Assessment of motor function in hemiplegic patients using virtual cycling wheelchair

R Ishikawa[1], N Sugita[2], M Abe[1], M Yoshizawa[3], K Seki[4], Y Handa[4]

[1]Department of Electrical Engineering, Graduate School of Engineering,
[2]Department of Management Science and Technology, Graduate School of Engineering,
[3]Cyberscience Center,
Tohoku University,
6-3 Aoba, Aramaki, Aoba-ku, Sendai 980-8578, JAPAN

[4]Sendai School of Health and Welfare,
2-1-1 Akedori, Izumi-ku, Sendai 981-3206, JAPAN

r-ishikawa@yoshizawa.ecei.tohoku.ac.jp

[1-3]*www.ecei.tohoku.ac.jp,* [4]*www.sugawara.ac.jp/welfare/*

ABSTRACT

A cycling wheelchair (CWC) is a rehabilitation tool for hemiplegic patients. In previous studies, our group developed a virtual reality system that allows patients to practice driving a CWC. This study proposes a new method to estimate the torque of each leg extension of a hemiplegic patient while driving the virtual CWC. Experimental results from four healthy subjects and four hemiplegic patients showed the usefulness of the proposed method in evaluating the motor function of the patients.

1. INTRODUCTION

Stroke is a common disorder among the elderly in Japan, and it often causes paralysis of the legs. Because the population is ageing, the number of stroke patients will increase. In general, people who have difficulties walking use wheelchairs in daily life. However, while moving with wheelchairs, they do not use their legs because wheelchairs are operated by their hands or an electric motor. Typically, when the legs perform work, blood is returned to the heart. Therefore, people who do not use their legs for a long period of time risk suffering from disuse syndrome, causing muscle weakness and a fall in cardiopulmonary functions.

To solve this problem, a cycling wheelchair (CWC) has been developed and explored as a new rehabilitation tool for hemiplegic patients (Figure 1). These individuals can drive the CWC by rotating the pedals with their non-paralyzed feet. CWCs allow hemiplegic patients to move quicker and drive longer distances without fatigue in comparison to conventional wheelchairs. Moreover, they can use their hands freely while driving a CWC.

However, CWCs require patients to pedal and steer simultaneously while changing direction. Therefore, driving a CWC is difficult for patients who are not accustomed to its operation. Patients must practice driving the CWC to avoid the danger of falling and being stranded. A large and safe area is required to practice driving the CWC. Additionally, to ensure safety, assistants must be present to monitor patients using a CWC.

In previous studies, a virtual reality (VR) system was developed, which allows patients to safely practice driving a CWC, as shown in Figure 2. By applying the VR technology, patients can practice driving in a narrow place. To confirm the efficacy of rehabilitation using the system, Suzuki et al. evaluated the input torque generated by the user's legs to move the CWC. However, it was difficult to evaluate whether the paralyzed leg recovered because they were not able to extract the torque of the paralyzed leg from the entire input torque. Since the torque of each leg includes gravity effects, the influence of gravity must be considered. Therefore, it is necessary to improve the method to analyze the motor performance of the patients.

In this study, we proposed a new method to estimate the torque produced by the power of each leg separately when the user is driving the virtual CWC. To calculate the torque of each leg, we attached force sensors to each pedal. Additionally, we estimated the torque produced by the power of each leg by assuming the gravity effects and devised a new evaluation index using the estimated torque. The efficacy of the proposed method was tested experimentally.

Figure 1. *Cycling wheel chair (CWC).*

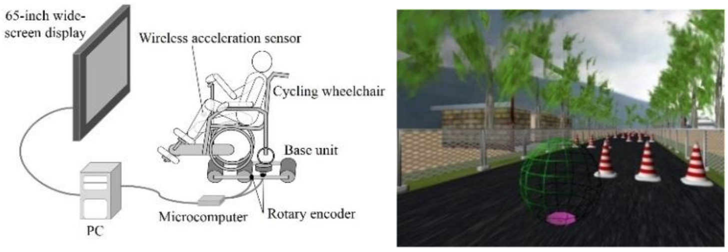

Figure 2. *Virtual reality system developed in previous study. Outline of system (left); Screenshot of VR (right)* [Sugita, 2012].

