Development of Self Support Device and Control for Operating the Wheelchair for Upper Limb Disabled Persons

Taku Itami[1], Toshihito Yabunaka[1], Ken'ichi Yano[1], Yasuyuki Kobayashi[2],
Takaaki Aoki[3] and Yutaka Nishimoto[4]
[1]*Dept. of Mechanical Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu City, 514-8507, Japan*
[2]*LUMINOUS JAPAN CO., LTD., 68 Hagae, Murakami, 959-3134, Japan*
[3]*Dept. of Rehabilitation and Orthopedics, Gifu University Hospital, 1-1 Yanagido, Gifu, 501-1193, Japan*
[4]*Dept. of Surgical Nursing, Gifu University School of Medicine, 1-1 Yanagido, Gifu, 501-1193, Japan*

Keywords: Exoskeleton, Rehabilitation, Operating Analysis, Electromyographic(EMG) Signals.

Abstract: Nowadays, it has been actively expanded to develop assist robots attached directly. In this study, we focused on developing an exoskeletal robot, specifically, a force transmission robot with a rotary drive type ratchet mechanism, to enable users with upper limb disability to make use of their residual function to achieve better function of their upper limbs. A lock/unlock mechanism on the elbow joint is effectively used to transmit the user's residual function around the shoulder to the hand. We conducted verification experiments on whether the developed mechanism enables the user to transfer the remaining force in the shoulder joint to operation force in the hand. Three subjects with C5 and C6 spinal cord injury with disabilities affecting their hands, lower limbs, and trunk muscles performed the verification experiment with the developed device. We confirmed that they could operate a wheelchair on a slope and on grass when using the developed device, and they could use their residual function around the shoulder more strongly. It can be expected to rehabilitation effect.

1 INTRODUCTION

The number of disabled people who have lost body function due to accident or illness has recently been increasing. Injuries sustained in a road or sports accident where damage to the cervical cord means the person cannot feel pain or temperature, and cannot move their upper limbs and lower limbs in many cases. These injuries are one of the main factors why people need to use a wheelchair in daily life. There are over 100,000 people with spinal cord injury, and it is estimated that more than 5,000 people newly suffer such injury every year.

In recent years, there has been considerable research on exoskeletal robots that substitute for users' the loss of function or amplify their power (Tsukahara et al., 2015),(M. H. Rahman and Archambault, 2015),(Juanjuan Zhang, 2015),(Mao et al., 2015),(Hsieh et al., 2015), and we have also developed upper limb motion support robots(N.Mizutani and Y.Kobayashi, 2013),(T.Watanabe et al., 2011),(T.Yabunaka et al., 2014).

Figure 1: Motion assist robot for the upper limbs.

However, the power assist exoskeletal robots developed in previous studies have required a high-power drive system because the robots support movement directly by using motors and other mechanisms. This has meant that people with cervical cord injury are not able to make use of their residual function because their limbs are moved by external power sources. This also introduces many device problems such as increased weight due to using a battery and

Itami, T., Yabunaka, T., Yano, K., Kobayashi, Y., Aoki, T. and Nishimoto, Y.
Development of Self Support Device and Control for Operating the Wheelchair for Upper Limb Disabled Persons.
DOI: 10.5220/0005990404660471
In *Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2016) - Volume 2*, pages 466-471
ISBN: 978-989-758-198-4

large motor, reduced portability, and limits on the duration of continuous use. These problems reduce the utility, and there are also concerns over the loss of residual function resulting from support by an external power source.

We are therefore focusing our present work on the residual function of the upper limbs in people who use manual wheelchairs. We aim to develop a robot orthosis that can make use of their residual function. In cases of paralysis due to stroke or cervical cord injury, the paralysis has a great effect on terminal nerves. However, muscles which are nearer to the trunk often experience milder symptoms. In particular, although people might not be able to exert force because they have strong paralysis of the hands and forearms. However, the area within the shoulder circumference on the trunk is often not paralyzed and has muscles to exert force. There are many relatively large muscles within the shoulder circumference, and large movements can be achieved by using them. If people can utilize these muscles as an assist source, the robot orthosis is able to support the movement based on their intention. The robot does not require a high-power drive system as used in previous studies. The robot orthosis is able to provide support by using only a drive system with the minimum requirements for transmitting residual function to help operate the hand.

