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Substitution of motor function of polio survivors who have Permanent Paralysis of Limbs by using Cybernic Voluntary Control

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***Abstract*—There are 10 to 20 millions polio survivors living around the world. Some of them cannot move their limbs by themselves. They feel inconveniences at several situations: climbing stairs; moving in a narrow space; walking. It is very difficult for polio survivors, who have permanent paralysis, to restore motor functions by using conventional rehabilitation approaches. Our aim is the assistance of motor functions of these polio survivors by using HAL. The movement support by using HAL with Cybernic Voluntary Control is possible if electrical signals based on intention of motions can be detected from the polio survivors. However, there are two issues to apply the CVC: First, the bioelectrical signal activity is extremely small and sparse in comparison with unimpaired person's signals. Second, we cannot apply conventional calibration methods to these polio survivors. This paper proposes a specific simplified CVC method for polio survivor with permanent paralysis or severe muscle weakness in their limbs. The method consists of two parts to solve the mentioned issues: a preprocessing algorithm for particular bioelectrical signals and a procedure for assistive torque generation without calibration. We applied the proposed method to the participant who has paralysis due to polio viral infection and confirmed the effectiveness. As a result, the HAL with proposed method generated enough assistive torque to lift up the participant's shank from extremely small and sparse bioelectrical signals. Although the participant's bioelectrical signal activity was extremely small and sparse, and also he could not move the left knee by himself. After we applied the proposed method, the participant was able to move his knee voluntarily. Consequently, we confirmed that the proposed method could assist the basic motor function of paralyzed polio survivor.**

I. INTRODUCTION

Acute polio is an infectious disease caused by poliovirus. The polio epidemic occurred several decades ago. The number of the polio cases was 350000 in 125 countries in 1988 [1]. Poliovirus attacks anterior horn of spinal cord cells, motor neurons, and so on, the paralysis of limbs or the respiratory paralysis may occur. The characteristics of the acute paralysis-related polio are limbs muscle weakness and atrophy. The flaccid paralysis occurs 1 to 2% of all infects. And it permanently remains in some cases. World Health Organization estimated that 10 to 20 millions polio survivors are living around the world. Some of them use a wheel chair or a brace in their daily life in order to move themselves [2], but they feel inconvenience at several situations: climbing stairs; moving at a narrow space; walking. The new health problem of polio survivor related to moving. According to the nation-wide survey in Denmark (3607 subjects), 54% of subjects felt health problem with climbing stairs [12]. Furthermore these physically challenged people have a great demand to live same as unimpaired people. However, it is very difficult for polio survivors, who have permanent paralysis or severe muscle weakness, to restore motor functions by using conventional rehabilitation approaches. Because the destroyed motor neurons are not restored and muscle strength becomes weak, they cannot move their joint voluntarily. Therefore new approaches such as assistance of motor function by using assistive technologies are necessary.

Our research group has developed the Robot Suit HAL (Hybrid Assistive Limb) and its control algorithms in order to assist human physical abilities [4]-[10]. Robot suit HAL is a wearable robot that has an actuator in each joint in order to generate assistive torque, which supports wearer's motions. HAL equipped with various sensors such as bioelectrical signal sensors in order to estimate intention of motion of wearer, angular sensors, and foot pressure sensors. There are various types of Robot Suit HAL that is called HAL-5 series: Full-body type, lower body type, single leg type, and single joint type. These are shown in Fig. 1. HAL-5 series has the same control system architecture, and control algorithms customized according to each demand. By using HAL-5s, our research group has been developing control algorithm for physically challenged people, who have various types of impairments caused stroke, spinal cord injury, amyotrophic lateral sclerosis [7], [10]. Our goal of this study is the assistance of motor functions of polio

(a) (b) (c)

Fig. 1. Robot Suit HAL-5 series: (a) Full body type Robot Suit HAL supports heavy work such as nursing care or heavy weight lifting. (b) Lower body type HAL. (c) Single joint type HAL. These robot suits has same control system architecture.

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survivors who have a permanent paralysis in their limbs by using HAL.

The related works of human movement support with wearable robot are as follows. The RoboKnee was developed as a wearable robot for assistance of knee joint movements. RoboKnee uses knee angle and ground reaction force for its movement control [13], [14]. A wearable robot for walking support of people, who has a disability such as paraplegia, amputee, and cerebral palsy, was developed [15], [16]. The wearers control these robots via control interface. The Berkeley Lower Extremity Exoskeleton (BLEEX) supports human task of load carrying. The BLEEX uses only proprioceptive information for its control [19], [20].

