Control Method of Robot Suit HAL working as Operator's Muscle using Biological and Dynamical Information

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基本观点：外骨骼是一种仿生肌肉

***Abstract* - For assisting human motion, assistive devices working as muscles would be useful. A robot suit HAL (Hybrid Assistive Limb) has been developed as an assistive device for lower limbs. Human can appropriately produce muscle contraction torque and control joint viscoelasticity by muscle effort such as co-contraction. Thus, to implement functions equivalent to human muscles using HAL, it is necessary to control viscoelasticity of HAL as well as to produce torque in accordance with operator's intention. Therefore the purpose of this study is to propose a control method of HAL using Biological and Motion Information. In this method, HAL produces torque corresponding to muscle contraction torque by referring to the myoelectricity that is biological information to control operator's muscles. In addition, the viscoelasticities of HAL are adjusted in proportion to operator's viscoelasticity that is estimated from motion information by using an on-line parameter identification method. To evaluate the effectiveness of the proposed method, the method was applied to a swinging motion of a lower leg. When this method was applied, HAL could work like operator's muscles in the swinging motion, and as a consequence, the muscle activities of the operator were reduced. As a result of this experiment, we confirmed the effectiveness of the proposed method.**

粘弹性

***Index Terms* - robot suit, viscoelastic properties, impedance control, on-line parameter identification, myoelectricity.**

I. Introduction

Assistive devices that can work as motor organs would be useful for assisting or enhancing human motion. We have developed a robot suit HAL (Hybrid Assistive Limb) as an assistive device for operator's lower limb [1-3].

In order to use HAL as operator's muscles, HAL has to work as a torque generator like muscles. It is necessary that HAL detect operator's intention to produce muscle torque voluntarily, in order to produce torque. It is useful to use biological information such as myoelectricity to detect operator's intention [2, 4]. Additionally, the operator cannot only produce the muscle torque, but also control joint viscoelasticity by muscle effort such as co-contraction of the flexor and extensor [5, 6]. The joint stiffness is adjusted for different motions. When the operator needs a high joint viscoelasticity, it is useful to increase a viscoelasticity of an actuator of HAL for assistance. Hence, it is also necessary to control viscoelasticity of HAL adaptively by referring to operator's joint viscoelasticity. It is necessary to estimate operator's viscoelastic properties using motion information because it is difficult to measure them directly.

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Therefore, the purpose of this study is to propose a control method of the robot suit using Biological and Motion Information to use the robot as operator's joint muscles.

In this paper, the proposed method is applied to HAL Mark three (HAL-3) [2, 3] in the case of swinging motion of the lower leg. Fig. 1 shows the configuration of HAL-3. It consists of exoskeleton frame with actuators for knee and hip joints in each leg. The angle of each joint is measured with a potentiometer attached to the joint. To prevent hyperextension or hyperflexion, every actuator is equipped with mechanical limiters.

关节角度使用电位计进行测量

II. Control Method of HAL by Referring to Operator's Biological and Motion Information

A. Actuator Control based on Biological Information

In this section, we describe a method to produce torque corresponding to muscle contraction torque by actuators of HAL using the myoelectricity.

To detect myoelectricity, two sensor units are attached on operator's skin near the flexor and the extensor driving the targeted joint as shown in Fig. 2. The sensor unit consists of two electrodes and an instrumentation amplifier. Two signals of myoelectricity from the flexor and extensor are filtered and amplified. The myoelectric activity $E(t)$, which is an amplitude envelope of myoelectricity, is defined as follows:

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$$E(t) = \sqrt{(1/T)\int_{t-T}^{t} m^2(t)\,dt} \qquad (1)$$

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where m is the measured myoelectricity. This equation is applied to both the flexor and extensor of the targeted joint. The myoelectric activity is calculated online.

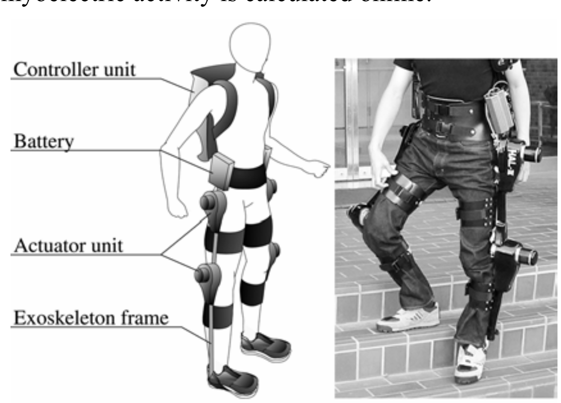

Fig. 1 Configuration of the robot suit HAL-3.