2 UPPER LIMB DYSFUNCTION

The Modified Zancolli classification is usually used to evaluate upper limb function in people with cervical spinal cord injury. According to this system, the C5 classification indicates the person can operate a manual wheelchair, C4 or lower injury indicates the need to use an electric wheelchair as they have little residual function, and C5 or C6 indicates the boundary between using a manual wheelchair and an electric wheelchair.

First, we measured the remaining power in the shoulder joint circumference and the elbow joint circumference of a person with cervical cord injury. The subject was a man with modified Zancolli classification of C6B1 in his right arm and C5B in his left arm. In this experiment, we measured the extension and flexion power of his shoulder and elbow joints five times each using a push-pull gauge, and calculated the joint torque by taking the average. Table 1 shows the experimental results.

In the experimental results, the extension torque of the elbow joint could not be measured. In other words, the former power of the elbow to extend was fully lost.

As the next step, we measured the tangential operating force on the wheel rim of the wheelchair comparing 1 link of the elbow joint (Subject's elbow is locked at 90[deg].) and 2 link of the elbow joint (Subject can operate the wheelchair freely.) by using the Push-pull gauge. We experimented that the subject's hand position started from 140[deg] of the wheelchair backward to 30[deg] of the wheelchair forward by 10[deg]. The experiment was performed twice for each hand position, and calculated the average value as the operating force. Fig 2 shows the results of the experiment. As the result, the subject whose elbow joint is locked can put power to the wheel rim of the wheel chair to operate in the entire operation area compared to 2 link of the elbow joint. In particular, a meaningful difference was seen in initial operation interval. This result is thought that the power of the shoulder can translate to the hand directly by locking the elbow joint. In other words, the subject can add torques to operate on such steps with high resistance. We also confirmed that the power loss in the elbow joint had a large influence during wheelchair operation.

Table 1: Residual torque at the shoulder and elbow joints for modified Zancolli classification of C6B1.

Subject	Extension torque	Flexion torque
Shoulder joint	8.6[Nm]	11.3[Nm]
Elbow joint	0.0[Nm]	20.3[Nm]

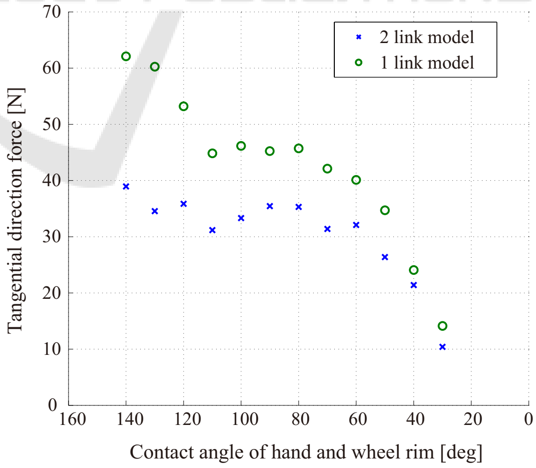

Figure 2: Measured results of operation force between 2 link and 1link.

3 DEVELOPED ROBOT ORTHOSIS

The lock mechanism in the elbow joint is created by using a static element such as an orthosis and a free mechanism depending on the situation by using a drive system. The developed robot orthosis is intended to support the independence of disabled people in everyday life. Therefore it is desirable for the orthosis to be light, compact, and inexpensive. It is also desirable for it to offer long-term use and durability. We use a ratchet mechanism that is able to withstand the load of the lock mechanism and that has flexibility in the rotational direction. We use the small-size DC motor to drive the component, and we control these parts to lock or unlock in a timely fashion. Figure 1 shows the robot orthosis that transfers the residual function from the shoulder joint circumference to the hands.

