Power Assist Method for HAL-3 using EMG-based Feedback Controller *

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Abstract – *We have developed the exoskeletal robotics suite HAL (Hybrid Assisitve Leg) which is integrated with human and assists suitable power for lower limb of people with gait disorder. This study proposes the method of assist motion and assist torque to realize a power assist corresponding to the operator's intention. In the method of assist motion, we adopted Phase Sequence control which generates a series of assist motions by transiting some simple basic motions called Phase. we used the feedback controller to adjust the assist torque to maintain myoelectricity signals which were generated while performing the power assist walking. The experiment results showed the effective power assist according to operator's intention by using these control methods.*

Keywords: HAL, exoskeleton, power assist, Phase Sequence, EMG.

1 Introduction

People with gait disorder can only move around by a wheelchair or by using a wheeled walker. Unfortunately, barriers such as bumps and steps restrict the area that these people have access to. Elderly people who are unable to walk without assistance may lose muscular strength in their legs and become bedridden. Caring for bedridden people entails a large physical burden, and in aging societies such as Japan, this has resulted in a growing perception of this issue as a social problem for the entire community to deal with. The most effective method ensuring that people do not become bedridden is to provide a way for them to be able to continue walking without assistance from a care-giver. So, We have developed the exoskeletal robotics suite HAL (Hybrid Assisitve Leg) which is integrated with human and assists suitable power for lower limb of people with gait disorder[1].

The exoskeleton system is constructed as master/slave system that master is incorporated into slave system. Using the exoskeleton as a master device in a master/slave system enables the operator attached to the exoskeleton (master) to control HAL(slave) and to generate amplified power. In the primary study of the exoskeletal power assist system for the lower limb or the entire body of human, Hardyman was the first attempt in 1960's [2]. Hardyman was developed with the intent to augment lifting and carrying capabilities of soldiers. The human operator manipulate the inner exoskeleton, and the outer exoskeleton driven by hydraulic actuators provided power assist. Hardyman was bulky, unstable, and unsafe for the operator. In 1970's, an exoskeleton assist system of lower limb was designed for the rehabilitation of walking for paraplegia patients [3]. It was actuated by pneumatic actuators. However,it was difficult to assist the leg of the patient with technology of those days. Lately the five-year Exoskeletons for Human Performance Augmentation (EHPA) program, supported by DARPA, is started to develop devices and machines to increase the capabilities of soldiers [4].

In utilizing the exoskeleton as a human power assist, we should consider what kind of motion and how much torque the exoskeleton provides. So, we focus on assist motion and assist torque respectively for the power assist method. The scope of the present research is to propose the method of assist motion and assist torque respectively to according to the operator's intention. 1) For assist motion, we use Phase Sequence method which generates a series of assist motions by transiting some simple basic motion called Phase. 2) For assist torque, we adopt the method to adjust assist torque in according to myoelectricity condition. We adopt these method to HAL system and verify the effectiveness of these method by experiments in power assist walking.

2 HAL system

HAL-3 system is composed of three main parts: skeleton and actuator, controller, and sensor. The schema of HAL-3 system is shown in Fig.1.

Exoskeletal frame consists of a four-link, three-joint mechanism with the links corresponding to the hip ,the thigh, the lower thigh and the foot, and the joints corresponding to the hip, the knee and the ankle joints of the human body. Aluminum alloy and steel are used as the material for the exoskeletal frame in consideration of

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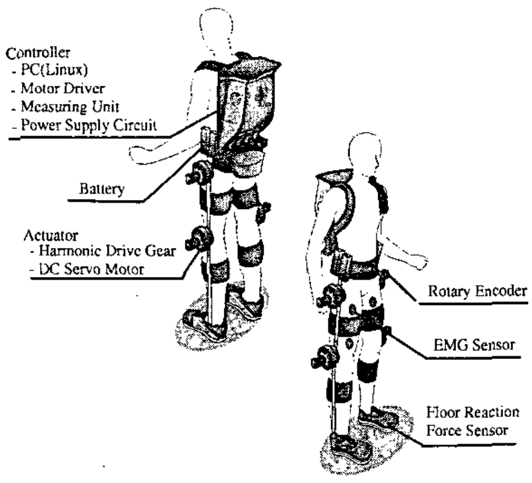