Then, the estimated muscle torque $\hat{\mu}$ is given by

$$\begin{aligned}\hat{\mu} &= \hat{\mu}_{ex} - \hat{\mu}_{flex} \\ &= (a_e E_e(t) + b_e) - (a_f E_f(t) + b_f)\end{aligned} \tag{2}$$

where $E_f(t)$ and $E_e(t)$ are the myoelectric activities of the flexor and extensor respectively, a_f, a_e, b_f and b_e are conversion coefficients from myoelectric activities to the contraction torque. By using estimated muscle torque, the torque τ_μ which HAL produces is given by

$$\tau_\mu = \alpha_\mu \hat{\mu} \tag{3}$$

where α_μ is a gain parameter.

A calibration exercise is necessary in order to obtain the conversion coefficients in (2). For the calibration, HAL has outputted steady torque pattern as a reference torque, and the operator putting on HAL has produced torque to compete against the reference torque without producing co-contraction as far as possible. The calibration exercise has been individually performed to the flexor and extensor of the joint. To obtain values of the conversion coefficients, a conventional least-square method has been applied. One of the results of the calibration exercise is shown in Fig. 3. The conversion coefficients apparently depend on operator's physical condition and the attached location of the sensor unit. Hence, the calibrating motion must be carried out, whenever the operator put on HAL.

校准：使用肌肉力去抵抗驱动力，同时不产生肌肉的拮抗效用

B. Musculoskeletal Model of Operator's Lower Limb Working with HAL

We have constructed a musculoskeletal model of operator's lower limb equipped with the exoskeleton-actuator of HAL for estimating viscoelastic properties of operator's joint muscles and for controlling the properties of HAL.

In this study, muscles acting on a joint are regarded as one muscle group. Fig. 4 shows a model of muscle group around operator's knee joint as an example. The muscles in the group can respectively produce torque toward the contracting direction, but cannot produce it toward the extending direction. Thus, the muscle group needs two torque generators corresponding to the two directions.

Viscoelastic properties of the muscle group can be represented as a combination of a viscous element and an elastic element. We have assumed that the operator can modify the viscosity and elasticity with time. Hence, the two elements are defined as time-varying parameters.

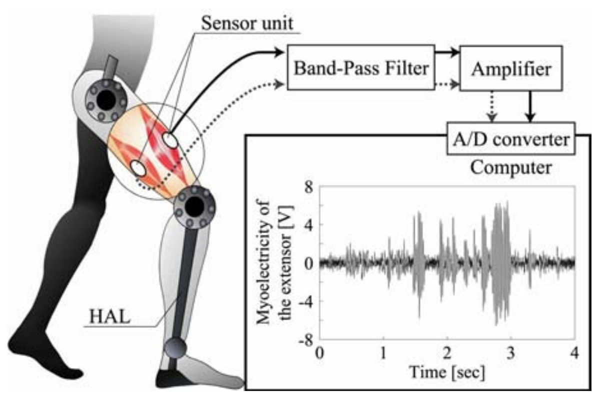

Fig. 2 Process of measuring myoelectricity.

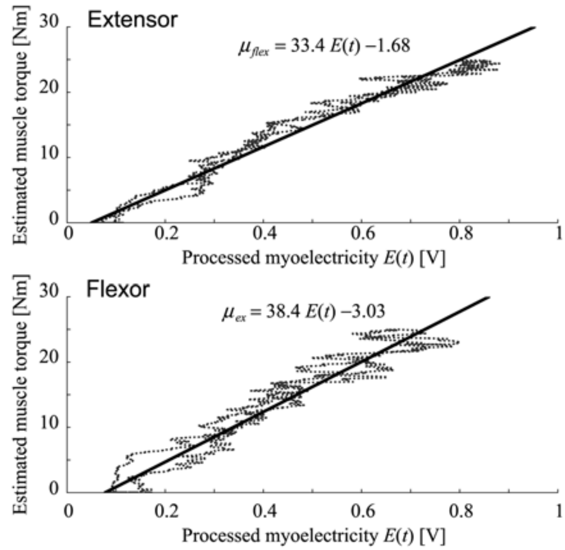

Fig. 3 One of the results of the calibration exercise.

Operator's leg with HAL is regarded as a multilink pendulum system to construct the musculoskeletal model. Fig. 5 shows the musculoskeletal model of operator's lower leg as an example. The motion equation of the i-th link of the model is expressed as follows:

基本动力学

$$I_i \ddot{\theta}_i + (D_i + R_i)\dot{\theta}_i + K_i \theta_i + M_i g l_i \sin\theta_i = \tau_i + \mu_i + \sigma_i \tag{4}$$

where θ is angle of a joint, I is total inertia around the joint, D and K are respectively the viscous and elastic coefficients of operator's muscle group, R is the viscous coefficients of the actuator of HAL, M is the mass of operator's leg link equipped with exoskeleton-actuator of HAL, g is the gravitational coefficient, l is the distance between the joint and the center of mass of operator's leg link with the exoskeleton, τ is torque produced by the actuator of HAL, μ is muscle torque produced by the operator, σ is the total interaction torque between adjacent links and suffix i is joint id. The parameters D and K are defined as time-depending parameters.