Our device consists of a drive mechanism, battery, control board in one part, and this device has the special orthosis, and the glove sensor attached to the hand that can detect contact to the rim of the wheelchair. Our robot orthosis can be programmed to drive independently. The sensors used are a small rotary encoder for detecting the elbow joint, a glove sensor for detecting contact with the wheel rim of the wheelchair, a photo interrupter for controlling the motor. When people with a cervical cord injury operate a wheelchair, they operate it by pushing their hand on the rim because they are unable to grasp the rim. We therefore use a force sensor to detect contact with the rim. In terms of the orthosis, we developed a special orthosis by using two types of materials to transfer power from the muscles within the shoulder to their hands. This orthosis can provide legged robot-enhancing capability, and also provides pronation and supination to the forearm.

3.1 Rotary Drive Type Ratchet Mechanism And Control

We developed a component that employs a ratchet mechanism which has an externally toothed gear and an internally toothed gear in one part. Two claws that correspond with teeth on each are attached to this part. This mechanism is therefore able to lock both direction linking the flexion and extension of the elbow joint by using only one part. This makes it possible to reduce the size of the robot orthosis. We consider the physiological excursion of the elbow, which is flexural, to be about 140[deg] from the greatest extension and we removed the area that is not needed. We created a tilt of 8.0[deg] at the point where the aspect of the gear comes into contact with the aspect of the forearm frame. This is because the robot orthosis might block the movement of flexural extension of the elbow joint. The claw is linked to the DC motor through two leaf springs. The system is such that each claw is inserted and removed from the gear. We use the small DC motor for driving the ratchet mechanism. There are two leaf springs of size 0.5[mm] thickness between the claw of the ratchet and the DC motor, and the two leaf springs are branched to hold the eccentric cam that is attached to the output shaft edge of the DC motor. The eccentric cam has two flat surfaces on the bottom, and each surface can touch the upper arm frame. Because the DC motor occurs resistance when the flat surface of the cam comes into contact with the upper arm frame by rotating, the electric current to the motor increases. This system sends a stop instructiomjn by monitoring the increase in the electric current levels to allow the system to stop the motor at the desired position. Figure 4 shows the results for the motor electric current levels. In this experiment, we lock or unlock by pushing the glove sensor. The electric current levels increase after pushing

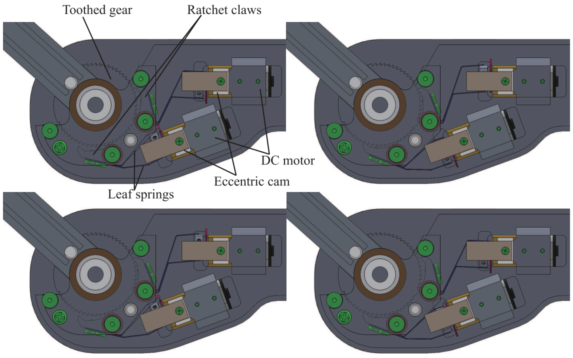

Figure 3: Upper left; Pattern of the meshing of ratchet mechanism which elbow joint moves freely. Upper right; Pattern of the meshing of ratchet mechanism which elbow joint is completely locked. Lower left; Pattern of the meshing of ratchet mechanism which elbow joint is completely locked in the direction of the flexion movement and moves freely in the direction of the extension movement. Lower right; Pattern of the meshing of ratchet mechanism which elbow joint is completely locked in the direction of the extension movement and moves freely in the direction of the flexion movement.

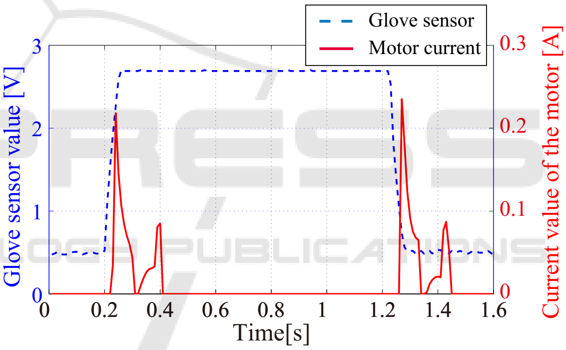

Figure 4: Monitoring motor current.