HAL is controlled by a hybrid control system. The system consists of Cybernic Voluntary Control (CVC) and Cybernic Autonomous Control (CVC). A typical CVC method is a power assist method based on bioelectrical signal activity. The HAL, which contains the CVC method, estimates intention of motions of wearer from bioelectrical signals. The movement supported by using HAL with CVC is possible if electrical signals based on intention of motions are able to detect from the polio survivors. There is a possibility that the polio survivors with paralysis will be able to assist their motor functions by using HAL. However, the physical conditions such as the number of neurons and muscle strength of the polio survivor are greatly different from unimpaired people's physical conditions. Therefore when we apply the CVC in order to assist their motor functions, we must consider the polio survivors' physical conditions.

The purpose of this study is assistance of degenerated lower limb motor function in polio survivors who has paralysis or severe muscle weakness in their limbs by using CVC, we propose a control method for them and confirm the effectiveness of the method through clinical trial.

The following is an outline of the remaining sections of this paper. Section II. Provides the information of the target disorder and issues. Section III. Proposes the method to regenerate the mobility function using CVC. Section IV. Presents experimental setup and results. Section V. Discuss the present investigations. Section VI. Provides the summary of the research.

II. Impairment of Motor Function due to Polio Infection and Issues

A. Impairment of Motor Function due to Polio Infection

1) Flaccid paralysis: When poliomyelitis virus attacks gray matter part such as anterior horn of spinal cord cell and motor neurons, the paralysis of limbs or the respiratory paralysis may occur. The characteristics of the acute paralysis related polio is muscle weakness and atrophy of limbs. The flaccid paralysis occurs 1 to 2% of all in polio infects. And it remains permanently. In this research, we focus on limbs paralysis in chronic phase.

2) Characteristics bioelectrical signal: Because the number of neurons and muscles are decreased by polio infection, activity of the bioelectrical signal becomes small. In case of the polio survivor who is equivalent to class II, III, IV in the limb classification of the National Rehabilitation Hospital (NRH) [3], positive sharp waves appear as a typical signal. It means the existence of giant motor units. Furthermore, the amplitude of the signal becomes extremely small when motor nerves and muscles decrease. In case of the polio survivor who has severe muscle atrophy or paralysis in limbs, they cannot move the limbs at all. However, there is a possibility that the bioelectrical signal appears on some area. Figure 2 shows data, which were measured from the surface of the skin of a paralyzed polio survivor and an unimpaired person. The amplitude of the bioelectrical signal of the polio survivor is lower than that of the unimpaired person, and also there are few interference patterns.

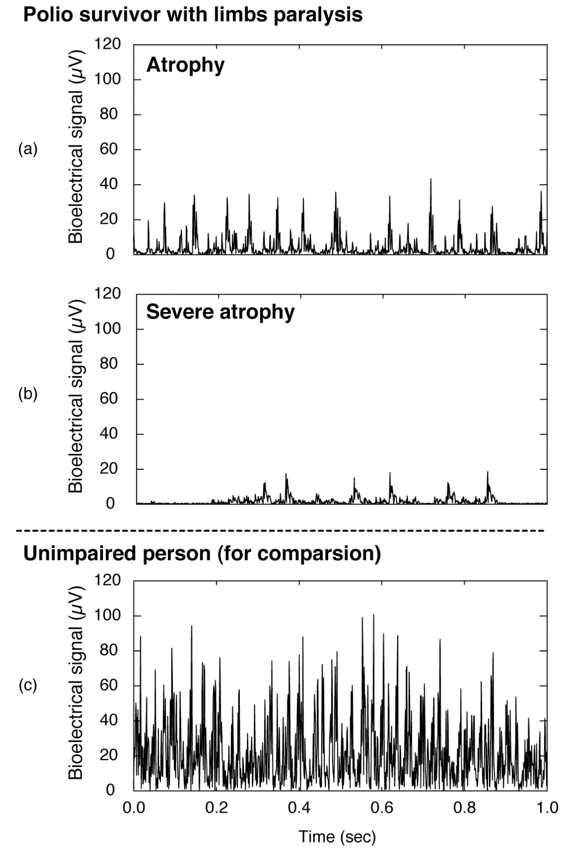


Fig. 2. The bioelectrical signal activity of knee flexor in a flexion movement. (a) The signal of a paralyzed polio survivor. Low amplitude and sparse. (b) The signal of the paralyzed polio survivor. The measurement point is a sever atrophy. (c) The signal of an unimpaired person's.
Note. (a) and (b) are measured from the same person. The measurement positions are different from each other.