2. METHODS

2.1 Rehabilitation system

Figure 3 shows the system developed in this study. The user sits on the virtual CWC, which is fixed to the base unit, and rotates the pedals while measurements are taken. In reality, the measurement is influenced by the change in road surface conditions. Using the virtual CWC, a user can rotate the pedals in fixed conditions. The angle of the crankshaft is measured by a rotary encoder (E6A2-CWZ3C; Omron Corp.) and the data are transmitted to a personal computer (PC) using a microcomputer (Arduino; Arduino Software Corp.). To measure the forces applied to the left and right pedals, wearable force plates (M3D-FP-U; Tec Gihan Corp.) are attached to both pedals. The force plates contain three-axis force sensors, an accelerometer, and a gyroscope. To observe the change in torque produced by the user's legs, a brake system that changes the load required to drive the virtual CWC is introduced.

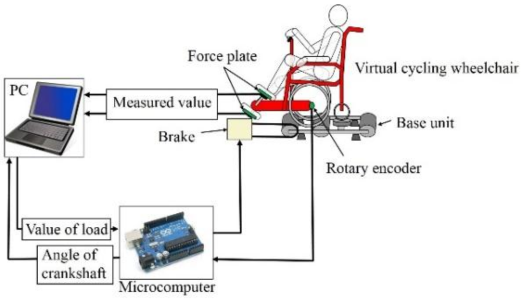

Figure 3. *System developed in this study.*

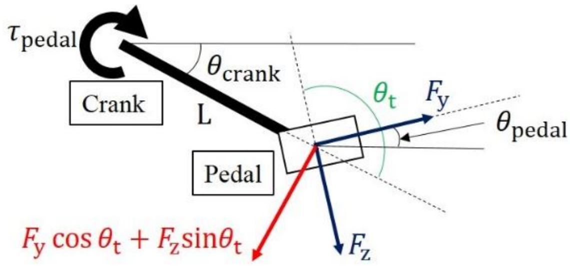

Figure 4. *Torque estimation in the pedal.*

2.2 Leg torque estimations

The torque of each leg, τ_{pedal}, is calculated using the forces applied to the pedals as follows:

$$\tau_{\mathrm{pedal}} = \mathrm{L} \times (F_{\mathrm{y}} \cos\theta_{\mathrm{t}} + F_{\mathrm{z}} \sin\theta_{\mathrm{t}}) \tag{1}$$

where F_{z} is the force perpendicular to the pedal, F_{y} is the force parallel to the pedal, L is the length of the crankshaft, and θ_{t} is the angle consisting of the angle of the pedal, θ_{pedal}, and the angle of the crankshaft, θ_{crank}. These forces and angles are represented in Figure 4. To calculate the torque of each leg, it is necessary to acquire the angle of pedal. Therefore, we use the Kalman filter.

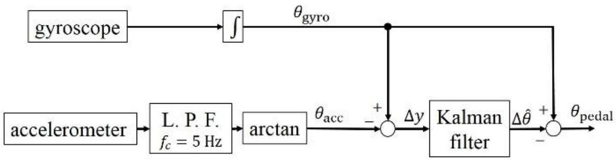

Figure 5. *Block diagram of angle measurement using the Kalman filter.*

2.2.1 Pedal angle estimation using the Kalman filter. To acquire the angle of the pedal, we applied the steady-state Kalman filter. This method uses the outputs of both an accelerometer and a gyroscope. The angle of the pedal is obtained by integrating the gyroscope outputs, and including the error caused by the offset drift of the gyroscope. Figure 5 shows a block diagram of this method, where θ_{gyro} is the angle obtained by the gyroscope outputs, θ_{acc} is the angle obtained by the accelerometer outputs, and Δy is difference between θ_{gyro} and θ_{acc}. We acquired θ_{pedal} by reducing the error of the angle, $\Delta\hat{\theta}$, which is estimated from θ_{gyro} using the Kalman filter. To apply this method, we determined the Kalman gains, which were required to estimate the error of the angle, using a preliminary experiment.