D. Method to Control Viscoelastic Properties of HAL

In this section we describe a method to control viscoelastic properties of HAL. In this study, actuator torque τ_ζ to control viscoelastic properties is determined based on impedance control method. τ_ζ of i-th joint is given by

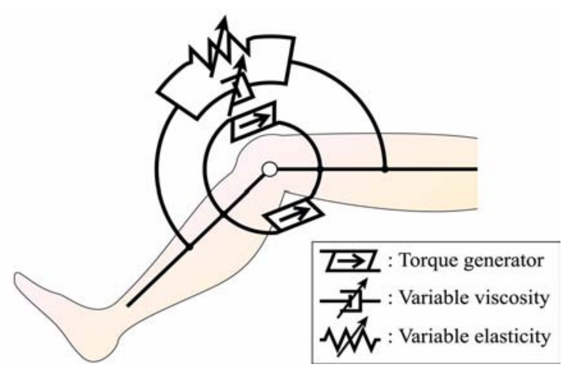

Fig. 4 Model of operator's muscle group around knee joint. Arrows in this figure mean contraction directions.

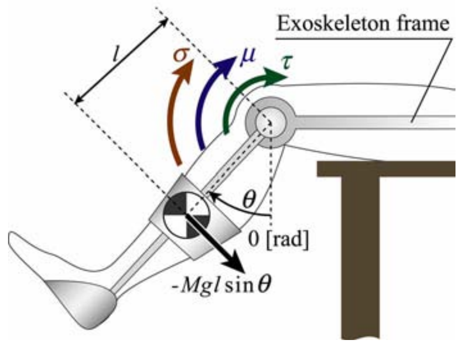

Fig. 5 Configuration of the musculoskeletal model of operator's lower leg equipped with HAL.

调整外骨骼的动态特性

$$\tau_{i\zeta} = \alpha_{i\zeta}\left(-D_i\dot{\theta}_i - K_i\theta_i\right) \tag{5}$$

where $\alpha_{i\zeta}$ is a gain parameter.

In order that HAL works as muscles, the torque τ produced by its actuator is expressed as follows.

$$\tau_i = \tau_{i\zeta} + \tau_{i\mu} + \tau_{ic}. \tag{6}$$

where τ_{ic} is the torque to compensate mechanical impedance depending on exoskeleton-actuators of HAL [7, 8]. Although it is difficult to compensate all mechanical impedance of HAL absolutely, applying the compensation torque can sufficiently reduce the load derived from the impedance in actual use.

Substituting (6) into (4) gives

$$\begin{aligned}&(I_i - I_{ih})\ddot{\theta}_i + (1+\alpha_{i\zeta})D_i\dot{\theta}_i + (1+\alpha_{i\zeta})K_i\theta_i + M_i g l_i \sin\theta_i \\ &= (1+\alpha_{i\mu})\mu_i + \sigma_i.\end{aligned} \tag{7}$$

This equation suggests that HAL produces actuator torque as if it amplified operator's muscle torque and viscoelastic properties according to the gain parameters $\alpha_{i\mu}$ and $\alpha_{i\zeta}$. In consequence, the proposed method would reduce loads on operator's muscles.

C. Estimation of Viscoelastic Properties of Operator's Muscle

In this section, we describe a method to estimate viscoelastic properties of operator's muscle group in real time in order to control viscoelastic properties of HAL. We take operator's lower leg as an example to describe the method to estimate operator's viscoelastic properties.

To linearize (4), some parameters are defined as

$$\begin{aligned}&D' = D + R \\ &K' = K + G(\theta) \\ &G(\theta) = \begin{cases}(Mgl\sin\theta)/\theta & (\theta \neq 0) \\ Mgl & (\theta = 0).\end{cases}\end{aligned} \tag{8}$$

By regarding the sum of τ, μ and σ as the input of the lower leg system, we can express the state-space form of the system (1) as follows.