B. Issues

We should consider two issues in order to apply CVC method to paralyzed polio survivors.

1) Participant's bioelectrical signal activity is greatly different from unimpaired person's signal: In CVC use, HAL estimates the wearer's intention of motion from the bioelectrical signals through electrodes. Compared with unimpaired person's bioelectrical signal activity, the impaired one is extremely small and also sparse. The estimation accuracy decreases according to the activity.

2) Calibration and Assist-gain settings: An assistive torque, which is generated by HAL to support the wearer's joint motion, is calculated from wearer's estimated joint torque $\hat{\mu}$ and an assist-gain α [4], [6], [9]. The assistive torque τ_{assist} is given by

$$\tau_{assist} = \alpha\hat{\mu} \tag{1}$$

In order to estimate the wearer's torque, we must calibrate the relationship between bioelectrical signal activities and the wearer's torque. Our research group proposed several calibration methods for CVC [4]-[6], [8], [9]. These methods are based on wearer's joint torque. However, we cannot apply these calibration methods to the paralyzed polio survivors because they almost cannot generate joint torque required for the calibration. Even though extremely small joint torque of polio survivors was measured, we cannot apply the methods because of the safety reason: the assist-gain becomes huge value to generate the enough assistive torque, HAL becomes sensitive and unstable; There is a possibility that the process of the torque measurement bring on overuse of impaired person's muscle [11].

We should solve these issues to provide the CVC method for them and to assist the basic motor functions.

III. METHOD

We propose a CVC method for paralyzed polio survivors. Our aim is assistance of a motor function of them by using the method. The method consists of two parts to solve the mentioned issues: a preprocessing algorithm for particular bioelectrical signals and a procedure of assistive torque generation without calibration. The proposed CVC method is summarized in Fig. 3.

A. Preprocessing algorithm for particular bioelectrical signals

This algorithm provides an artificial complete tetanus from sparse bioelectrical signal. We focused on frequency summation mechanism of the skeletal muscle contractions. When an action potential frequency sent to muscular fiber increases, the contractile force of the muscle also increases. Fig. 4 shows a relationship between action potential and contractile force. In case of the paralyzed polio survivor whom bioelectrical signal activity was shown in Fig. 2-(a), (b), we considered that a frequency of action potential decreased due to damage of neurons. This affects contractile force decreases. Instead of damaged neurons and weak muscles, we provide artificial incomplete/complete tetanus by using a peak-holding method. In the preprocessing algorithm, a peak of bioelectrical signal is held for a several tens of milliseconds. The bioelectrical signal is

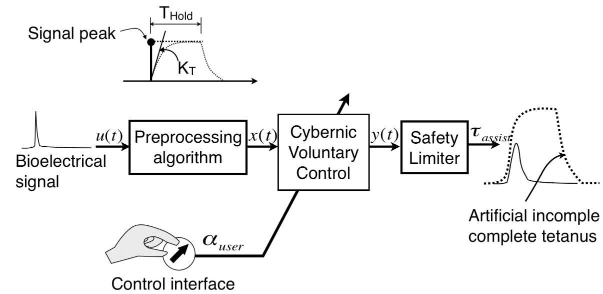


Fig. 3. The block diagram of the proposed method. Sparse bioelectrical signal translate into artificial incomplete/complete tetanus. Assist gain parameter is adjusted manually via control interface.

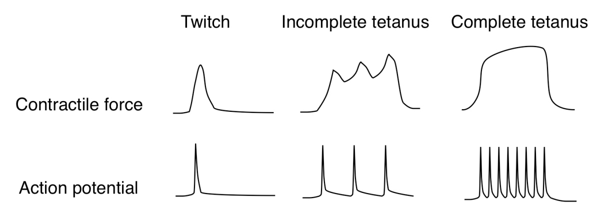


Fig. 4. Relationship between action potential and contractile force

approximated by the following formula

$$x(t+1) = x(t) + \frac{V_{peak} - x(t)}{T} \tag{2}$$

where $x(t)$ is the preprocessed bioelectrical signal, T is the time constant. V_{peak} is the peak of the signal given by

