the center of the crank is obtained as

$$\tau_{drive} = (f_{rz}\cos\phi_r + f_{ry}\sin\phi_r - f_{lz}\cos\phi_l - f_{ly}\sin\phi_l) r_{crank} \quad (1)$$

where f_{lz} and f_{rz} are the forces perpendicular to the left and right pedals, respectively, and f_{ly} and f_{ry} are the forces parallel to the left and right pedals, respectively, directed from toe to heel. These forces are represented diagrammatically in **Fig. 3**. Two DOF of the sensors are used because the direction of the third DOF is parallel to the rotational axis of the pedals, to prevent the sensors from affecting the driving torque. The pedal angles, ϕ_l and ϕ_r are measured by two potentiometers mounted to the pedals; the subscripts l and r denote left and right, respectively.

The force exerted by the user on the system, f_h, is calculated from the driving torque τ_{drive} as follows.

$$f_h = \tau_{drive} R_{gear} r_{wheel} \quad (2)$$

where R_{gear} is the gear ratio between the crank and wheel, and r_{wheel} is the wheel radius.

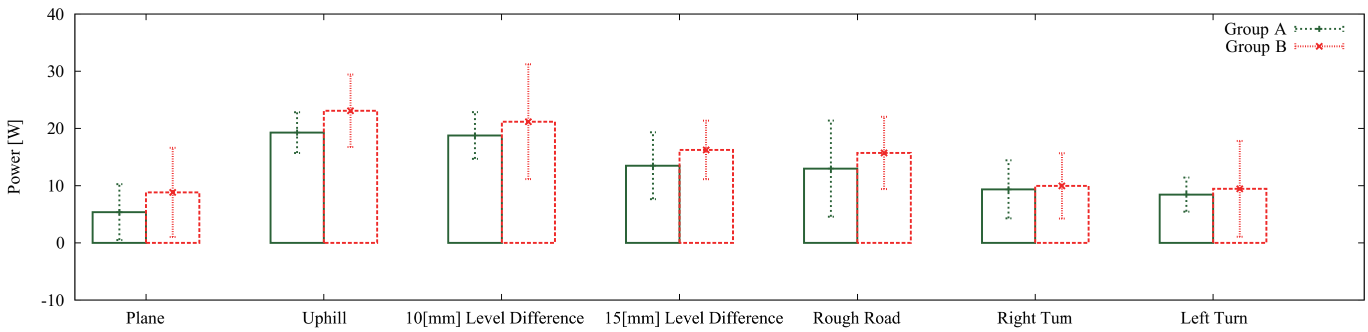


Fig. 4. Power costed on user in each environment.

3. Investigation of User Load in Different Environments

Patients with lower-limb disabilities can travel much more smoothly and easily in cycling wheelchairs than in other devices. However, several environments, for example uphill slopes and uneven surfaces, are not accessible by cycling wheelchairs. This section investigates the load on unimpaired and lower-limb disabled subjects using the cycling wheelchair in such difficult environments.

3.1. Measurement Environments

This research is aimed at everyday use of the cycling wheelchair, including outside environments. The selected environments present major barriers in daily use. The stepwise level difference that characterizes public roads is problematic to sight-impaired persons. Other difficult environments are gravel roads and Braille blocks. Different from straight travel across a planar surface, users negotiating outdoor environs must also frequently turn left and right.

Nine lower-limb disabled subjects and twelve unimpaired subjects participated in the study. Throughout the course, each participant encountered the following.

- Plane floor
- 4% uphill
- 10 mm level difference
- 15 mm level difference
- Rough road
- Right turn on planar floor
- Left turn on planar floor

An uphill grade of 4% was selected for its general use in rehabilitation; thus, it should be manageable to the disabled patients. Although the batter angles of roads can reach 12%, such steep slopes would be prohibitive to some of the subjects. The rough road surface was imitated by wall material.

All patients consented to participate in this investigation, and a therapist was present throughout. Seven of the nine disabled patients were hemiplegic (Brunnstrom Stage II to III; three right-side impaired, four left-side impaired). All nine patients had experienced riding the cycling-wheelchair during rehabilitation exercises. Unimpaired subjects, with no previous experience, undertook several practice sessions prior to measurement.

