Proceedings of the 2003 IEEE International Workshop on
Robot and Human Interactive Communication
Millbrae, California, USA, Oct. 31 - Nov. 2, 2003

Power Assist Method for HAL-3 Estimating Operator's Intention Based on Motion Information

Hiroaki Kawamoto, Shigehiro Kanbe, Yoshiyuki Sankai
Sankai Lab., Inst. of Eng. Mech. and Systems, University of Tsukuba
1-1-1 Tennodai, Tsukuba, 305-8573, Japan
Tel/Fax:+81-29-853-5460
E-mail:sanlab-hal@golem.kz.tsukuba.ac.jp

Abstract

This paper describes the recognition method and the control method to realize the power assist which reflects operator's intention by grasping the interaction between operator's intention and motion information. The basic control method for HAL had been performed by using myoelectricity which reflects operator's intention. As the application of the basic method, we considered the control method of power assist based on another information by considering the relation between myoelectricity and another information of motion, and the recognition method for the control method. We adopted Phase Sequence control which generated a series of assist motions by the transition of some fundamental motions called Phase. The result of experiments showed the effective power assist which reflected operator's intention by using this control method.

1 Introduction

The researches for lower body power assist system HAL (Hybrid Assistive Leg) have been done as one of such appliance in our lab.[1]. The basic control method for HAL is performed by using myoelectricity which reflects operator's intention[2]. As the application of this basic method, we considered the control method of power assist by considering the interaction between myoelectricity and another information of motion. In addition, it is necessary to recognize operator's condition to perform correct power assist for the control method. In this research, we propose the recognition method and the control method to realize the power assist which reflects operator's intention by grasping the interaction between operator's intention and the information of motion. We focused on floor reaction force (FRF) as the information which was considered the interaction with myoelectricity. FRF enables the control of HAL to know the operator's intention earlier than operator's motion, and uncomfortable power assist as against EMG-based power assist[3]. We analyzed the interaction between transition of myoelectricity and the behavior of FRF, and performed power assist by using FRF as the input for the control, and considered the assist motion for the active movement in walking and standing up. In order to realize the recognition method and the power assist control which reflects operator's intention, we adopted Phase Sequence which generates a series of motions by the transition of some fundamental motions called Phase.

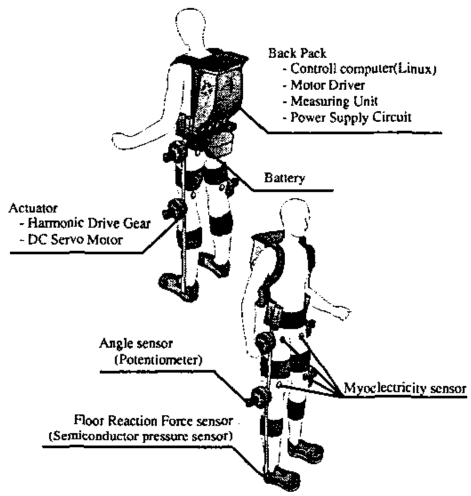

Figure 1: *HAL system overview*

2 HAL system

The system configuration of HAL-3, is shown in Figure 1. The HAL-3 consists of actuator, exoskeletal frame, sensor system and controller. The actuator used in HAL-3 is DC servo motor attached with the harmonic drive gear, which can generate the enough assist force on the hip and the knee joints. Each joint of exoskeletal frame has 1DOF, and has the same limitation of the movable range as a human. The frame is fixed to leg of experimental subject (operator) with molded plastic, and transmits the torque of actuator to the leg. The sensor system which consists of angular sensors, FRF sensors and myoelectricity sensors, are used to cognize the motion information of the HAL-3 and the operator. The small size potentiometer as angular sensors are attached to the each joint to measure the each joint angle. The FRF sensors are implanted in the front and rear of shoe sole of the foot utilizing the semiconductor-type pressure sensors. The myoelectricity sensors which electrodes and amplifiers make up are attached on the surface of the skin of the leg to estimate the muscle activity and the joint torque of the knee and hip joints. A compact type computer, motor driver, the measurement unit, power supply unit are contained in backpack as the controller of HAL-3. The controller can acquire the measured data, and control the actuators in real time. Furthermore by the battery included in the powersupply unit, it is possible for HAL-3 to act as the stand-alone system[2].

3 Control and recognition method

This section describe how to divide series of motion into Phase and how to transit each Phase in order to apply the Phase Sequence method to control method to control of HAL, and how to recognize operator's condition.

3.1 Phase Sequence

We adopted Phase Sequence as assisting control method of HAL. In this method, a sequence of motions is divided into several kinds of motion like standing up, walking. We named these divided motions Task. Additionally, Task is divided into fundamental motion. For example, bending body forward, swinging up leg, etc. We defined these elements of the motion as Phase. Each Phase includes motion with a specific intention. A Task is accomplished by rearranging and linking related Phases. In order 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 Phase according to the operator's intention with focus on FRF.