$$V_{peak} = \begin{cases} u(t) & \left(u(t) \geq V_{peak}\right) \\ V_{peak} & \left(u(t) < V_{peak} \cap C_{Hold}(t) > 0\right) \\ 0 & \left(C_{Hold}(t) \leq 0\right) \end{cases} \tag{3}$$

where $u(t)$ is the input signal. C_{Hold} is the remaining hold time given by

$$C_{Hold}(t+1) = \begin{cases} T_{Hold} & \left(u(t) \geq V_{peak}\right) \\ C_{Hold}(t) - Tc & \left(u(t) < V_{peak} \cap C_{Hold}(t) > 0\right) \\ 0 & \left(C_{Hold}(t) \leq 0\right) \end{cases} \tag{4}$$

where T_{Hold} is the constant value of the hold time, Tc is the periodic time intervals of measurement.

B. Procedure of assistive torque generation without calibration

We add two functions to the conventional torque generation procedure of CVC to solve the calibration issue. One function is the manual setting of the assist gain parameter, and the other one is safety limiter.

1) Manual setting of the assist gain parameter: Instead of existing calibration methods based on wearer's joint torque, we use a linear proportional parameter α_{user} that is adjustable via a control interface. The CVC output $y(t)$ is given by

$$y(t) = \alpha_{user}\left(x_{flx}(t) - x_{ext}(t)\right) \tag{5}$$

where $x_{flx}(t)$ and $x_{ext}(t)$ are the preprocessed bioelectrical signal of the flexor and extensor respectively.

2) Safety limiter: For the safety, we give the limit, which is called safe limit, to an assistive torque output. Because the assistive torque is generated by HAL to support the wearer's motion, is extremely large in comparison with the paralyzed polio survivors'. When the bioelectrical signal is extremely small, an assist-gain is set to large value to improve a response performance of HAL. The large assist-gain enables to generate large torque, which increase the risks. Therefore the assistive torque must be limited appropriately. The safe limit is decided based on wearer's physical body parameters such as a link length and weight. For example, in order to support the movement of knee flexion in a standing position, a maximum assistive torque $\tau_{K\max}$ is limited to enough torque to lift up a lower thigh to horizontal. Equation (4) calculates the $\tau_{K\max}$ based on the link model shown in Fig. 5.

$$\tau_{K\max} = mgl \tag{6}$$

where m is a weight of lower thigh, g is the gravity acceleration, l is the length of the lower thigh.

3) Assistive torque generation:

The procedure is summarized as follows. First, we use preprocessed bioelectrical signals into CVC as an input. Second, adjust the assist gain parameter manually via the control interface. Finally, the safety limiter limits the output of CVC. The assistive torque τ_{assist}, which is generated by HAL using this algorithm, is given by

$$\tau_{assist} = \begin{cases} \tau_{K\max} & \left(y(t) \geq \tau_{K\max}\right) \\ y(t) & \left(y(t) < \tau_{K\max}\right) \end{cases} \tag{7}$$

IV. Clinical Trial and Results

To evaluate the effectiveness of the proposed method, it was applied to a knee flexion motion of a paralyzed polio survivor. The goal of the experiments is to provide a knee flexion motion based on the bioelectrical signal activity with Robot Suit HAL. First, we explain the participant, and then show experimental setup, finally show results.

A. Participant

Our research was conducted with a polio survivor who has a flaccid paralysis and severe muscle weakness in his left leg. He lost his mobility function due to polio viral infection at the age of 11 months. He has been using long leg braces (LLB) for 50 years to straighten his knees in daily life for walking. The participant gave informed consent. Figure 6 shows his lower legs. The condition of his left knee is equivalent to NRH Class V. He has few muscles around left knee and ankle, and hence cannot move the knee and the ankle but hip joint.