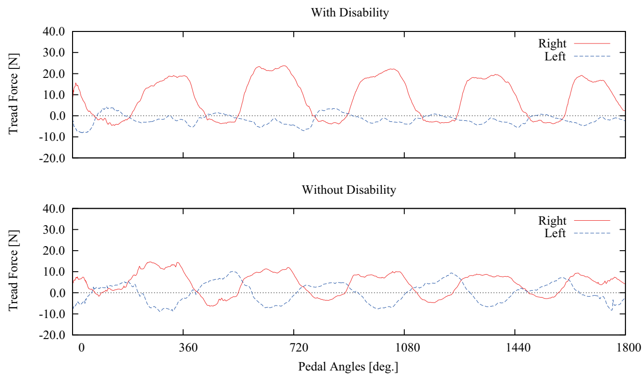


Fig. 5. Tread force on pedals exerted during a 4% uphill climb; (top) hemiplegic subject, (bottom) unimpaired subject.

3.2. Measurement Results

During the measurement, two subjects who are lower-limb disabled could not accomplish the 4% uphill climb. We classified the lower-limb disabled subjects in Group A if they could achieve the 4% uphill climb (Group A; 7 subjects). The 12 unimpaired subjects were classified into Group B.

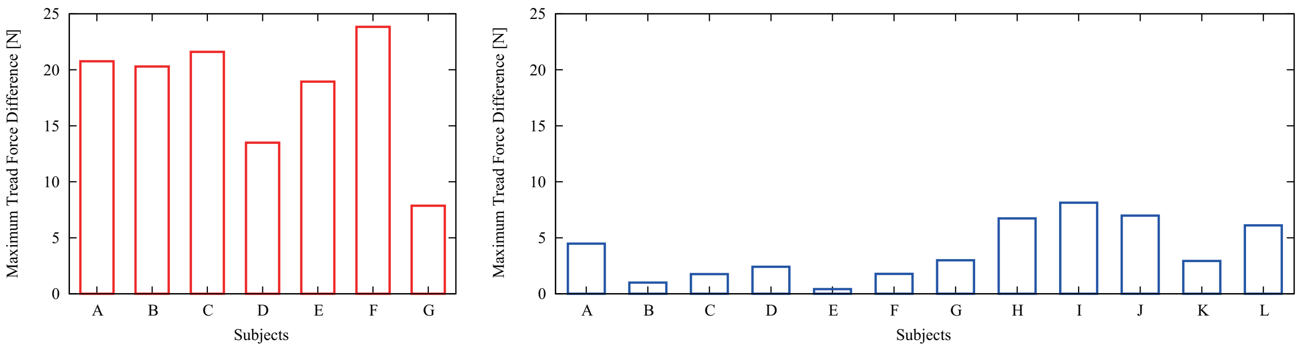
The average power consumed by users in each environment is shown in **Fig. 4**. The power is calculated as

$$Power = \frac{W}{\Delta T} = \int_C F_h ds \frac{1}{\Delta T} \quad \ldots \ldots \ldots \quad (3)$$

where W is the work done by F_h, F_h is the force exerted on the system by the user, C is the trajectory, s is the distance along the trajectory, and ΔT is the travel time.

Both groups consumed similar power in various environments. This can be attributed to constant powers required in each environment. The highest power was consumed in traveling uphill.

Examples of uphill measurement data are shown in **Fig. 5**. The Group A data were collected from a left



(a) Group A (b) Group B

Fig. 6. Maximum difference in tread force between left and right legs (Group A: lower-limb disabled subjects; Group B: unimpaired subjects).

side hemiplegic subject. Though both groups could accomplish uphill climbing, Group A subjects pedaled only with their unimpaired side. Given that the overall power consumption by Groups A and B is similar (as mentioned above), the hemiplegic subject is considered to have generated all power from the unimpaired side to compensate the impaired side. **Fig. 6** shows the difference in maximum tread force exerted by the left and right legs of each user. The asymmetry in force distribution is much more prominent in Group A users than in Group B users, demonstrating that hemiplegic subjects exerted larger force on their unimpaired legs to actuate the system.

We investigated user load in several environments. Although the same power was consumed by lower-limb disabled subjects and unimpaired subjects, **Figs. 5** and **6** reveal that hemiplegic subjects exerted large tread force on their unimpaired limb.