$$\begin{cases}\dfrac{d}{dt}\begin{pmatrix}x_1(t)\\x_2(t)\end{pmatrix} = \begin{pmatrix}0 & 1\\ -K'/I & -D'/I\end{pmatrix}\begin{pmatrix}x_1(t)\\x_2(t)\end{pmatrix} + \begin{pmatrix}0\\1/I\end{pmatrix}u(t)\\ \theta(t) = \begin{pmatrix}1 & 0\end{pmatrix}\begin{pmatrix}x_1(t)\\x_2(t)\end{pmatrix}\end{cases} \tag{9}$$
$$u(t) = \tau(t) + \mu(t) + \sigma(t).$$

We applied the Delta-Operator δ to the discrete-time form for realizing high sampling rate. For the state-space form written as (9), the discrete-time form in is given by

$$\begin{cases}\delta\begin{pmatrix}x_1(k)\\x_2(k)\end{pmatrix} = \begin{pmatrix}0 & 1\\ -K'/I & -D'/I\end{pmatrix}\begin{pmatrix}x_1(k)\\x_2(k)\end{pmatrix} + \begin{pmatrix}T_d/(2I)\\ (1-DT_d/(2I))/I\end{pmatrix}u(k)\\ \theta(k) = \begin{pmatrix}1 & 0\end{pmatrix}\begin{pmatrix}x_1(k)\\x_2(k)\end{pmatrix}.\end{cases} \tag{10}$$

有时间推导一下

The solution of (10) for $\theta(k)$ gives ？？？

$$\begin{aligned}&\theta(k) = \boldsymbol{\varphi}^T(k)\,\mathbf{X}(k)\\ &\mathbf{X}(k) = [e_1 - D'/I \quad e_2 - K'/I \quad T_d/(2I) \quad 1/I]\\ &\boldsymbol{\varphi}(k) = [\delta\theta(k)/E(\delta) \quad \theta(k)/E(\delta) \quad \delta u(k)/E(\delta) \quad u(k)/E(\delta)]\end{aligned} \tag{11}$$

where $E(\delta)$ is a state variable. When $\hat{\mathbf{X}}(k)$ is defined as an estimated parameter vector, the prediction error $e(k)$ is given by

$$e(k) = \theta(k) - \hat{\theta}(k) = \theta(k) - \boldsymbol{\varphi}(k)\hat{\mathbf{X}}(k). \tag{12}$$

By using weighted least-squares method, the update formula of the estimated parameter vector to minimize $e(k)$ is derived as follows.

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$$\begin{aligned}&\hat{\mathbf{X}}(k+1) = \hat{\mathbf{X}}(k) + \mathbf{P}(k)\boldsymbol{\varphi}(k+1)\frac{\theta(k+1) - \boldsymbol{\varphi}^T(k+1)\hat{\mathbf{X}}(k)}{\rho + \boldsymbol{\varphi}^T(k+1)\mathbf{P}(k)\boldsymbol{\varphi}(k+1)}\\ &\mathbf{P}(k+1) = \frac{\mathbf{P}(k) - \mathbf{P}(k)\boldsymbol{\varphi}(k+1)\boldsymbol{\varphi}^T(k+1)\mathbf{P}(k)}{\rho\{\rho + \boldsymbol{\varphi}^T(k+1)\mathbf{P}(k)\boldsymbol{\varphi}(k+1)\}}\\ &\mathbf{P}(0) = \beta\,\mathbf{I} \qquad (\beta > 0)\end{aligned} \tag{13}$$

where ρ is a forgetting factor ($0 << \rho < 1$) and $\mathbf{I}$ is the unit matrix of 4×4.

To obtain parameters of the viscoelasticity of the muscle group, we should identify invariant parameters M, g, l and R in (4) before the estimation of the parameters of viscoelasticity. If the operator does not activate his muscles, the motion of operator's lower leg equipped with HAL can be expressed as follows.

$$I\ddot{\theta} + (D+R)\dot{\theta} + Mgl\sin\theta = \tau. \tag{14}$$

Additionally, the link model of the exoskeleton frame for the lower leg with the actuator of HAL is expressed as follows.

$$I_h\ddot{\theta} + R\dot{\theta} + M_h g l_h \sin\theta = \tau \tag{15}$$

where I_h is inertia around exoskeleton-actuator of HAL, M_h is the mass of the exoskeleton with the actuator, and l_h is the distance between the knee joint and the center of mass of the exoskeleton-actuator. Parameters in (14) and (15) have been beforehand identified [7-9].