Figure 1: HAL system overview

lightness. The hip and the knee joints have one degree of freedom each, and joint limiters are being equipped at the respective joint to prevent the hyperextension of the hip and the knee joints. This exoskeleton system attaches to the hip, the thigh, the lower thigh and the foot area of the body. At these areas except the foot area, belts which are designed as shell garment of these areas worn by the user are located at each link respectively. At each foot area, a sole is fitted at the end of the lower thigh frame. Since the human lower limb and the exoskeleton are mechanically linked, the movements of both legs of both the human and the exoskeleton are identical. The actuators of HAL-3 provide assist torque for knee and hip joints. Each actuator has a DC-motor with harmonic drive to generate the assist torques at each joint. The total weight of the skeleton system with the actuators is about 15 Kg. The operator does not have to bear the weight load of the exoskeleton, because the weight of the exoskeleton is transmitted to the floor bypassing the soles.

Sensor Systems are equipped on HAL-3 to detect the conditions of HAL and the operator. Rotary encorders are used to measure the hip and the knee joint angles. Floor reaction force (FRF) sensor is developed to measure FRF which are generated in front and rear parts of the foot (ball and heel of foot). This sensor structure is shown in Fig.2. It consists of sole and electronic circuits parts. In the sole of shoe, two coiled polyvinyl chloride tubes (inner diameter 3mm) sandwiched by circular aluminum borboardsds are installed. One end of the tube is connected to a solid state pressure sensor attached on the electronic circuits part. When the foot presses the tube, the air pressure in the tube changes. The change of the air pressure is measured by the pressure sensor. With this, we can detect the floor reaction force from the change of the air pressure. Myoelectricity sensors are attached on the surface of the extensor and the flexor of the knee and the hip to detect muscle activity. Each myoelectricity sensor consists of a bipolar electrode and a preamp, which reduce noise substantially. The myoelectricity signals are first measured through the bipolar skin surface electrodes attached to the skin on top of the muscle, and amplified by 10^6 times, and then filtered using a low pass filter (with cut off frequency at 500 Hz) and a high pass filter (with cut off frequency at 33 Hz) in the back pack to remove noise caused by motion artifact.

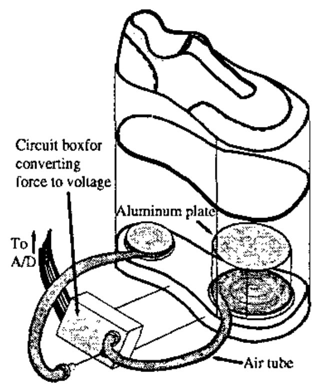

Figure 2: Floor reaction force sensor

The control system of HAL-3 is mainly developed to enhance by the mobility because the field of activities of HAL-3 assistance is expected to be like outdoors activities such as walking in corridors or stairs climbing stairs. So we designed a compact type PC which is the controller, the motor drivers, the power supply for the PC and other circuits, EMG signals processing board and sensor interface boards to be packed in the back pack. For the specification of the PC, CPU is Celeron 566Hz, wireless LAN(Local Area Network) card which has 11Mbps transmission speed, A/D(Analog to Digital) converter card which has 32ch(12bit resolution) inputs and D/A(Digital to Analog) which has 8ch outputs(12bit resolution) are selected respectively. Realtime processing and network communication are required for the control scheme. To make the development environment convenient , we adopt different operating system for measurement process and control process. RT-Linux is used for measurement process. It is able to measure sensor information in real time. On the other hand, we use Linux for the control process. Real-time processing can be achieved in practical use by modifying only one parameter of the Linux kernel source file. So, the control loop is executed in user mode by using this approach which almost guarantees a fixed control period. To monitor sensor information with the remote controller in real time, radio communication using UDP (User Datagaram Protocol) is utilized between HAL controller and the remote controller.

3 Power assist method

3.1 Phase Sequence Control

In this section we describe how to divide series of motion into Phase and how to transit each Phase in order to apply the Phase Sequence method to power assist system HAL-3.