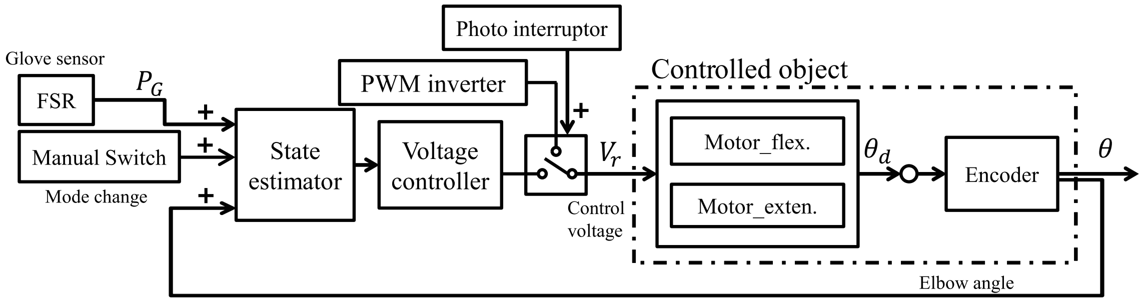

Figure 5: Block diagram of basic control.

the glove sensor. After that, the electric current levels decrease, and then increase again at around 0.3[s]. This is because the flat surface of the cam comes into contact with the upperframe. In this system, sending the stop instruction to the motor by monitoring the increase the electric current levels at the second salient. For this reason, We can reduce power consumption and the total lock/unlock frequency of this system are 41,000 in one charge.

3.2 Basic Control And Timing Chart

Figure 5 shows a block diagram of the basic control. We use the FSR406 of the glove sensor, the rotary position sensor attached to the device and the manual switch for changing mode. The FSR406 is the force sensor that can measure the force over a large area, and the system judges the contact with the wheel rim or other objects. We use the encoder for sensing the elbow angle. V_r is the control voltage, θ_d is the angle of the device in the block diagram. In the basic movement, if the output voltage from the signal received from the glove sensor is more than 0.847[V], a voltage instruction is sent to lock the motors. After this, the system changes into PWM drive mode from the signals from the photo interrupters and is driven at 50% duty ratio. We give consideration for the cam to make softly make contact with the upper arm frame by changing the PWM drive mode. This makes it possible to reduce electricity consumption by using PWM drive mode to increase the longevity of the battery. Figure 6 shows the timing chart for this as a series of events.

If output voltage from the signal received from the glove sensor is less than 1.8[V], a voltage instruction is sent to unlock the motors. The system changes the PWM drive mode from the signals from the photo interrupters, and sets the drive duty ratio to 50% to unlock the motor. In other words, the system judges the state of contact between the wheel rim and the FSR406 of the glove sensor. If the objects make contact with each other, the motors rotate direction to lock, and when the FSR406 of the glove sensor detaches from the wheel rim, the motors rotate in the unlock direction. We can change the output voltage of the glove sensor and the duty ratio. For this reason, it is possible to set the lock/unlock of the elbow joint at the timing of the operator.

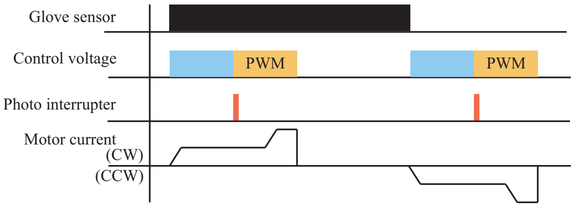

Figure 6: Timing chart.

4 WHEELCHAIR OPERATION EXPERIMENTS INVOLVING SUBJECTS WITH CERVICAL CORD INJURY

The subjects were three people with cervical cord injury. The modified Zancolli classifications were as follows: Subject 1, C6B1 for the right arm and C5B for the left arm; Subject 2, C5A for the right arm and C5B for the left arm; Subject 3, C6 for the right and left arm. We verified differences between using and not using the developed device, by using motion analysis and electromyography for a road with high resistance and on a slope. The subject who has the most serious symptoms among the three is not able to

Figure 7: Left; Situation of the experiments on a slope which set the inclination to 3.4[deg] in accordance with the barrier-free law of Japan. Right; Situation of the experiments on a lawn way simulated the irregular ground.