B. Experimental setup

We used the HAL single joint version (HAL-SJ). Figure 7

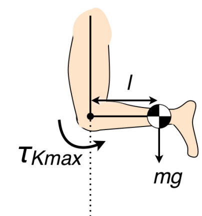
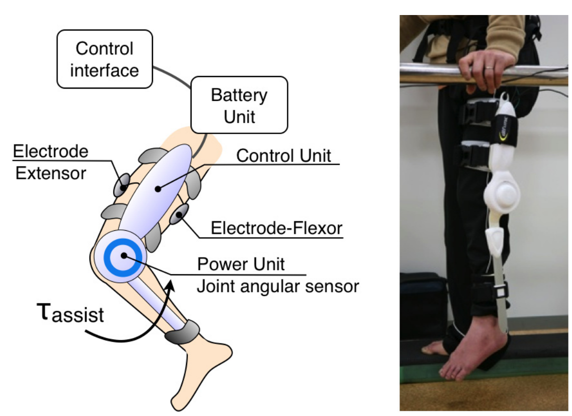


Fig. 5. Joint torque to support weight of lower thigh

(a) (b)

Fig. 6. Participant has flaccid paralysis in his left leg. (a) Participant immobilizes knee and ankle with LLB in daily lives. (b) Left leg, which is affected side, is thinner than healthy side. He cannot move left knee at all.



(a) (b)

Fig. 7. Experimental setup. (a) Configuration of the experimental system. (b) The participant put on HAL-SJ.

shows the configuration of this Robot Suit. HAL-SJ consists of a control unit, an actuator, sensors, a battery unit and a control interface like a stopwatch. The participant is able to tune the assist gain parameter via the control interface shown in Fig. 8. The participant put on HAL-SJ to the left knee, and the electrodes were attached on the surface of his skin of flexors and extensors. We measured his bioelectrical signal in multi point, and selected the point that the highest amplitude signal of all measurement points appeared based on intention of motion. Target motion is knee flexion movement in standing position. The participant moved his knee depending on voice guidance. And the participant grasped parallel bar to keep postural balance while the experiment.

C. Results

Figure 9 presents experimental results. Figure 9-(a),(b) presents bioelectrical signal activity of the flexor side in the flexion movement. The participant tried to bend the knee joint after 1.5 seconds from a start, and the bioelectrical signal appeared for six seconds. We can see the typical signal pattern, which is similar to Fig. 2-(a), in the magnified view. The amplitude of the signal is lower in comparison with unimpaired persons', and sparse. The peak of the signal is approximately 40 μV and the time length of the peak of the signal is 80 to 100 ms.

Figure 9-(c) presents generated assistive torque. The torque like incomplete/complete tetanus was generated in proportion to the amplitude of the signal. The maximum torque is approximately 11 Nm.

The bottom graph of Fig. 9-(d) presents a joint angle of knee. The angle increases from 0.1 to 2.3 rad.

Figure 10 presents the sequential photographs of the knee flexion movement. The lower thigh was lifted up to horizontal by HAL-SJ. Because the participant flexed a left hip joint, the angle of the knee joint became over 1.5 rad.

V. Discussion

It is very difficult for paralyzed polio survivors to restore motor functions using conventional rehabilitation approaches. HAL and its control algorithm are developed in order to assist such kind of severe physically challenged people. There are characteristic issues, such as an extremely small and sparse bioelectrical signals, and calibration; we cannot apply the conventional method of HAL to paralyzed polio survivors. The objectives of the work presented in this paper are to develop a control algorithm for HAL so that it could be used to support motions for paralyzed polio survivors.

We confirmed that the proposed method provided the motion support based on their characteristic bioelectrical signals. Although the amplitude of his bioelectrical signals was extremely small and sparse, the HAL-SJ, which had the proposed method, could generate assistive torque like incomplete/complete tetanus from that signal. The participant put on HAL-SJ on paralyzed left knee, and then he could lift up lower thigh by using HAL-SJ with his intention of motion.

The results indicate the possibility that HAL is able to assist motor function of paralyzed polio survivors by using the proposed method. This work presented fundamental principles of the assistance of motor function. In order to realize the assistance of complex motor functions such as