2.2.2 Elimination of leg gravity effects. To estimate the torque produced by the power of each leg, we must eliminate the gravity effects on the legs. The torque of the gravity effects on the leg consists of the torques of the hip, knee, and ankle joints, which are caused by the gravity effect on the thigh, shin, and ankle, respectively. Kaisumi et al. estimated the leg gravity effects by applying a model of the human leg. However, the previous study assumed that the hip and knee joints are active joints that exert torques, but the ankle joint is not. Because gravity exists on the ankle, we must consider the ankle as an active joint with torque. Thus, this study estimates the effect of gravity on the leg by applying a model of the human leg that has not only hip and knee joints, but also an ankle joint. The torque produced by the power of each leg is given by

$$\tau_{\text{human}} = \tau_{\text{pedal}} - \tau_{\text{gravity}} \tag{2}$$

where τ_{human} is the torque produced by the power of each leg, and τ_{gravity} is the torque of the gravity effects on the leg.

2.3 Index to evaluate user's motor performance

A new evaluation index using the torque produced by the power of each leg was proposed as follows:

$$\tau_{\text{left}} = \tau_{\text{lpedal}} - \tau_{\text{lgrav}} \tag{3}$$

$$\tau_{\text{right}} = \tau_{\text{rpedal}} - \tau_{\text{rgrav}} \tag{4}$$

$$T_{\text{dif}} = \frac{1}{360}\sum_{\theta=0}^{359} |\tau_{\text{left}}(\theta_{\text{crank}}) - \tau_{\text{right}}(\theta_{\text{crank}} + 180)| \tag{5}$$

where τ_{left} and τ_{right} are the torques produced by the power of the left and right legs, respectively; τ_{lpedal} and τ_{rpedal} are the torques of the left and right legs, respectively; and τ_{lgrav} and τ_{rgrav} are the torques of the gravity effects on the left and right legs, respectively. All torques are the mean values for 10 rounds of the crankshaft. T_{dif} is the difference in the torque produced by the power of the healthy leg and that of the paralyzed leg. We expect that if the motor function of the patient is recovered, the value of T_{dif} will become smaller.

2.4 Experiment

An experiment was performed to test the efficacy of the evaluation index using the torque estimated by the proposed method. Four healthy subjects (three males and one female) and four hemiplegic patients (four males; Brunnstrom stages II to IV; two right-side impaired, two left-side impaired) participated in this experiment. The age range for the healthy subjects was 18 to 22 and for the hemiplegic patients was 46 to 83. All subjects had previously used a CWC.

In the experiment, the subjects sat on the virtual CWC and rotated the pedals for 30 s. The speed of pedaling was controlled at 30 rpm. The conditions of the load were changed in two steps: 0 Nm and 2 Nm. Prior to measurement, subjects practiced pedaling at each load condition and measurement was aborted if the subject could not rotate the pedals because of the excess load. The torque produced by the power of the leg and the value of T_{dif} were calculated using MATLAB.

3. RESULTS AND DISCUSSION

All subjects could rotate the pedals at both load conditions. Figure 6 shows the mean values of T_{dif} for the healthy subjects and the hemiplegic patients. For both load conditions, the values of T_{dif} for the hemiplegic patients were larger than those of the healthy subjects. Independent t-test analysis showed that these differences are significant ($p < 0.05$). These differences occurred because the paralyzed leg was not able to generate the same torque as the healthy leg, Figures 7 (a) and (b) show examples of the torque produced by the power of each leg for the healthy subject and the hemiplegic patient, respectively. For the healthy subject, the torque of each leg is similar. However, the hemiplegic patient results show that the paralyzed leg produced a negative torque because it hardly moved and did not rotate the crankshaft. In addition, the healthy leg needed to generate a larger torque to compensate for the shortage of torque from the paralyzed leg. Thus, the value of T_{dif} for the hemiplegic patients is larger than that for the healthy subjects. The difference of the values of T_{dif} between the hemiplegic patients and the healthy subjects was larger in 2 Nm than in 0 Nm. This result is because the hemiplegic patients had to rotate the pedal on healthy leg more strongly when the condition of the load was 2 Nm. This means that applying load can estimate the motor function in more detail.

