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Power Assist Control for Walking Aid with HAL-3 Based on EMG and Impedance Adjustment around Knee Joint

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Abstract

This paper describes the power assist control for walking aid based on EMG and impedance adjustment with HAL-3 we have developed. Virtual Torque derived from EMG is adopted as a basic control method, and the motion assist control as to operator's intention can be realized by this method. And we suggest the impedance adjustment around knee joint for more effective power assist control. Experiments for simple motion and walking motion were performed to verify the proposed approach, with impedance parameters found by RLS(Recursive Least Square) method. The evaluation of assisted motion was done by Assist Efficiency calculated based on EMG in nearly proportion to the operator's muscle force. The results showed the amplitudes of EMG were reduced significantly, the operator was able to swing the leg lighter by reducing the inertia around knee, and the strain of knee in foot-grounding could be alleviated by adding the stiffness to joint.

1 Introduction

Nursing care and rehabilitation are required to be improved in accordance with aging in several country. It is important to enable physically weak person i.e., the old as well as the disabled to take care of themselves in that society. The spheres of the aged persons who suffer a muscular atrophy, or the persons who have some disorders like as a neuromuscular diseases are restricted in spite of using wheelchair due to stairway or unlevel ground, and it is desirable for such people to walk by themselves with respect to their requirement to move, burden of caregiver, and effectiveness of rehabilitation from the point of view of locomotion. Nevertheless, only few attempts have been made at another device to assist the leg's movement for such people. And now, recent progress of robotics technology brings a lot of benefits in many other fields like welfare, medicine as well as in the industry. In particular, integrating humans and robotic machine into one system offer the opportunities for creating new assistive technologies that can be used in such fields [1, 2]. We have developed the EMG based exoskeleton system for lower body, HAL in recent years for the context as mentioned above [3, 4]. The power assist control of HAL has been performed essentially based on balance of EMG (ElectroMyogram / Myoelectricity) generated on flexor and extensor muscle. HAL can recognize the operator(experimental subject put on HAL)'s condition by sensors, and enables the operator do a motion such as walking by transferring the intention of operator to motivity of actuator through EMG. Our objective in this research is to realize the more effective assisted motion based on EMG with the impedance adjustment around knee joint. This paper describes the hardware configuration of HAL-3 in Section 2, the control method with EMG and impedance adjustment based on estimated parameters in Section 3, the evaluation method derived from EMG and experimental results to verify the proposed approach in Section 4.

2 HAL(Hybrid Assistive Leg)-3

Figure 1 shows the hardware configuration of the exoskeleton type power assist system, HAL(Hybrid Assistive Leg)-3 we developed. All devices for control of HAL-3 such as CPU board, motor driver, measuring units, and power sources(battery) are contained in backpack. So HAL can work alone without external operational environment. Harmonic drive gear and DC servo motor is adopted as actuator of HAL-3, which has sufficient motivity to support human's motion. So the specification of actuator is determined on the basis of human's motion data as maximum angular velocity in walking motion, and maximum torque around joint in standing up motion [5]. HAL-3 can recognize and be operated along to the operator's condition by the sensors attached on main body of HAL-3 for detecting EMG at each flexor and extensor muscle, angle of joints, and floor reaction force beneath the soles. A experimenter can adjust the experimental settings and monitor the operator's con-

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dition constantly with palm-top computer through wireless LAN.