3.1.1 Phase Sequence

Task such as walking is divided into some basic motion called Phase. Each Phase includes motion with a specific intention. Phase sequence is used as a method for transition of motion Phase during task execution for humanoid robots. The humanoid robot is able to generate series of motions like human by the broad motion commands without continuous reference motions for each joint. However it is necessary to divide into Phases accurately according to the aim or the application of the robot system. In the case of the power assist system, the exoskeleton generates the motion to support the operator's force. In series of motions, each muscles generate force mainly based on three conditions, active, passive and free, depending on muscle activity and direction of muscle length contraction as shown in Fig.3. In the case of rectus femoris, the muscle length is shortened as it's contractive force is generated in active mode (Fig.3(a)). It is mainly based upon the contractile element. In passive mode (Fig.3(b)), the muscle length is lengthened as it's contractive force is generated. These muscles play the role of an elastic element. In free mode (Fig.3(c)), the muscle contractive force is not generated, however, the muscle length is shortened. The movement of lower thigh is generated by the inertia force caused by knee acceleration. As the result, the knee joint behaves like the free joint. It should be effective for the power assist to generate assist motions corresponding to the operator's muscle condition. To provide the comfortable assist motion to the operator, each Phase generated by the exoskeleton have to correspond to the Phase which the operator intends. Phase shift timing needs to be determined from the operator's intention or condition. Therefore, we will divide the task into some Phases focused on muscle condition and decide the transit timing of each Phases according to the operator's intention.

3.1.2 Phase division

We analyse the motion of a normal person during each Task(walking) to divide into some Phases. The joint angle is assumed to be proportional to muscle length. The muscle condition are estimated for each Phase from the behavior of myoelectricity signals of the flexor and the extensor, as well as the joint angle of legs. The subject is a normal 28 years old male. Figure 4 shows the joint angles and myoelectricity signals for hip and knee joint, and floor reaction forces in the front and rear parts of the sole of the feet while in walking. Each joint angle is set as 0[rad] in standing posture. Its positive and negative direction indicate flexion and extension respectively. Positive sign of the myoelectricity corresponds to the flexor muscles and negative corresponds to the extensor muscles. The activation level of the myoelectricity is represented in the range of $\pm$ 5[V]. The motion of walking is mainly divided into two phases, the support phase and the swing phase. The swing phase is the behavior that the foot lefts from the ground surface, and the leg swings forward. The support phase is the behavior that the foot stay in contact to the ground surface and the body is supported by the leg. In the swing phase(Phase1), when the hip joint is bent, the myoelectricity signals at the flexor of the hip are generated. The hip flexor works in active mode. At the same time, the knee joint is bent from the extension position, and is extended after that. During the swing period the myoelectricity signals at the flexor and the extensor of the knee joint is generated slightly. It is considered that the lower thigh is to move by the inertial force generated by the thigh. Therefore the knee joint works in the free joint mode. In the support phase(Phase2), when the hip joint is extended, the myoelectricity signals at the extensor of the hip are barely generated. The hip extensor works in active mode. The knee joint is slightly bent from the extension position, and is extended after that. The myoelectricity signals at the extensor of the knee joint is largely generated when the knee joint is bent. The antagonist muscle (the extensor) performs lengthening contraction to absorb the shock to the knee joint from upper body when the foot make contact to the ground surface. Therefore the knee joint would work in passive mode. Figure 5 shows joint part, direction and mode of muscle force conditon in each Phase for walking,

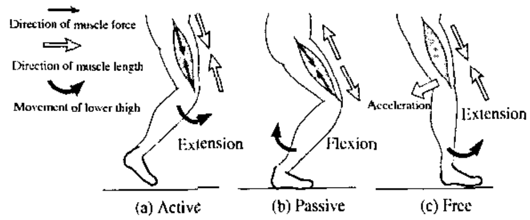

Figure 3: Muscle condition

3.1.3 Phase-shift Timing

To realize power assist by using Phase Sequence, the prepared Phases have to smoothly transited. The Phase-shift Timing need to reflect the operator's intention. If the Phase generated by HAL does not accord to the Phase which the operator intends, HAL may pro-