3.2 Phase division and detection of Phase shift timing

The subject was a normal 28 years old male. We analyzed the motion of a normal person during each Task(walking and standing up) to divide into some Phases and to determine Phase shift timing. The joint angle was assumed to be proportional to muscle length. The muscle conditions were estimated for each Phase from the behavior of myoelectricity signals of the flexor and the extensor, as well as the joint angle of legs. For determination of Phase shift timing, it was necessary to transit the prepared Phases smoothly to realize power assist by using Phase Sequence. So it was thought that the Phase shift timing needed to reflect the operator's intention. If the Phase generated by HAL does not accord to the Phase which the operator intends, HAL may provide unnecessary load to the operator and he would feel uncomfortable. Most motions of the lower limbs of a person are performed reacting to the FRF. Therefore, it would be effective to determine Phase shift timing from the condition of FRF.

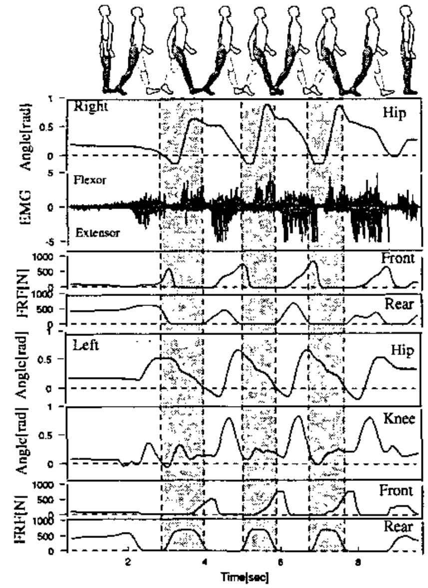

Figure 2: *The motion of walking of a normal person*

3.2.1 Walking

In walking motion, we consider the movement of hip joint as the active movement. Figure 2 shows the joint angles and myoelectricity signals of hip joint, and FRF in the front and rear parts of the sole of the feet while in walking Task. Each joint angle was set as 0[rad] in standing position. Its positive and negative direction indicated flexion and extension respectively. Positive sign of the myoelectricity corresponded to the flexor muscles and negative corresponded to the extensor muscles. The activation level of the myoelectricity was represented in the range of ± 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(Phase 1), when the hip joint was bent, the myoelectricity signals at the flexor of the hip were generated. In the support Phase(Phase 2), when the hip joint was extended, the myoelectricity signals at the extensor of the hip were barely generated. We determined the Phase shift timing, and estimated the start and end motion of walking by the result of division into Phases were considered. During walking the right leg swings (Phase 1 starts), when the rear part of the left foot contacted with the ground surface. At this time, we should be able to detect FRF at the rear part of left foot and this detection could be used as an indication for the start of Phase 1. On the other hand, Phase 2 started when the right foot contracted with the ground surface while the ground contacted parts of the left foot shifted 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 used it as the indicator for the start of Phase 2. Based on these characteristics of FRF, we set thresholds for FRF at the front and rear part of the left foot which indicated the ground contact. If the FRF value at the front part of the left foot exceeded the threshold of the FRF at the front part of the left foot, Phase 1 shifts to Phase 2. 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, Phase 2 shifts to Phase 1. We used the same method to determine the Phase shift timing of the left leg based on the FRF of the right foot. When operator started and stopped walking, FRF value shows characteristic behavior. We analyzed FRF to recognize the start and end of walking motion. In Figure 2, operator starts walking, and then FRF at front part of right foot increased before left leg swings. This behavior of FRF showed that the center of gravity was moving forward. So we set this behavior of FRF for the detection of the start of walking. We focused on the condition of FRF of the supporting leg to estimate the end of walking motion. In Figure 2, we compared the condition of FRF at the front part of the right leg at the time operator stops walking and FRF at the front part of right leg at the time operator keeps walking. The increasing of FRF at the front part of right leg at the time operator stopped walking was lower than the increasing of FRF