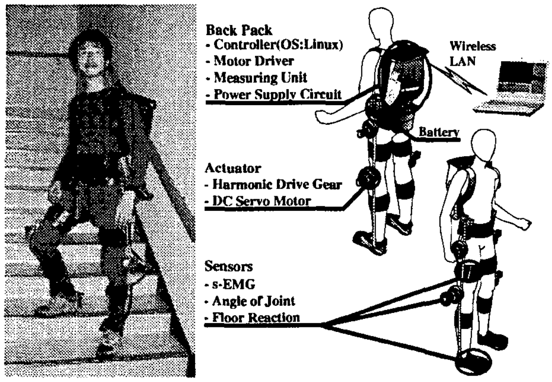

Figure 1: *Hardware configuration of HAL-3*

3 Control Method

3.1 Virtual Torque Based on EMG

The EMG is electric signal that is generated in muscle when it shrinks. So necessary muscle power and the timing of joint's movement can be estimated indirectly through the EMG. The procedure to acquire the EMG signal is indicated as *Figure 2*. For unprocessed EMG is inappropriate to use itself for control, its raw signal is filtered through RMS (Root Mean Square) process after amplified and filtered through the analog circuit [4]. Then, the control of HAL with operator's animus to move can be performed by converting the myosignal balance of flexor and extensor muscle to operational signal of actuator. Actually, estimated torque around joint, called Virtual Torque [6], is found as follows

$$\tau_{virtual}(t) = K_f E_{flx}(t) - K_e E_{ext}(t) \qquad (1)$$

where
$\tau_{virtual}(t)$ Virtual Torque;
K_f, K_e Conversion factor from EMG to torque;
$E_{flx}(t)$, $E_{ext}(t)$ Filtered signal of EMG at flexor and extensor.
The conversion factors were determined by trial and error in former research, and now, these are also decided automatically through simple motion by Neural Network or Recursive Least Square algorithm [6].

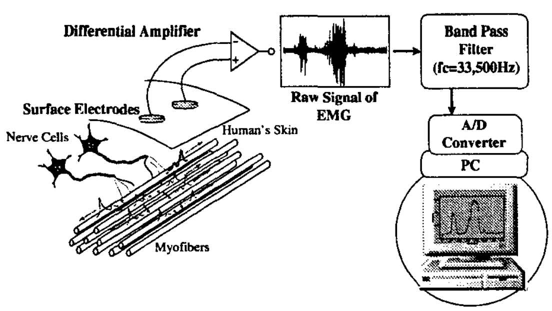

Figure 2: *Measurement and filtering process of EMG signal*

3.2 Virtual Torque with Impedance Adjustment around Knee Joint

The harmonic drive gear and DC servo motor with relatively high torque-to-weight ratio is adopted as the actuator of HAL, but it cannot be operated with flexibility in an ordinary way. Then, we regard that it is possible to perform the more effective assisting control if the characteristics around joints including the exoskeleton can be regulated according to a motion as human enables his/her joints to be flexible or stiff by adjusting the strain of muscle. When muscle force around knee joint is not generated, and external force works to the same direction as torque of actuator, the lower thigh of operator put on HAL-3 can be represented by 1link pendulum model. The motion equation is expressed in this case as equation(2),

$$I\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + C\left(\theta, \frac{d\theta}{dt}\right) = \tau + J^T F_e \qquad (2)$$

where I and D are inertia and viscous coefficient around knee joint, respectively, $C(\theta, \frac{d\theta}{dt})$ is non-linear term including gravity and coulomb friction, τ is torque of actuator, J^T is transposed matrix of Jacobian, and F_e is external force. When the target impedance, M, B, K found based on operator's condition in contacting the environment, and target posture is set, the motion equation can be expressed by equation(3)

$$J^T F_e = M\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K(\theta - \theta_0) \qquad (3)$$

where
M, B, K target value of inertia, viscous coefficient, elastic coefficient;
θ_0 angle of joint in target posture.
In order to regulate the impedance, compensation torque generated by actuator is determined as

$$\tau_{com} = (I - M)\frac{d^2\theta}{dt^2} + (D - B)\frac{d\theta}{dt} + K(\theta_0 - \theta) + C\left(\theta, \frac{d\theta}{dt}\right) \qquad (4)$$