4. Traveling Resistance Compensation Control on Cycling Wheelchair

This section introduces power assistance control to the cycling wheelchair.

Currently-researched power assistance control methods are divisible into 3 categories: a) basic power assistance control in which the input force is multiplied by a constant; b) compensation for environmental differences using sensors such as tilt angle sensors; c) traveling resistance compensation control based on perceived disturbance.

Category (a), power assistance control, is widely applied to bicycles. This method may not be applicable to cycling wheelchairs because the input force is insufficiently amplified to overcome all environments such as steep hills. Because the target users of cycling wheelchairs have lower limb impairment, they may be unable to unseat themselves and push the device uphill when the required driving force is too high.

Category (b) uses sensors such as tilt angle sensors and laser range finders to detect road steepness and obstacles such as steps. This method is useful for adapting to different environments, but requires accurate system models; otherwise, it moves itself on slopes and other difficult terrains.

Control systems in category (c) observe environmental disturbances according to input, output and given system model, and perform compensative actions. The compensative action alters in different environments, enabling users to pedal on the modeled load. This method has been applied to tricycles [9, 10] and wheelchairs [11, 12].

Thus, we consider that category (c) control methods are suitable adjuncts to the cycling wheelchair.

In the following subsection, traveling resistance compensation control is applied to the cycling wheelchair. Its effectiveness is evaluated on the same travel course as used in the previous investigation. In this test, the resistance was adjusted to match the capabilities of the user by altering the compensation ratio.

4.1. Motion Equation and Travel Resistance Compensation Control

The motion equation of the system is

$$M\dot{v} + Dv + \tilde{g} = f \quad (4)$$

where

- M: mass
- D: friction viscosity
- v: velocity
- $\tilde{g}$: environmental disturbance

$\tilde{g}$ denotes the environmental disturbance on the system such as gravity on slopes or the required force to overcome bumps and steps on the surface. The net force f_{net} on the system is given by

$$f_{net} = f_h + f_a \quad (5)$$

where f_h denotes the force exerted on the system by the user and f_a denotes the assistive force exerted by the actuator.

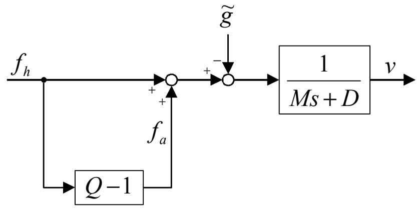


Fig. 7. Power-assistance control for bicycles.

In basic power assistance control, the assistive force f_a is product of the force f_h and a constant Q:

$$f_a = f_h(Q-1) \quad \ldots \ldots \ldots \ldots \quad (6)$$

A block diagram of this control is shown in **Fig. 7**. While this simple control is perfectly adequate for bicycles, it may not sufficiently empower the cycling wheelchair to accomplish the most difficult everyday task, namely, traveling uphill or ensure safe downhill descent.

In our proposed control system, the system velocity v is controlled such that the system receives input force $f = f_h + f_a$. The disturbance $\tilde{g}$ is observed by feedback of velocity v and input force f_{net} without specific sensors such as tilt angle sensor. In addition, the control imitates the system by the specified parameters M and D. Even if these parameters are not assigned their real values, the control realizes the motion characteristics of the given values.

To minimize observer on Eq. (4) we define $\mathbf{x}$ as follows:

$$\mathbf{x} = \begin{bmatrix} v \\ \hat{g} \end{bmatrix}. \quad \ldots \ldots \ldots \ldots \quad (7)$$

Denote the observer gain by L. Ignoring the temporal differentiation of the disturbance (i.e., set $\dot{\tilde{g}} = 0$), we obtain

$$\dot{\hat{g}} = L\dot{v} + \frac{D}{M}v + \frac{1}{M}\hat{g} - \frac{1}{M}(f_h + f_a). \quad \ldots \quad (8)$$

The disturbance $\hat{g}$ is obtained by Laplace transformation, where $L = -MP$,

$$\hat{G} = -MPV + \frac{P}{s+P}(MP-D)V + \frac{P}{s+P}(F_h + F_a). \quad (9)$$

Finally to realize travel resistance compensation control, the motor is controlled as follows.

$$f_a = \hat{g} \quad \ldots \ldots \ldots \ldots \quad (10)$$

A block diagram of the control is shown in **Fig. 8**.