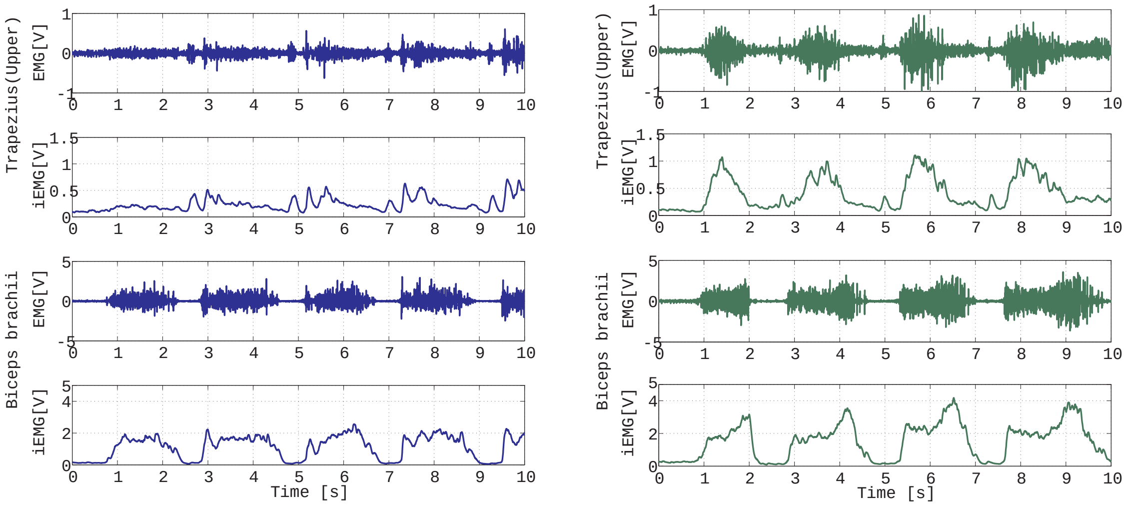

Figure 8: Left; activity of the upper trapezius and biceps brachii muscles without the proposed device by a subject with C5A for the right arm and C5B for the left arm of cervical cord injury. Right; activity of the upper trapezius and biceps brachii muscles with the proposed device by a subject with C5A for the right arm and C5B for the left arm of cervical cord injury.

perform extension movement of the elbow joint and has very weak flexion movement and we describe his results. This study was approved by an institutional review board and was performed in accordance with the Declaration of Helsinki governing human studies. Figure 7 shows the situation of the experiments.

In the experiment on a slope, we measured the muscle power of the shoulder circumference by using an EMG sensor. We used a treadmill to simulate the slope and set the inclination to 3.4[deg] in accordance with the barrier-free law of Japan. Figure 8 shows the muscle power of the shoulder circumference.

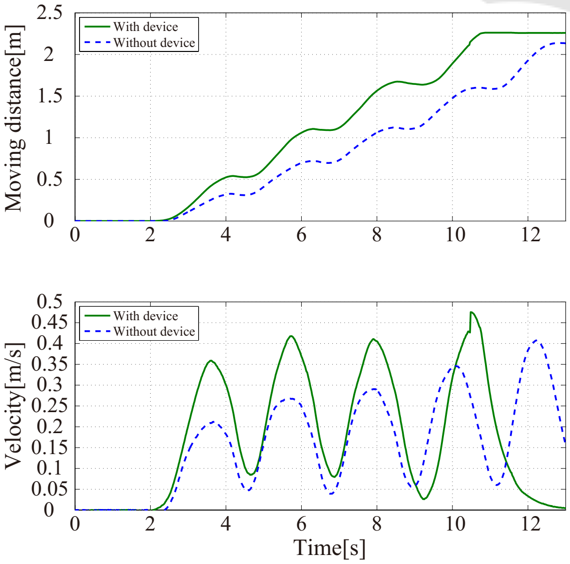

Figure 9: Experimental results of overlapped waveforms of operation in grass with/without the proposed device by C5A and C5B of cervical cord injury.