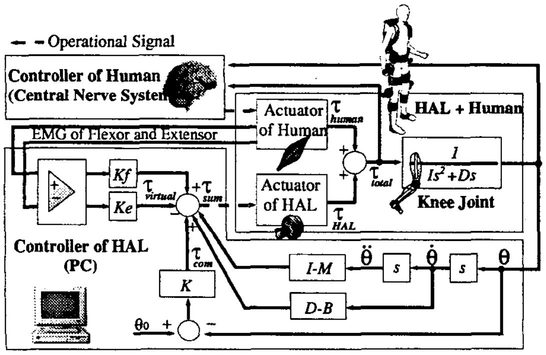

Figure 3: Virtual Torque with impedance adjustment around knee joint

Hence, Virtual Torque with impedance adjustment around knee joint is decided as follows

$$\tau_{sum} = \tau_{virtual} + \tau_{com}$$
$$= K_f E_{flx} - K_e E_{ext} + (I - M)\frac{d^2\theta}{dt^2} + (D - B)\frac{d\theta}{dt} + K(\theta_0 - \theta) + C(\theta, \frac{d\theta}{dt}) \quad (5)$$

Figure 3 shows the block diagram of these process. The power assist control according to operator's intention with variable impedance, inertia, viscous friction, stiffness, can be performed by feedback of detected angle of joint, and calculated angular velocity and acceleration. Non-linear term is omitted in this figure.

3.3 Parameter Identification around Knee Joint with Recursive Least Square (RLS) Method

The parameters around knee joint must be acquired in order to apply the control method mentioned above. RLS method is adopted for parameter estimation in this research. So inertia, viscous coefficient, and mass of joint can be calculated easily all at once (In this paper, the mass of lower thigh doesn't be used to control) . Discrete transfer function of operator's lower thigh is as following form.

$$\frac{\theta(z)}{\tau(z)} = \frac{T^2/2I\left(z^{-1} + z^{-2}\right)}{1 + (DT/I - 2)\, z^{-1} + (mglT^2/I + 1 - DT/I)\, z^{-2}} \quad (6)$$

where

$\tau(z)$ torque generated by actuator (input) ;
$\theta(z)$ angle of knee joint (output) ;
T sampling time (10msec) .

Parameters are represented by coefficient of following ARX model derived from equation(6)

$$\theta(k) + a_1\theta(k-1) + a_2\theta(k-2) = b_1\tau(k-1) + b_2\tau(k-2) + e(k) \quad (7)$$

$$I = \frac{T^2}{2b_1} \quad (8)$$

$$D = \frac{(a_1 + 2)T}{2b_1} \quad (9)$$

$$m = \frac{a_1 + a_2 + 1}{2glb_1} \quad (10)$$

So they can be found by coefficient $a_1 \sim b_2$. If these parameters are unidentified, estimated coefficient vector and recursive vector are represented by

$$\hat{\alpha} = (a_1\ a_2\ b_1\ b_2) \quad (11)$$

$$\varphi(k) = [-\theta(k-1)\ \ -\theta(k-2)\ \tau(k-1)\ \tau(k-2)] \quad (12)$$

$$P(k) = \left(\sum_{t=1}^{k} \varphi(t)\varphi^T(t)\right)^{-1} \quad (13)$$

Then, estimated coefficient vector is found as follows

$$\hat{\alpha}(k) = \hat{\alpha}(k-1) + K(k)\left[\theta(k) - \varphi^T(k)\hat{\alpha}(k-1)\right] \quad (14)$$

$$K(k) = \frac{P(k-1)\varphi(k)}{\lambda + \varphi^T(k)P(k-1)\varphi(k)} \quad (15)$$

$$P(k) = \frac{1}{\lambda}\left[P(k-1) - \frac{P(k-1)\varphi(k)\varphi(k)^T P(k-1)}{\lambda + \varphi^T(t)P(t-1)\varphi(t)}\right] \quad (16)$$

where λ is forgetting factor $(0 < \lambda < 1)$. *Figure 4* shows experimental data of parameter estimation. The experimental subject (operator) is 25-years-old, physically unimpaired male(height: 176cm, weight: 68kg). The operator was seated put on HAL-3 with weakness of muscles, and actuator of knee joint generated the torque randomly for irregular angle pattern. The length between joint and COG was determined as l=0.13[m], initial value of forgetting factor and recursive vector were selected as λ=0.998, $P(0) = \Delta I$, $\Delta = 12000$ in this experiment. Table 2 shows found parameters of both lower thigh. Considering the exoskeleton, these parameters was confirmed as adequate value by [7].