To control the viscoelastic properties of HAL according to (5), it is necessary to know the angular velocity of the joint. In this study, the state observer is adopted. Applying a state observer to (10) gives

$$\begin{aligned}\delta\begin{pmatrix}x_1(k)\\x_2(k)\end{pmatrix} &= \begin{pmatrix}0 & 1\\ -K'/I & -D'/I\end{pmatrix}\begin{pmatrix}x_1(k)\\x_2(k)\end{pmatrix} + \begin{pmatrix}T_d/(2I)\\ (1-DT_d/(2I))/I\end{pmatrix}u(k)\\ &+ \begin{pmatrix}g_1(k)\\g_2(k)\end{pmatrix}\{\theta(k) - \hat{\theta}(k)\}\end{aligned} \tag{16}$$

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where g_1 and g_2 are observer gains. These gains must be adjusted to keep stability of the state observer because the lower leg model shown in (4) is designed as a time-varying system. In addition, it is desirable that a time constant of the state observer remains smaller than the electromechanical delay [10] in order to ensure tracking performance of the

观测器的时间常数小于肌电延迟

parameter estimation. We have, therefore, predefined the time constant of the state observer. Then, stable eigenvalues λ_1 and λ_2 for the observer have been defined for satisfying predefined time constant. Two observer gains have recursively been updated. The updating forms of observer gains are

$$\begin{aligned} g_1(k) &= \lambda_1 - \lambda_2 - D'(k)/I(k) \\ g_2(k) &= \lambda_1 \lambda_2 - g_1(k) D'(k)/I(k). \end{aligned} \tag{17}$$

III. Experiments

To evaluating the proposed method, it was applied to a swinging motion of a lower leg. The operator putting on HAL sat on a chair that has enough height to prevent his foot from grounding. The operator swung his right lower leg up and down. The operator was asked not to actuate other joints except the right knee. We have assumed a combination of foot and lower leg as one link, because ankle joints have been locked. From the above conditions, σ in (4) can be ignored.

To evaluate effectiveness of the proposed method, two types of experiments were carried out. In the first experiment (Experiment 1,) no assisting method was applied. HAL produced only the torque τ_c in (6) compensating its mechanical impedance. In the second experiment (Experiment 2,) the proposed method was applied. Torque produced by the actuator of HAL in this experiment was calculated according to (6). The gain parameters α_μ and α_ζ in were defined as 1.0 and 0.5 respectively.

For the experiments, targeted frequency for the swinging motion was 0.5 Hz. Targeted maximum angles for the extending direction and the flexing direction were respectively 1.0 and -0.3 radians. However, the operator was not required to follow “exactly” the targeted angles. The operator could confirm angle of the joint by a computer display in real time. For the experiments, multiple rehearsals were carried out before each experiment. The operator rested sufficiently between trials to curb the influence of muscular fatigues on his motions and myoelectricity [11].

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A strain of the exoskeleton frame was measured in order to evaluate force applied to operator’s lower leg by HAL. The strain gauge was attached to the frame between the fastening equipment for the lower leg and the actuator of the knee joint as shown in Fig. 6. When operator's joint is fixed, the obtained signal is proportional to the actuator torque produced by HAL. In the swinging motion, the obtained signal is thought to include influences of dynamics of exoskeleton system of HAL. However, the influences of dynamics are thought to be enough smaller than the applied force by HAL. Therefore, in this paper, we assume that the obtained signal is proportional to the force applied to operator's leg by HAL. In all experiments, the strain gauge signal was not used at all for the control of HAL.

IV. Results

A. Experiment 1 (Without Any Assisting Method)

Fig. 7 shows a typical cycle of the swinging motion without applying any assistance by HAL. Fig. 7-A shows transitions of the angle of the knee joint. Increase of the angle corresponds to the extension of the knee joint, and decrease of the angle corresponds to the flexion of the joint. To compare experimental results, we have defined swing-up phase and swing-down phase. The swing-up phase is defined as the period in which the angle and angular velocity of the knee joint are positive. The swing-down phase is defined as the period in which the angle and the angular velocity of the joint are positive and negative respectively.

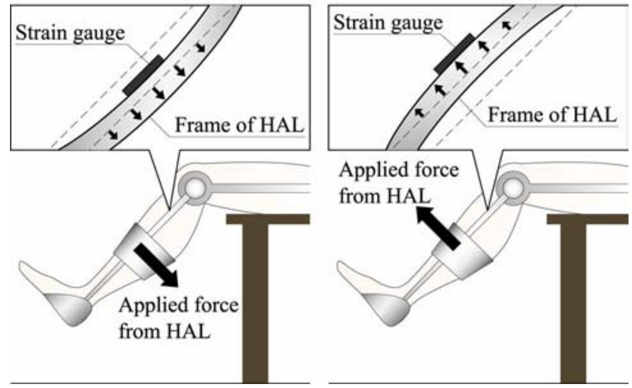

Fig. 6 Configuration to measure a strain of the exoskeleton-frame of HAL.