Fig. 8. Control interface for parameter setting

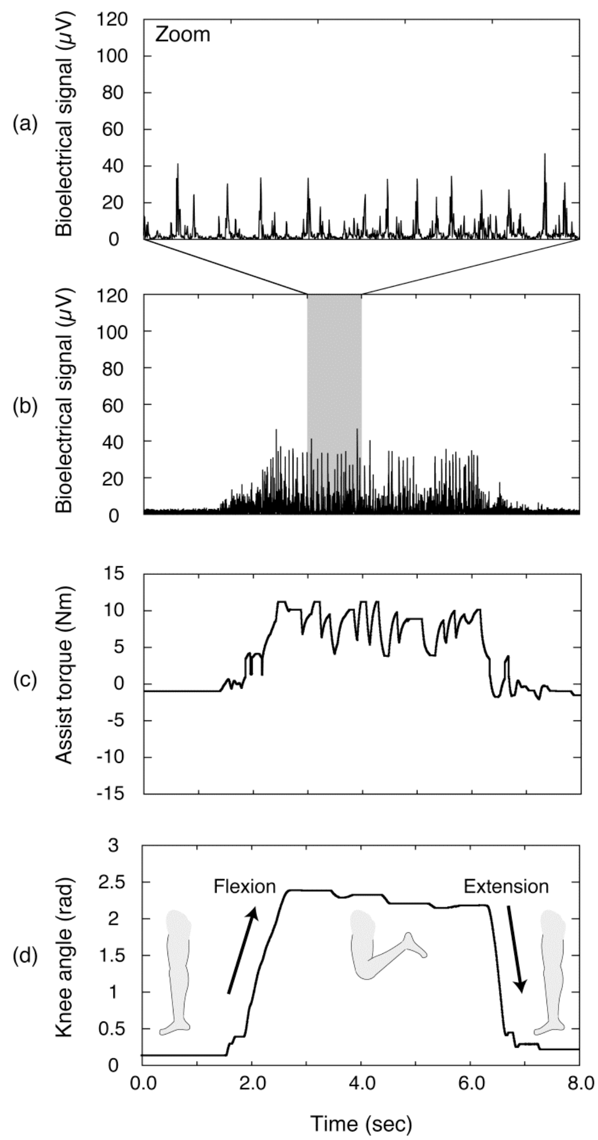


Fig. 9. Generated flexion movement using proposed CVC. (a) and (b) represents the bioelectrical signal activity of the flexor side of the participant. (c) represents the generated assistive torque by HAL. (d) represents joint angle of the knee.
Note. T_{Hold}=100 ms. $\tau_{K\max}$ = 11 Nm.

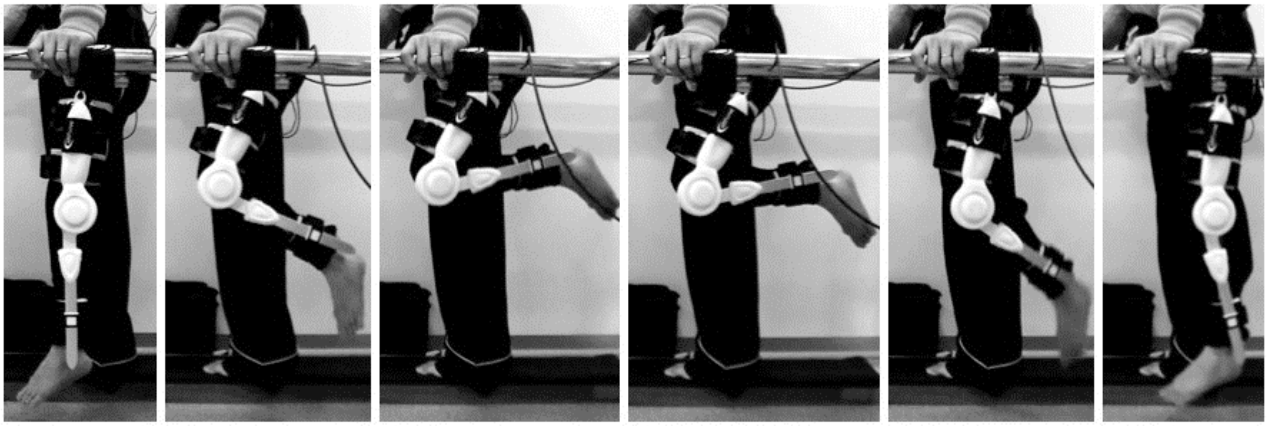


Fig. 10. Sequential photographs of the knee flexion with HAL-SJ

walking, climb up stair or standing up, the knee movement such as flexion is indispensable element. This approach is the first step of the assistance of functions. After this, we intend to extend this method so that HAL is able to assist complicated motor functions such as the walk. However, when the bioelectrical signal is not detectable due to severe impairment, proposed method is not useful to assist motor functions. In order to assist multi motor functions even if it is difficult to measure the bioelectrical signal, we intend to combine the proposed method with Cybernic Autonomous Control (CAC) such as Phase-sequence method [5].