4 Experimental Result

4.1 Evaluation of Assisted Motion

As the amplitude of EMG is nearly commensurate with the torque around joint, the assisted motion by HAL-3 can be evaluated with form as

$$AE = \frac{EMG_{avH} - EMG_{avA}}{EMG_{avH}} \times 100 \quad (17)$$

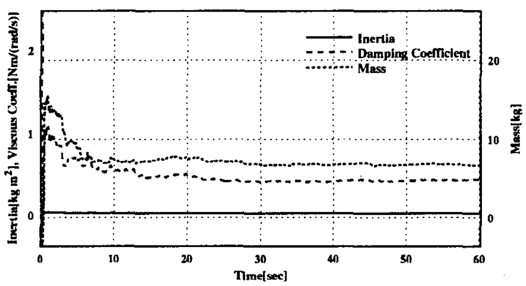

Figure 4: Experimental result of parameter estimation (left lower thigh)

Table 1: Estimated parameter of operator's lower thigh (including exoskeleton)

Parameter	Right Lower Thigh	Left Lower Thigh
Inertia[$kg \cdot m^2$]	0.0185	0.0179
Viscous Coef. [$N \cdot m/(rad/sec)$]	0.41	0.48
Mass [kg]	6.93	6.57

$$EMG_{avA} = \frac{1}{T}\int_0^T EMG_{Assist}(t)dt \qquad (18)$$

$$EMG_{avH} = \frac{1}{T}\int_0^T EMG_{Human}(t)dt \qquad (19)$$

where

AE Assist Efficiency[%];
EMG_{avA} average of EMG (with assist by HAL) ;
EMG_{avH} average of EMG (without assist by HAL);
$EMG_{Assist}(t)$ EMG signal (with assist by HAL) ;
$EMG_{Human}(t)$ EMG signal (without assist by HAL);
T measuring time.

Assist Efficiency is considered as the case of flexor and extensor separately. that is,

AE_{fl} Assist Efficiency of flexor muscle;
AE_{ex} Assist Efficiency of extensor muscle.

e.g., $AE_{fl} = 60\%$ means that HAL generates 60% of torque required to perform the same motion human have done without assist of HAL by flexor muscle.

4.2 Simple Motion Assisted by Virtual Torque with Impedance Adjustment

Figure 5 shows setup of experiment for simple motion. The operator made his lower thigh move up and down as to set target angle and initial angle with assist of HAL-3 in this experiment (at 1sec interval) . The same motion had done without HAL-3 before

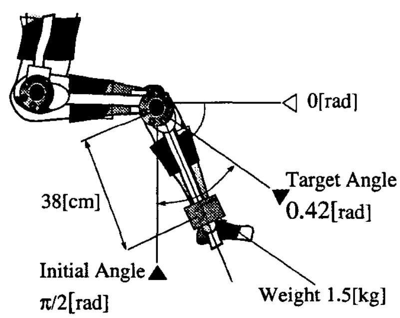

Figure 5: Experimental setup for simple motion

this experiment to compare the amplitude of EMG and calculate the AE. *Figure 6* indicates the experimental results. *Figure 6-(a)* represents the amplitude of filtered EMG and the angle of knee joint in the case of no motion aid by HAL, and *6-(b)* shows the case of motion assisted by HAL with only Virtual Torque ($AE_{fl} = 62\%$, $AE_{ex} = 57\%$) . Though the power assist for same motion was performed according to set target angles, amplitude of EMG in *Figure 6-(c)* is remarkably reduced compared to *Figure 6-(b)*. In this case, AE was calculated as $AE_{fl} = 83\%$, $AE_{ex} = 86\%$, that is, HAL-3 assists the torque of operator by 86% concerning the extensor of knee in the case of inertia-viscosity compensation, and operator can move the lower thigh with less power with his intention to move. In *Figure 6*, e.g., 30% compensation of inertia means reducing 30% of amount from the estimated value of inertia.