Fig. 7-B shows myoelectric activities. The myoelectric activity of the extensor has been plotted as positive, and that of the flexor has been plotted as negative. Myoelectric activities of the extensor and flexor were approximately 0.1 [V] and 0.04 [V] respectively, whenever operator's muscles around the knee joint were relaxed in all evaluation experiments. During swing-up phase, the myoelectric activity of the knee extensor was predominant and the direction of the muscle torque was the same as the rotating direction of the knee joint. This result suggests that the extensor worked as an agonist. During swing-down phase, the myoelectric activity of the extensor was predominant, suggesting that operator's muscle torque was found in the opposite direction of the rotation of the knee joint. In addition, simultaneous activation of both the extensor and flexor has been observed in swing-down phases, which suggests a co-contraction of the extensor and flexor.

Fig. 7-C shows the strain of the exoskeleton frame. The strain signal has been defined as positive values, when torque derived from HAL acts on operator’s lower leg in the extending direction. During swing-up phases, the strain signal was found negative. Thus, the force applied to the lower leg from HAL worked in the flexural direction. During swing-down phase, the strain signal remained almost positive, which suggests that the force acted in the extending direction. Therefore, HAL, which has not produced assisting torque, is thought to have approximately acted in the direction opposite to the rotation of the knee joint.

B. Experiment 2 (Using the Proposed Method)

Fig. 8 shows a typical cycle of the swinging motion in which the proposed method was applied. For a comparison, the cycle of swinging motion without any assisting method is superposed here as dotted lines. Fig. 8-A shows the transition of the angle of the actuator of the knee joint.

Myoelectric activities around the knee joint are shown in Fig. 8-B. In this experiment, the myoelectric activity of the extensor was smaller than the activity in the case of not applying assisting method. In addition, the co-contraction of the extensor and flexor has hardly been observed.

The strain of the exoskeleton frame is shown in Fig. 8-C. In swing-up phases, the strain signal was approximately positive. In addition, in the middle of swing-down phase, the strain signal increased. These results signify the force applied to the lower leg from HAL worked in the extending direction.

C. *Comparison of Experimental Results*

To confirm the effectiveness of the proposed method, in this section, we compare results of two experiments by focusing on the swing-up phase and swing-down phase. Fig. 9-A and Fig. 9-B show the mean values of the average myoelectric activities per each phase. The average myoelectric activities decreased when the proposed method was applied. On the other hand, average myoelectric activities of the flexor in swing-up phases were approximately 0.04 [V]. These results signify that the operator has not used the flexor and any assisting method had no effect on the flexor in swing-up phases. The average myoelectric activities of the flexor in swing-down phases were approximately 0.8 [V] through all experiments. This result signifies that the proposed method had little effect on the flexor during swing-down phases.

Fig. 9-C and Fig. 9-D show the mean values of the average strain gauge signals per each phase. The average strain signal was negative in swing-up phases without any assisting method. This result suggests that HAL acted on operator's knee joint in the flexing direction. In contrast, the average strain signals in swing-up phases were positive, when the proposed method was applied. These results suggest that HAL has effectively acted on operator's knee joint in the extending direction. Fig. 9-D suggests that HAL has most strongly acted on operator's knee joint in the extending direction during swing-down phases when the proposed method was applied.

V. Discussion

The swinging motion of the knee joint was carried out to confirm the effectiveness of the proposed method. In swing-up phases through the experiments, the extensor worked as the agonist and simultaneously the flexor was relaxed. Therefore we consider that the role of operator's muscles in swing-up phases was to produce the voluntary contraction torque to extend his knee joint. On the other hand, in swing-down phases, myoelectric activities of extensor were predominant. In addition, co-contractions of the extensor and flexor were observed, when the proposed method was not applied. Therefore, we consider that the major role of operator's muscles in swing-down phases was to restrain the flexion of his knee joint appropriately.