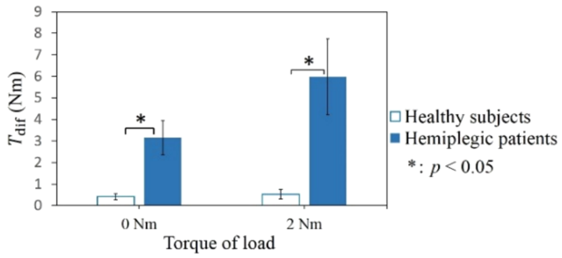

Figure 6. *Results comparison between the healthy and hemiplegic subjects.*

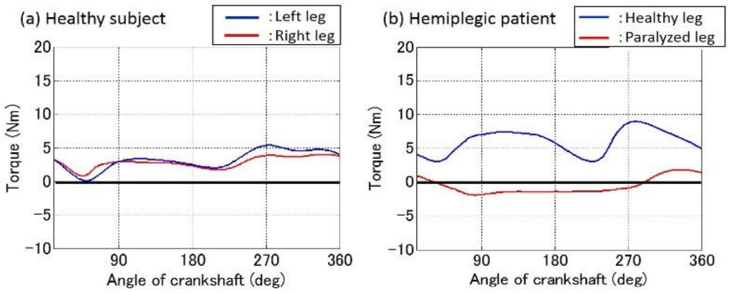

Figure 7. *Torque produced by the power of the leg for (a) a healthy subject and (b) a hemiplegic patient.*

3. CONCLUSIONS

In this study, we proposed a new method to estimate the torque produced by the power of each leg separately for a hemiplegic patient driving a virtual CWC. Moreover, we evaluated the motor function by an evaluation index using the torque, which is estimated by the proposed method. The experimental results show that the torque difference for the hemiplegic patients is significantly larger than that for the healthy subjects. These results indicate that the proposed method is useful in evaluating the motor function of the patient.

In the future, we plan to evaluate the motor function of patients driving the CWC while viewing the VR. To raise motivation for patient rehabilitation, patients must know the evaluation results using the VR. Therefore, we will develop a rehabilitation system that enables the patients to undergo rehabilitation and obtain feedback about their motor function. Moreover, we will collect long-term experimental results for the patients to evaluate the validity of the system.

Acknowledgements: The authors wish to thank the staff and patients of the Miki Hospital and the staff of TESS Co., Ltd., for their technical contributions. This study was supported by JST Revitalization Promotion Program.

5. REFERENCES

Kaisumi, A, (2014), A Pedaling-Assistive Control Method of a Cycling-Wheelchair, *Dissertation for the degree of Doctor of Philosophy*, *Dept. Mech. Eng., Tohoku Univ., Sendai, Japan*.

Saito, H, Watanabe, T, and Arifin, A, (2009), Ankle and Knee Joint Angle Measurements during Gait with Wearable Sensor System for Rehabilitation, *Proceeding of World Congress on Medical Physics and Biomedical Engineering*, **25**, *9*, pp.506-509.

Seki, K, Sato, M, and Handa, Y, (2009), Increase of Muscle Activities in Hemiplegic Lower Extremity During Driving a Cycling Wheelchair, *Tohoku J. Exp. Med.*, **219,** *2*, pp.129-138.

Sugita, N, Kojima, Y, Yoshizawa, M, Tanaka, A, Abe, M, Homma, N, Seki, K, and Handa, N, (2012), Development of a Virtual Reality System to Evaluate Skills Needed to Drive a Cycling Wheel-Chair, *IEEE International Conference on Engineering in Medicine and Biology Society*, pp.6019-6022.

Suzuki, S, (2005), Rehabilitation System for Patients with Leg Paralysis Using Virtual Reality, *M.S thesis, Dept. Elect. Common. Eng., Tohoku Univ., Sendai, Japan*. (In Japanese).

Takagi, M, (2005), *How to prevent and cure cerebral infarction*, Kodansha press, Japan. (In Japanese)