VI. Conclusion

In this paper, we have proposed the method for assistance of degenerated motor functions of polio survivors so that HAL could support limbs motion instead of their degenerated motor function by using CVC. The proposed method consists of following elements: the preprocessing algorithm for particular bioelectrical signal, and the procedure of assistive torque generation without calibration.

We applied the proposed method to the participant who has a left leg paralysis and severe muscle weakness due to polio viral infection and evaluated the effectiveness. Although the participant's bioelectrical signals were extremely small and sparse and also he could not move left knee against the gravity by himself. The participant could move his knee applying the proposed method.

We confirmed that the proposed method could assist degenerated motor function of polio survivors. This work is the first step for assistance of motor functions. We intend to combine the proposed method with CAC so that the proposed method could assist complex motor functions.

References

[1] Elizabeth M. Kilgore and Lauro S. Halstead, "Post-Polio Syndrome: Diagnosis, Evaluation and Management," *Journal of clinical rehabilitation*, vol. 16, No. 2, pp. 121-128

[2] K. Makino and K. Hachisuka, "Leg orthosis for polio survivors," *Journal of clinical rehabilitation*, vol. 16, No. 2, pp. 135-139

[3] Halstead, AC Gawne, "NRH proposal for limb classification and exercise prescription," *Disability and rehabilitation*, 1996, pp. 311-316

[4] T. Nakai, S. Lee, H. Kawamoto, and Y. Sankai, "Development of power assistive leg for walking aid using EMG and linux," in Proc. *The 2nd Asian Conf. on Industrial Automation Robotics*, Bangkok, Thailand, 2001, pp. 295–299.

[5] H. Kawamoto and Y. Sankai, "Power assist method based on phase sequence and muscle force condition for HAL," *Advanced Robotics*, vol. 19, no. 7, pp. 717–734, 2005.

[6] T. Hayashi, H. Kawamoto and Y. Sankai, "Control Method of Robot Suit HAL working as Operator's Muscle using Biological and Dynamical Information", *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2005)*, 2-6 Aug. 2005, pp. 3455-3460.

[7] K. Suzuki, G. Mito, H. Kawamoto, Y. Hasegawa, and Y. Sankai, "Intention-based walking support for paraplegia patients with robot suit HAL," *Advanced Robotics*, vol. 21, no. 12, pp. 1441–1469, 2007.

[8] H. Kawamoto, Y. Sankai, "Comfortable Power Assist Control Methodfor Walking Aid by HAL-3", *Proc. Of IEEE SMCTP1B3 (CD-ROM)*, 2002

[9] J. Okamura, H. Tanaka and Y. Sankai: "EMG-based prototype powered assistive system for walking aid", *Proceedings of Asian Symposium on Industrial Automation and Robotics*, pp. 229–234, 1999

[10] A. Tsukahara, Y. Hasegawa and Y. Sankai, "Standing-Up Motion Support for Paraplegic Patient with Robot Suit HAL," *Proc. of the 2009 IEEE 11th Int'l Conf. on Rehabilitation Robotics (ICORR 2009)*, pp. 211-217, 2009.

[11] M. Mizuma, "Therapeutic exercise for patient with post-polio syndrome," *Journal of clinical rehabilitation*, vol. 16, No. 2, pp. 129-134

[12] Lonnberg F, "Late onset polio sequelae in Denmark. Presentation and results of a nation-wide survey of 3,607 polio survivors," *Scand J of Rehabili Med Suppl 28*, pp. 7-15, 1993

[13] Jerry E. Pratt, Benjamin T. Krupp, Christopher J. Morse and Steven H. Collins: "The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance During Walking," *Proceedings of the 2004 IEEE International Conference on Robotics and Automation (ICRA '04)*, pp.2430-2435, 2004.

[14] J. Pratt, B. Krupp and C. Morse: "Series elastic actuators for high fidelity force control," *Industrial Robot: An International Journal*, vol.29, no.3, pp.234-241, 2002.

[15] David C. Johnson, Daniel W. Repperger and Greg Thompson: "Development of a mobility assist for the paralyzed, amputee, and spastic patient," *Proceedings of the IEEE Southern Biomedical Engineering Conference*, pp.67-70, 1996.

[16] D. Repperger, B. Hill, C. Hasser, M. Roark and C. Phillips: "Human tracking studies involving an actively powered augmented exoskeleton," *Proceedings of the IEEE Southern Biomedical Conference*, pp.28-31, 1996.