In Experiment I, The strain gauge signal was not zero

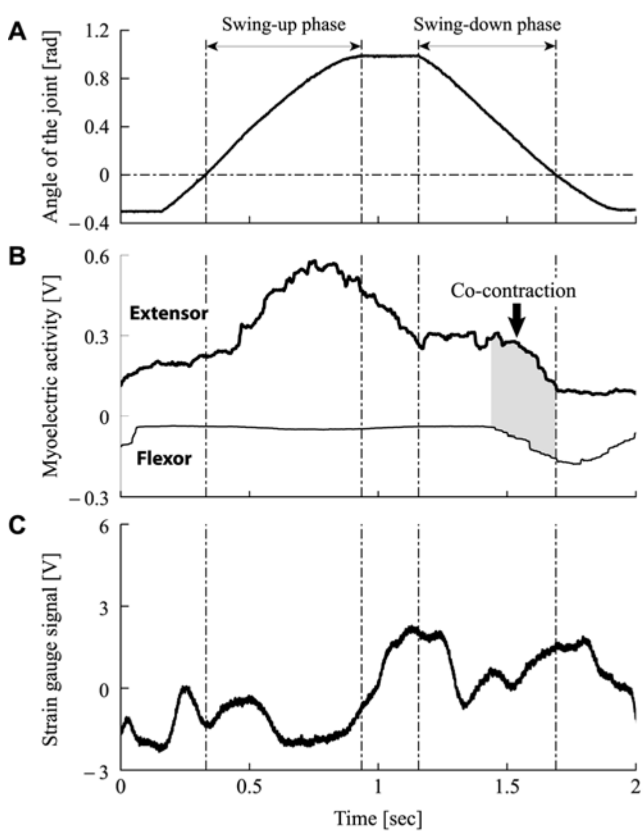

Fig. 7 A typical cycle of the swinging motion when no assisting method was applied

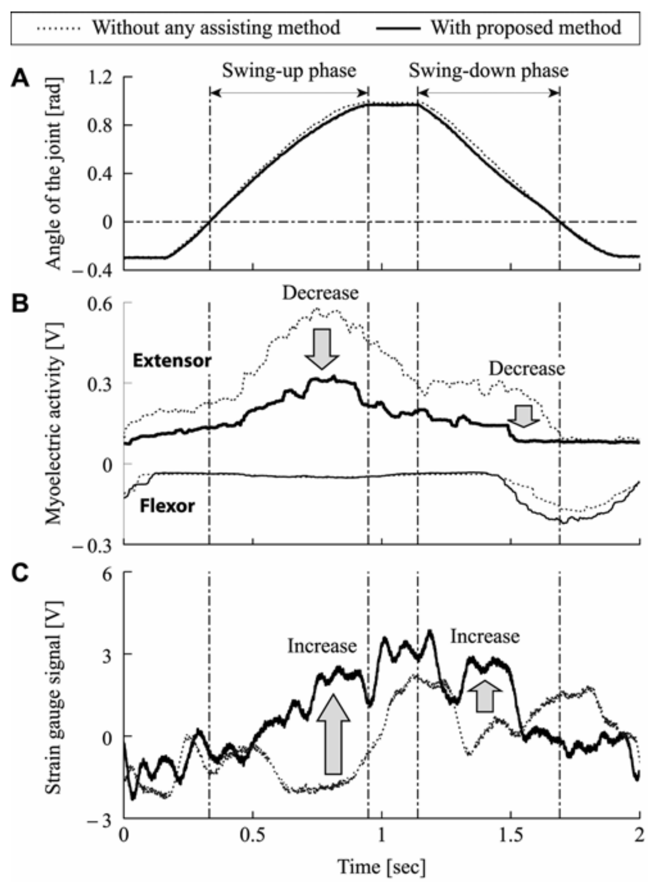

Fig. 8 A typical cycle of the swinging motion with applying the proposed method. Time-axis of this figure has been tuned so that the phase of the figure corresponds to those of Fig. 7.

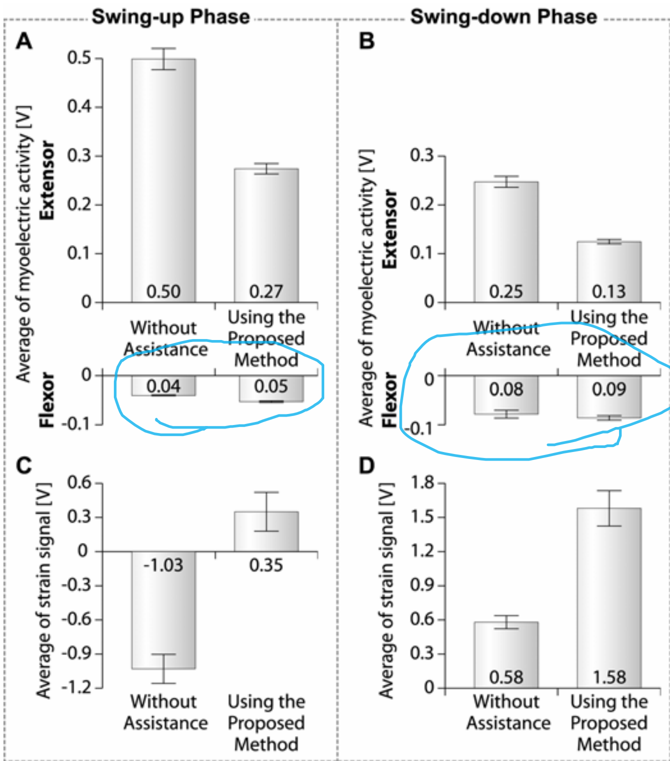

Fig. 9 Comparison of averages of myoelectric activities and strain gauge signals. Error bars represent the standard deviation of mean values.

although we compensated the mechanical impedance of HAL. It is very hard to completely compensate the mechanical impedance of practical exoskeleton-actuator system, because of an error of model parameters, a delay in control and so on.