From the motion analysis results, in the case of not using the developed robot orthosis, the subject reached the end of the slope after six strokes and about 13[s]. In the case of using the developed robot orthosis, he reached it after four strokes and about 8[s]. The movement distance per stroke is thus increased. In the muscle power measurement results, the muscle power of the upper trapezius became more active than without the device and the muscle power of the biceps brachii became active in the last part of the operation. This is because the movement distance per stroke is higher, and the graph shows that continuous operating power is added in the last part of the operation when the operation occurs at the wheel rim to the front of the wheelchair. Simulation of irregular ground includes a rough way, a lawn way, and a gravel path. We selected using a lawn way. The largest static coefficient of friction of the artificial lawn which we set placed in this experiment was approximately 0.07. We measured the behavior of the wheelchair by using a motion capture system. Figure 9 shows the behavior of the wheelchair. The upper graphs show the movement distance, and the lower graphs show the velocity of the wheelchair. In this experiment, the subject when using the developed robot orthosis moved a distance of 2[m] about 2[s] faster than when not using the developed robot orthosis, and he was able to operate the wheelchair strongly during the first stroke operation when using the developed robot orthosis. In the motion analysis results, when not using the developed robot orthosis, the subject reached a distance of 2[m] after about five strokes, compared with about four strokes when using it.

In other words, the movement distance per stroke was also increased, and he could operate the wheelchair strongly.

5 DISCUSSION AND CONCLUSION

We tested the robot orthosis on three subjects with cervical cord injury and verified the difference between using and not using the developed device based on motion analysis and electromyography at a road with high resistance and on a slope where it is difficult to operate a wheelchair. We performed experiments on a slope and lawn path. With the robot orthosis, the movement distance per stroke was found to increase and the muscle power of the upper trapezius became more active compared to without it, and the muscle power of the biceps brachii became active in the last part of operation.

Biceps brachii muscles support flexion of the elbow joint, and trapezius muscles support putting up the shoulder. This set of experiment results show that the subject can put up his shoulder by using biceps brachii muscles and also hold the rim of the wheelchair by using his hand. Therefore, it is indicated that the residual power of his shoulder transmitted to his hand strongly by using the force transmission orthosis which can lock elbow joint.

In the future, we need to investigate protection against dust, waterproofing, safety for the device and make further improvements. It is also necessary to accumulate more data by increasing the number of test subjects. Further development is needed to employ this mechanism and control system for industrial machinery and other products.

ACKNOWLEDGEMENTS

This work was supported by Projects for Developing Assistive Products in Ministry of Health Labour and Welfare of Japan.

REFERENCES

Hsieh, H.-C., Chien, L., and Lan, C.-C. (2015). Mechanical design of a gravity-balancing wearable exoskeleton for the motion enhancement of human upper limb. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 4992–4997.

Juanjuan Zhang, C. C. C. (2015). Passivity and stability of human-robot interaction control for upper-limb rehabilitation robots. *IEEE Transactions on Robotics*, 31:233–245.

M. H. Rahman, M. J. Rahman, O. L. C. M. S. J. P. K. and Archambault, P. S. (2015). Development of a whole arm wearable robotic exoskeleton for rehabilitation and to assist upper limb movements. *Robotica*, 33:19–39.

Mao, Y., Jin, X., Dutta, G. G., Scholz, J. P., and Agrawal, S. K. (2015). Human movement training with a cable driven arm exoskeleton(carex). *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23:84–92.

N. Mizutani, T. Watanabe, K. T. Y. and Y. Kobayashi (2013). A wheelchair operation assistance control for a wearable robot using with user's residual function. In *IEEE Int Conf Rehabil Robot*.

Tsukahara, A., Hasegawa, Y., Eguchi, K., and Sankai, Y. (2015). Restoration of gait for spinal cord injury patients using hal with intention estimator for preferable swing speed. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23:308–318.

T. Watanabe, K. Yano, T. Aoki, and Y. Nishimoto (2011). Extension motion assistance for upper limb using proxy-based sliding mode control. In *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on*.

T. Yabunaka, K. Yonezawa, N. Kato, K. Yano, Y. Kobayashi, T. Aoki, and Y. Nishimoto (2014). A wheelchair operation with an exoskeletal robot using user's residual function. In *Micro-NanoMechatronics and Human Science (MHS), 2014 International Symposium on*.