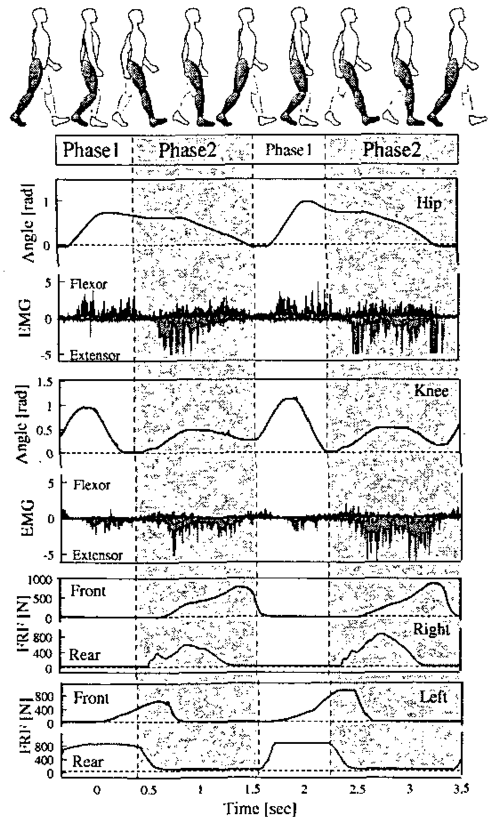

Figure 4: The motion of walking of a normal person

vide unnecessary load to the operator and the operator would feel uncomfortable. In this section, we determine Phase-shift Timing according to the operator's intention on the basis of the motion of a normal person. Most motions of the lower limbs of a person are performed reacting to the floor reaction force (FRF). Therefore, it would be effective to determine Phase shift timing from the condition of FRF.

We focus on the condition of the right floor reaction force for Phase-shift Timing of the right leg. During walking the right leg swings (Phase1 starts), when the rear part of the left foot contacts with the ground surface (Fig.4).At this time, we should be able to detect FRF at the rear part of left foot and this detection can be used as an indication for the start of Phase1. On the other hand, Phase2 starts when the right foot contracts with the ground surface while the ground contact parts of the left foot shifts to the front. As the result we should be able to detect the increasing of the FRF at the front part of the left foot, and use it as the indictor for the start of Phase2. Based on these characteristics of FRF, we set thresholds for FRF at the front and rear part of the left foot which indicate the ground contact. If the the FRF value at the front part of the left foot

	Phase1		Phase2	
Joint	Direction	Mode	Direction	Mode
Hip	Flexion	Active	Extension	Active
Knee	Flexion ↓ Extension	Free	Flexion ↓ Extension	Passive

Figure 5: Joint part, direction and dynamic mode in Phase for Walking

exceeds the threshold of the FRF at the front part of the left foot, Phase1 shifts to Phase2. Subsequently if the FRF value at the rear part of the left foot exceeds the threshold of the FRF at the rear part of the left foot, Phase2 shifts to Phase1. We use the same method to determine the Phase-shift Timing of the left leg based on the FRF of the right foot.

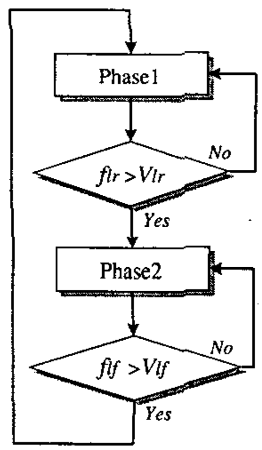

Figure 6: Flow chart in Phase Sequence control of right leg for walking power assist. Where f_{lf} and f_{lr} are represented as the FRF at the front and rear part of left foot, and V_{lf} and V_{lr} are represented as thresholds FRF at the front and rear part of left foot for Phase shift

3.2 Assist torque control

Exoskeleton have to provide appropriate assist torque in order to utilize the power assist according to operator's intention. In this section, we explain the method to adjust assist torque by using myoelectricity signal.