When the proposed method was applied, HAL extended operator's knee joint in swing-up phases and acted on operator's knee joint in the extending direction in swing-down phases. These workings of HAL are fitting to major roles of operator's muscles in each phase. Additionally, reductions of operator's myoelectric activities were observed. Therefore, We consider that HAL has acted as muscles instead of operator's muscles appropriately by using the proposed method to control actuators of HAL.

However, when the proposed method was applied, the myoelectric activities of the flexor increased as compared to the case without any assisting method. This result implies also that the operator produced the muscle torque to flex the knee joint because HAL has restrained knee flexion more than the operator has expected. We consider that the gain parameter α_ζ =0.5 is still too large in this experiment. It will be necessary to develop a method to adjust the gain parameters appropriately as a future work.

VI. Conclusion

We have proposed the method to control actuators of HAL by referring to Biological and Motion Information to use the robot suit as operator's muscles. In this method, HAL produces torque corresponding to muscle contraction torque by referring to the myoelectricity that is the biological information to control operator's muscles. In addition, operator's viscoelasticities are estimated from motion information using an on-line parameter identification method. The model of operator's lower limb equipped with HAL was constructed in order to estimate operator's viscoelastic properties. The viscoelasticity of the actuator of HAL was adjusted to be proportional to operator's viscoelasticity by using the impedance control method.

To evaluate the effectiveness of the proposed method, the method was applied to a swinging motion of operator's lower leg. The experimental results suggested that the proposed method is useful to use HAL as operator's muscles. As a result of this experiment, we have confirmed the effectiveness of the proposed method.

Acknowledgment

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References

[1] Okamura J., Tanaka H. and Sankai Y. EMG-based Prototype Powered Assistive system for Walking Aid. In Proc. Asian Symposium on Industrial Automation and Robotics (ASIAR'99), Bangkok, Thailand, pp.229-234, (1999).
[2] Nakai T., Lee S., Kawamoto H. and Sankai Y. Development of Power Assistive Leg for Walking Aid using EMG and Linux. In Proc. The 2nd Asian Conference on Industrial Automation Robotics (ASIAR2001), Bangkok, Thailand, pp.295-299, (2001).
[3] Kawamoto H. and Sankai Y. Power Assist System HAL-3 for Gait Disorder Person. In Proc. of International Conference on Computers Helping People with Special Needs (ICCHP 2002), Linz Austria, pp.196-203, (2002).
[4] Gordon K.E. and Ferris D.P. Proportional myoelectric control of a virtual object to investigate human efferent control. Experimental Brain Research, 159, pp.478-486.
[5] Winter D.A., Patla, A.E., Francois F., Ishac M. and Gielo-Perczak K. Stiffness Control of Balance in Quiet Standing. Journal of Neurophysiology 80, pp. 1211-1221, (1998).
[6] Gomi H. and Osu R. Task-Dependent Viscoelasticity of Human Multijoint Arm and Its Spatial Characteristics for Interaction with Environments. J Neurosci, 18, pp. 8965-78 (1998).
[7] Lee S. and Sankai Y. Power Assist Control for Walking Aid with HAL-3 Based on EMG and Impedance Adjustment around Knee Joint. In Proc. of IEEE/RSJ International Conf on Intelligent Robots and Systems (IROS 2002), EPFL, Switzerland, pp.1499-1504, (2002).
[8] Lee S. and Sankai Y. Power assist control for leg with hal-3 based on virtual torque and impedance adjustment. In Proc. IEEE International Conference on Systems, Man and Cybernetics (SMC), Hammamet, Tunisia, TP1B3 (CD-ROM), (2002).
[9] Lee S. and Sankai Y. The Natural Frequency-Based Power Assist Control for Lower Body with HAL-3. In Proc. of IEEE International Conference on System, Man and Cybernetics (SMC), Washington USA, (2003).
[10] Cavanagh, P.R., Komi, P.V. Electromechanical Delay in Human Skeletal Muscle under Concentric and Eccentric Contractions. European Journal of Applied Physiology, 42, 159-163 (1979).
[11] Park, E. and Meek, S.G. Fatigue compensation of the electromyographic signal for prosthetic control and force estimation. IEEE Transactions on Biomedical Engineering, vol. 40, Oct. (1993).