The transfer function of the observer is given by

$$\frac{\hat{G}}{\tilde{G}} = \frac{P}{s+P} \quad \ldots \ldots \ldots \ldots \quad (11)$$

$$\frac{\hat{G}}{\tilde{G}} = \frac{1}{1+\frac{s}{P}}. \quad \ldots \ldots \ldots \ldots \quad (12)$$

A one-dimensional low-pass filter with cut-off frequency P is the observer characteristic. Therefore, the frequency of environmental disturbance decides P. Furthermore, since the pole of the filter is $P = 0$, the control is unconditionally stable, and P must satisfy $P > 0$.

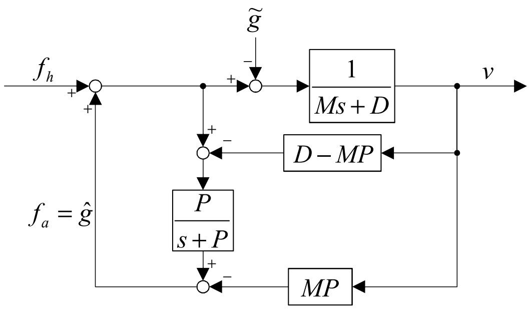


Fig. 8. Traveling resistance compensation control for cycling wheelchairs.

4.2. Testing the Travel Resistance Compensation Control

We applied the traveling resistance compensation control to the cycling wheelchair. We investigated the load exerted by the user on the controlled cycling wheelchair in the previously-discussed environments; 4% uphill climbing, 10 mm level difference, 15 mm level difference, rough road, and left and right turning. This experiment was conducted with the consent of six healthy subjects.

The power exerted on the system by the user is shown in **Fig. 9**. Without Control shows the power exerted by Group B users in the previous section. With the control installed, the power consumed on the uphill slope, rough road, and left turn decreased to that expended on the planar surface. Clearly, the control method cancels the traveling resistance imposed by the environment.

On the surfaces involving level differences, the power expenditure was higher than on the plane because this feedback control includes time delay against the step input. This time delay depends on the gain P. Thus P should be raised depending on the assumed environment or the pedaling speed of the user.

Less power was consumed during right turning than during straight planar travel because of the mechanical structure of the cycling wheelchair. Being right-wheel driven, the wheelchair slows less during a right turn than when driving straight. Since velocity control responds to the input force, more power is supplied during right turning to generate the same velocity as forward travel.

5. Discussion

From the investigation of Section 3, it is obvious that environments other than straight planes require more power by users. Furthermore, not all of the lower-limb disabled subjects could accomplish all environments, and hemiplegic subjects placed undue load on their unimpaired leg. According to these results, everyday use of cycling wheelchairs in real environments exposes the unimpaired leg to overuse. Therefore, power assistive control is required if the cycling wheelchair is to benefit users in everyday travel.

The purpose of the control method is to cancel travel

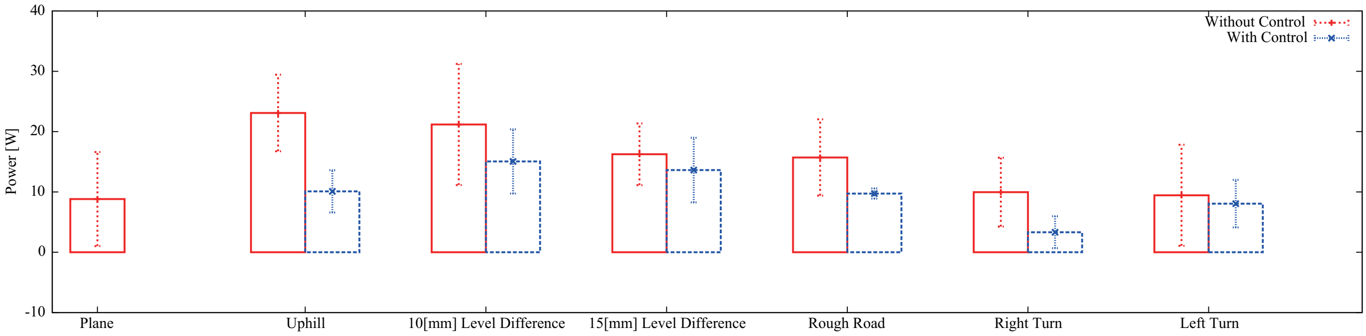


Fig. 9. Power of user with and without power assistive control.

resistance caused by adverse environmental change. The system was found to successfully cancel environmental resistance such that traveling uphill required the same level of exertion as traversing a plane surface. The control also cancels smaller-resistance environments during downhill travel, e.g., the system slows to the travel speed on a plane surface, thereby removing the danger normally incurred by downhill slopes.