3.2.1 Myoelectricity

The performance of appropriate power assist reduces the burden of muscle. This fact imply the reduction of muscle activation level. Muscle activation level is indicated by Myoelectricity signal. Myoelectricity is action potential generated in a muscle as the command signal from motion control system of human is transmitted to the muscle through the motor nerves. The amplitude of processing myoelectricity signal for joint muscle which is generated by the joint muscle corresponds to the joint torque. So it is considered that the efficiency of assist torque is verified by myoelectricity signal. Here, the following assist ratio is defined as power assist index to evaluate the performance of the power assist. The assist ratio is represented as the ratio between the muscle's activation with and without the exoskeleton assistive in 1. The muscle activation level, as a function of time, was estimated by myoelectricity during Phase.

$$G_A = \frac{A_H - A_{HE}}{A_H} \tag{1}$$

where
A_{HE} muscle activation level of the human during power assist using HAL;
A_H muscle activation level of the human without HAL;
G_A power assist ratio.

$$A_{HE} = \int_0^t u_{assist}(t)dt \tag{2}$$

$$A_H = \int_0^t u_{nonassist}(t)dt \tag{3}$$

where
$u_{assist}(t)$ myoelectricity of the human during power assist using HAL;
$u_{nonassist}(t)$ myoelectricity of the human without HAL.

3.2.2 Feedback controller

We are able to assume that the assist torque and the assist ratio are input signal and output respectively on the power assist system with HAL. In order to perform the power assist according to the operator's intention, we should provide the assist torque which make maintain the assist ratio. Here, we construct a feedback controller which adjusts the assist torque to maintain the assist ratio on the power assist system. When the assist motion for walking is generated using Phase Sequence, same Phase is performed repeatedly. We explain the feedback controller about the assist torque Phase1 (the slowing phase for walking task). The kth time assist torque of Phase1 is determined based on the assist ratio which result from the $(k-1)$th time assist torque of Phase1.

The error between the reference assist ratio of Phase1 and the assist ratio which result from the $(k-1)$th time assist torque of Phase1 is represented as

$$e(k-1) = G_R - G_A(k-1) \tag{4}$$

We achieve feedback control by setting the kth time assist torque equal to addition of the $(k-1)$th assist torque to gain times the error; i.e.,

$$\tau(k) = \tau(k-1) + Pe(k-1) \tag{5}$$

A block diagram of the power assist system with the feedback controller is shown in Fig.7. If the reference assist torque and the previous assist ratio is equal, the previous assist torque is used for the next assist toque. This feedback controller based on myoelectricity signal is motivated by the following idea: in adjusting the assist torque, the myoelectricity is used as feedback information, and assist torque is generated to maintain the assist ratio which is set.

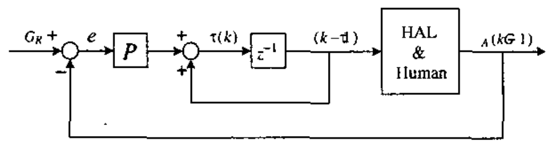

Figure 7: Feedback controller.

4 Experimental verification

The power assist experiments described in this section are performed with Phase Sequence control and the assist torque control defined in chapter 3.

4.1 Phase Sequence Control

In this power assist experiments to provide the assist motion by using Phase Sequence, the power assist is performed for active mode in each Phase. The assist torque in each active mode is adjusted according to each Phase on the base of the operator's suggestion. The assist torque pattern is generated as a rectangular wave. Each threshold of FRF for Phase shift is determined adequately from the exoskeleton performance without power assist. It is considered that the adequate power assist motion make the assisted muscle's activation level reduce comparing to the activation level of normal motion. The effect of the power assist is mainly evaluated from the amplitude of myoelectricity signal which represent the assisted muscle's activation level. The operator is normal 28 years old male. Typical experimental results are shown in Fig.8. Thresholds for FRF at the front and rear part of each foot for Phase shift are set as 560[N] and 80[N] respectively. The assist torques of hip joint on the active modes on Phase1 and Phase2 are 8[N] and -8[N] respectively. The relation between the hip joint angle and the assist torque indicates smooth Phase shift. It is clear that the amplitude of myoelectricity signals of left hip flexor and extensor are respectively reduced in Phase1 and Phase2 relative to the normal walking (Fig.4). This power assist would be realized corresponding with the operator's intention.