4.3 Walking Motion Assisted by Virtual Torque with Impedance Adjustment

Walking motion can be divided into two phases, Support Phase and Swinging Phase, as shown in *Figure 7* Switching impedance adjustment as to these phases enable the walking motion to be performed more efficaciously. The switching is accomplished with foot-grounding information from floor reaction force sensors, i.e., when foot contacts the ground, controller of HAL recognize as Support Phase.

$$if(FG > Threshold)\ phase = SupportPhase; \qquad (20)$$

where FG is acquired value from floor reaction force sensor. Viscous friction and stiffness are compensated in this phase to reduce the strain of knee joint as following

$$\tau_s = K_f E_{flx} - K_e E_{ext} + D\frac{d\theta}{dt} + K(\theta_0 - \theta) \qquad (21)$$

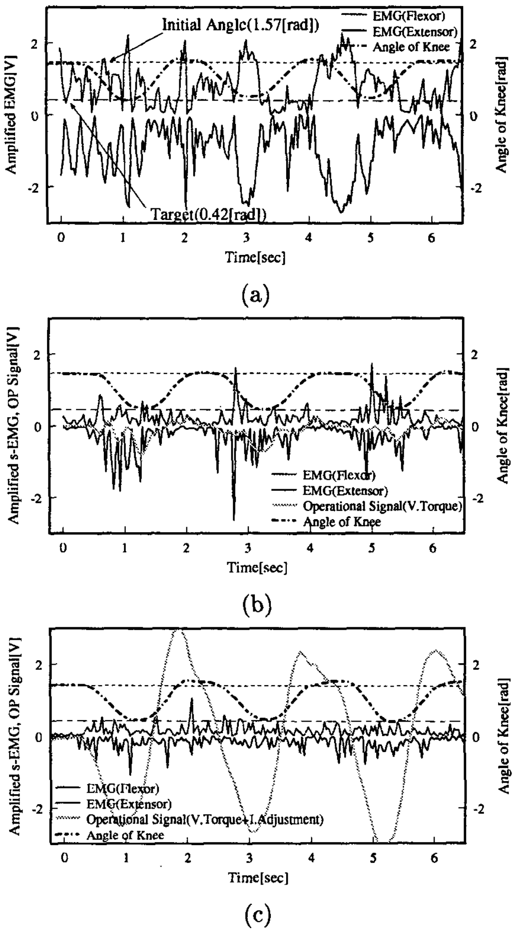

Figure 6: *Experimental result for simple motion (a)no assist with HAL, (b)Virtual Torque, (c)+ inertia* (30%), *viscosity compensation*

On the contrary,

$$if(FG < Threshold)\ phase = SwingingPhase; \quad (22)$$

then, inertia and viscous friction around knee joint are compensated to relieve the constrain and lighten the movement of lower thigh in this phase, Swinging Phase, as

$$\tau_o = K_f E_{flx} - K_e E_{ext} + (I - M)\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} \quad (23)$$

Figure 8 shows experimental data for walking motion assisted with Virtual Torque and impedance adjustment. Shaded portions and non-shaded portion represent Support Phases and Swinging Phases, respectively. Each data was acquired when the operator walked with stride of 40cm, pace of about

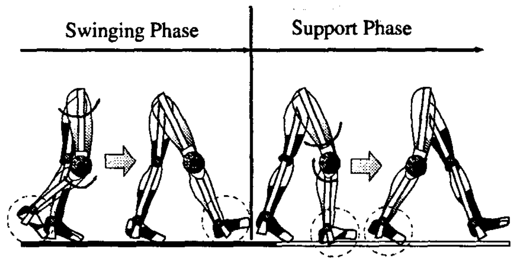

Figure 7: *Support Phase and Swinging Phase*

1m/sec, and walking motion had done by experimental subject (operator) without HAL-3 before experiment to assess the Assist Efficiency. In *Figure 8-(b)*, the amplitude of EMG declines notably at initiation of the Swinging Phase compared with the case of only Virtual Torque, *Figure 8-(a)*. It is clear that inertia(30%)-viscosity compensation in this phase make the operator swing the lower thigh lightly without the restriction. The muscle force of operator is also reduced in the Support Phase. In particular, as the operational signal by Virtual Torque and impedance adjustment is generated to hold the knee joint in foot-grounding owing to stiffness, decrease of EMG at extensor muscle is significant.