The experimental results of this study revealed clear reduction in user power when the cycling wheelchair is supplemented with travel resistance compensation control. It was also found that the P gain, which is related to observer response, alters with varying pedaling speed and the frequency of environmental changes.

6. Conclusion

This paper investigated power consumption of a cycling wheelchair driven in difficult environments and the effects of additional power assistance. We hypothesized that power assistance would render the cycling wheelchair suitable for everyday use as well as rehabilitation. To verify this idea, we clarified the power consumed by cycling wheelchair users in typical environments such as gentle uphill climbs, 10- and 15-mm level differences, rough roads, and left-and right-turning corners. Nine patients with lower-limb disabilities and twelve unimpaired subjects participated in the investigation.

The power consumed by lower-limb disabled subjects and unimpaired subjects was almost identical in each environment. However, hemiplegic subjects generated tread force solely with their unimpaired leg to compensate the immobile limb. Power consumption was the highest during uphill travel.

In the latter part of the study, a power assistance method was introduced to the cycling wheelchair. The method proposes to cancel the increased travel resistance, thereby maintaining the beneficial rehabilitation effects of the device. We implemented traveling resistance compensation control to realize a given model by controlling the velocity of the system. Tests demonstrated that the control successfully canceled the excess power consumption of the user in each environment.

In this paper, the proposing method was tested by healthy subjects. In future, the method will be assessed by subjects with lower-limb disabilities.

Acknowledgements

We would like to express sincere thanks to Professor Yasunobu Handa of Tohoku University, Miki Hospital in Iwate, Japan and the subjects who took part in this study.

References:

[1] K. Seki, T. Fujii, and Y. Handa, "Change of H wave and MEP during pedaling by one leg," 10th Annual Conf. of the Int. FES Society, 2005.

[2] T. Takahashi, Y. Nishiyama, Y. Ozawa, E. Nakano, and Y. Handa, "Cycling Chair: a novel vehicle for the lower limbs disabled," ICMIT 2005: Mechatronics, MEMS, and Smart Materials, Proc. of SPIE, Vol.6040, p. 60401X, 2005.

[3] A. Kraly and S. Grobelnik, "Functional Electrical Stimulation – A New Hope For Paraplegic Patients," Bulletin of Prosthetics Research, pp. 75-102, 1975.

[4] T. Takahashi, M. Takazawa, Y. Nishiyama, E. Nakano, and Y. Handa, "FES Cycling Chair for the Lower Limbs Disabled People with Electric Motor Power Assist," 9th Annual Conf. of the Int. FES Society, 2004.

[5] K. Seki, M. Sato, T. Fujii, and Y. Handa, "Driving a cycling chair without FES in the non-ambulatory hemiplegic patients," Proc. of 9th Annual Conf. on Int. FES Society, 2004.

[6] K. Seki, M. Sato, and Y. Handa, "Increase of Muscle Activities in Hemiplegic Lower Extremity During Driving a Cycling Wheelchair," The Tohoku journal of experimental medicine, Vol.219, No.2, pp. 129-138, 2009.

[7] N. Sugita, Y. Kojima, M. Yoshizawa, A. Tanaka, M. Abe, N. Homma, K. Seki, and N. Handa, "Development of a virtual reality system to evaluate skills needed to drive a cycling wheelchair," Conf. Proc. of Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society, pp. 6019-6022, 2012.

[8] N. Hiro, E. Takeuchi, K. Ohno, and S. Tadokoro, "Developing a Measurement System for Improving Daily Lives of Cycling Wheel Chair Patients," SICE Annual Conf., pp. 1656-1660, 2012.

[9] K. Kosuge, H. Yabushita, and Y. Hirata, "Load-free control of power-assisted cycle," TExCRA '04, First IEEE Technical Exhibition Based Conf. on Robotics and Automation, pp. 111-112, 2004.