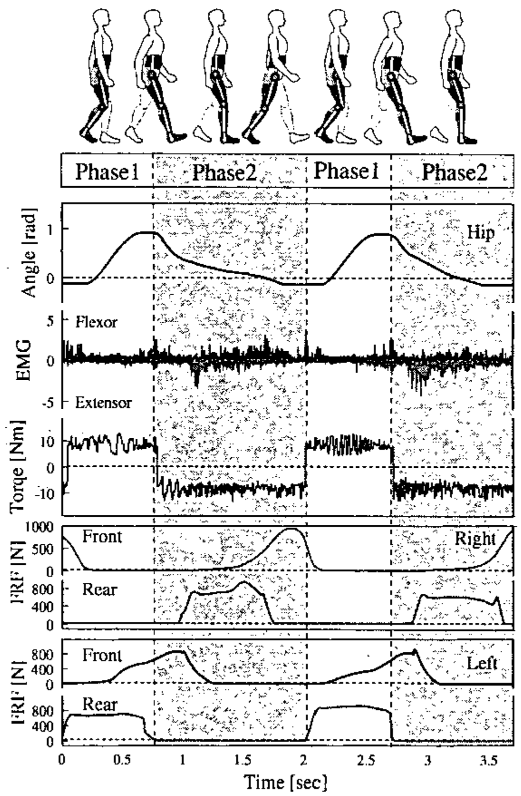

Figure 8: Power assit performances by using Phase Sequence contoller while walking.

4.2 Assist torque control

The power assist was performed by using the feedback controller to provide the assist torque to maintain the assist ratio ($G_R = 0.6$). In this experiments, the feedback controller based on myoelectricity (EMG) is used for hip joint of Phase1. Figure .9 shows the angle, the assist torque, the myoelectricity for right hip joint while power assist of HAL-3 was performed on Phase1 in walking. It is shown that EMG and the assist torque approach the constant values respectively during walking. This result means that the myoelectricity is controlled by adjusting the assist torque.

5 Conclusions

This study proposes a assist motion method using Phase Sequence control and the assist torque control using myoelectricity, respectively to provide the power assist by using Robotics Suits HAL-3. In Phase Sequence control, walking task were analyzed with a focus on the muscle force conditions to divide walking task into some Phases for power assist. The assist motion of hip and knee joint in each Phase of a task was composed of one of active, passive and free mode. To transit each

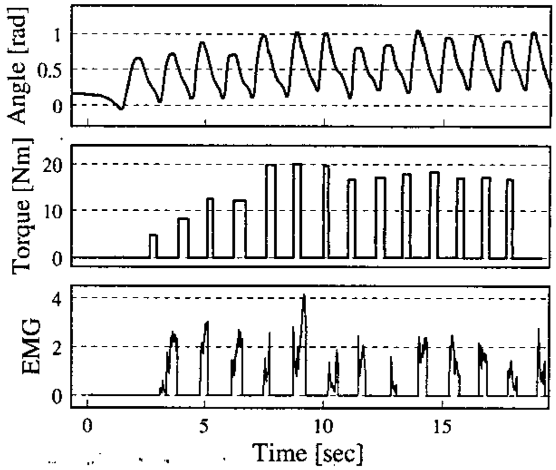

Figure 9: Power assit performances by using the feedback controller while walking.

Phase in the task, floor reaction forces was adopted.. The experiments in the power assist with a focus on the active mode in each Phase of walking was performed. The experiment results showed the effective power assist according to operator's intention by using these control method. In the assist torque control, we used feedback controller to adjust the assist torque. The power assist effect was evaluated by the assist ratio based on myoelectricity signals which were generated while performing the power assist walking. The feedback control was designed to maintain the assist ratio. In this experiment, We adopted this feedback controller for active mode. This control method were regarded as essential to realize the comfortable power assist according to the operator's intention.

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