5 Discussion

Concerning the experiment for walking motion, the operator was forced to walk with comparatively affected motion in the case of walking with only Virtual Torque. It is thought that knee joints tend to be restrained at times due to viscous friction, and the balance of EMG between flexor and extensor muscle.

Elastic coefficient is calculated on estimated torque around knee joint in Support Phase of walking motion, and the mass of hardware. As the result, the coefficient value up to 10N.m/rad is proper in walking motion. When the property of stiffness is added to knee joint, time period of Support Phase is rather longer than that in the case of only Virtual Torque.

6 Conclusion

The paper has proposed the power assist control for walking motion with HAL-3 using EMG and impedance adjustment around knee joint. As the control method of HAL-3, Virtual Torque based on EMG was adopted, and the motion assist as to intention of operator could be realized by this method. We suggested the impedance adjustment in order to attain the more effective power assist control. Experiment for simple motion and walking motion were performed based on parameters found by RLS method to verify the effectiveness of proposed method. The evaluation of assisted motion was carried out by Assist Efficiency calculated from average of EMG as its amplitude was almost in proportion to torque around joint. We will expand this method up to hip joint so as to carry out the adaptive power assist control to the operator by auto-regulation of each parameter as future works. And in near future, we plan to perform the experiment with person who have functional disorder in the lower body.

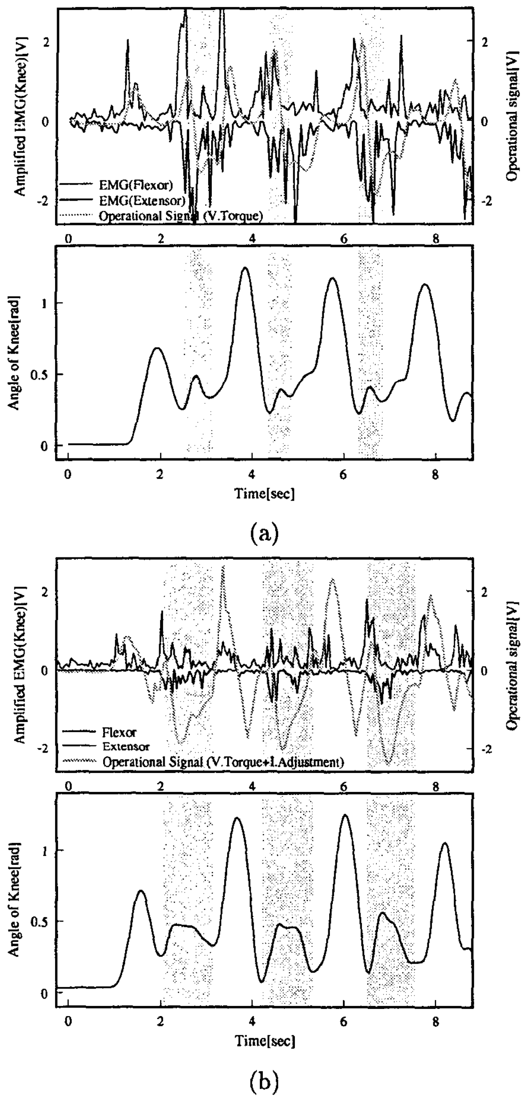

Figure 8: *Experimental result for walking motion (a)Virtual Torque,* $AE_{fl} = 20\%$, $AE_{ex} = 32\%$ *(b)+inertia*(30%), *viscosity, stiffness*($K = 8N \cdot m/rad$) *compensation,* $AE_{fl} = 49\%$, $AE_{ex} = 60\%$

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