[10] H. Yabushita, Y. Hirata, K. Kosuge, and Z. D. Wang, "Environment-adaptive control algorithm of power assisted cycle," IECON Industrial Electronics Society, Vol.2, pp. 1962-1967, 2003.

[11] S. Katsura and K. Ohnishi, "A wheelchair type mobile robot taking environmental disturbance into account," 7th Int. Workshop on Advanced Motion Control, pp. 0-5, 2002.

[12] S. Oh and Y. Hori, "Sensor Free Power Assisting Control Based on Velocity Control and Disturbance Observer," Proc. of the IEEE Int. Symposium on Industrial Electronics, pp. 1709-1714, 2005.

Name:
Aya Kaisumi

Affiliation:
Ph.D. Student, Department of Bioengineering and Robotics, Tohoku University

Address:
6-6-01 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Brief Biographical History:

2009 Received the B.E. from Tohoku University
2011 Received the M.E. from Tohoku University
2011- Ph.D. Student, Tohoku University

Main Works:

• "Development of Small Parts Handling Device based on Caging and Self-alignment Concept," ICRA 2011.

Membership in Academic Societies:

• The Japan Society of Mechanical Engineers (JSME)
• The Robotics Society of Japan (RSJ)
• The Institute of Electrical and Electronics Engineers (IEEE)

Name:
Yasuhisa Hirata

Affiliation:
Associate Professor, Department of Bioengineering and Robotics, Tohoku University

Address:
6-6-01 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Brief Biographical History:

2000-2006 Research Associate, Department of Bioengineering and Robotics, Tohoku University
2002-2004 Researcher, JST PRESTO
2004 Received Ph.D. in Mechanical Engineering from Tohoku University
2006- Associate Professor, Department of Bioengineering and Robotics, Tohoku University

Main Works:

• "Coordinated Transportation of a Single Object by Omni-Directional Mobile Robots with Body Force Sensor," J. of Robotics and Mechatronics, Vol.12, No.3, pp. 242-248, 2000.
• "Motion Control of Passive Intelligent Walker Using Servo Brakes," IEEE Trans. on Robotics, Vol.23, No.5, pp. 981-990, 2007.
• "Transporting an Object by a Passive Mobile Robot with Servo Brakes in Cooperation with a Human," Advanced Robotics, Vol.23, No.4, pp. 387-404, 2009.

Membership in Academic Societies:

• The Japan Society of Mechanical Engineers (JSME)
• The Robotics Society of Japan (RSJ)
• The Society of Instrument and Control Engineers (SICE)
• The Institute of Electrical and Electronics Engineers (IEEE)

Name:
Kazuhiro Kosuge

Affiliation:
Professor, Department of Bioengineering and Robotics, Tohoku University

Address:
6-6-01 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Brief Biographical History:

1980-1982 Research Staff, Department of Production Engineering, DENSO Corporation
1982-1990 Research Associate, Department of Control Engineering, Tokyo Institute of Technology
1988 Received Ph.D. in Mechanical Engineering from Tokyo Institute of Technology
1989-1990 Visiting Scientist, Department of Mechanical Engineering, Massachusetts Institute of Technology
1990-1995 Associate Professor, Nagoya University
1995- Professor, Tohoku University
1998-2001 Vice President, IEEE Robotics and Automation Society
2008-2009 President Elect, IEEE Robotics and Automation Society
2010-2011 President, IEEE Robotics and Automation Society

Main Works:

• "Dance Step Estimation Method Based on HMM for Dance Partner Robot," Trans. on Industrial Electronics, Vol.54, No.2, pp. 699-706, 2007.
• "Analytical Inverse Kinematic Computation for 7-DOF Redundant Manipulators With Joint Limits and Its Application to Redundancy Resolution," IEEE Trans. on Robotics, Vol.24, No.5, pp. 1131-1142, 2008.

Membership in Academic Societies:

• The Institute of Electrical and Electronics Engineers (IEEE) Robotics and Automation Society (RAS)
• The Robotics Society of Japan (RSJ)
• The Japan Society of Mechanical Engineers (JSME)
• The Society of Instrument and Control Engineers (SICE)
• The Institute of Systems, Control and Information Engineers (ISCIE)
• The Institute of Electrical Engineers of Japan (IEEJ)