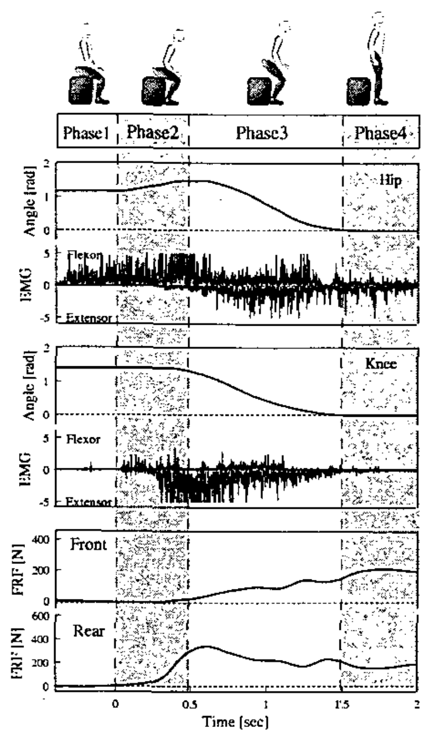

Figure 3: *The motion of standing up of a normal person*

at the front part of right leg at the time operator kept walking. So we should be able to detect FRF at the front part of right leg and this detection could be used as the indicator of the end of walking motion. As the result of the analysis for walking motion, it was estimated that the FRF at front sole of supporting leg shows initial stage of the operator's motion.

3.2.2 Standing up

Figure 3 shows the normal standing up. The motion of standing up from a chair is mainly divided into four Phases. Phase 0: sitting position, Phase 1: the upper body is bent forward. Phase 2: the upper body is lifted as the angles of hip joints attained the maximal value. Phase 3: standing position. Especially, Phase 1 and Phase 2 are important to assist standing up. We analyzed the muscle condition of dynamic motions from myoelectricity signals on Phase 1 and Phase 2. In Phase 1, myoelectricity signals were generated by the flexor of the hip, and the extensor of the knee, when the hip joint was flexed, the knee joint was slightly extended. In Phase 2, when the hip and knee joints were extended, myoelectricity signals are generated by the extensors of both joints. Because each muscle performed shortening contraction in Phase 1

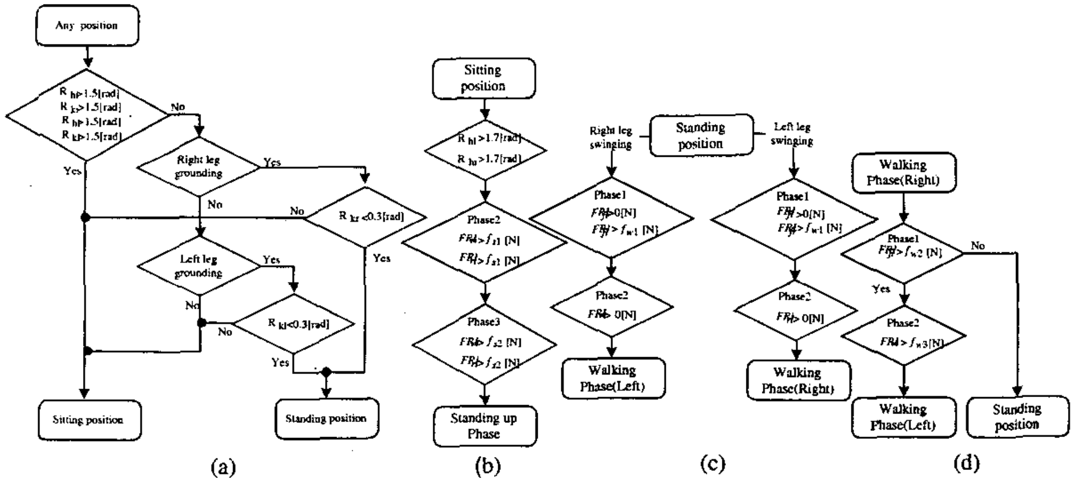

Figure 4: *Flow chart of recognition of operator's position (a), standing up in Phase Sequence (b), starting to walk in Phase Sequence (c), walking and stop walking in Phase Sequence(d).*

and Phase 2 respectively. We considered the active movement as movements of Phase 2 and Phase 3, and determined the Phase shift timing base on this analysis. As shown in Figure 3, while the upper body was slightly bent forward from sitting position (Phase 1), the rear FRF was detected. So, as the rear FRF threshold which indicated the upper body bend was attained, Phase 1 was changed into Phase 2. When the upper body began to be lifted, the rear FRF exceeded approximately 80% of the maximum value. As the rear FRF fulfilled the above condition, Phase 2 was changed into Phase 3. Finally, when hip and knee joint angles attain 0.3[deg], Phase 3 was changed into Phase 4.

3.3 Recognition method

By applying the analysis of the human motion, we realized to recognize method of the operator's motion. This method is configured with 1) detection method of grounding, 2) estimation method of position and 3) estimation method of the movement.

3.3.1 Detection method of grounding

Grounding is the condition which the operator's foot contacts on the ground surface. The grounding was detected by FRF of each part(front and rear, right and left). The threshold value for grounding was preset at 50[N] by the pre-experiment. And if the FRF value was larger than 50[N], we decided that the operator's leg contacted the ground surface. This detection method was applied to front and rear sole respectively.

3.3.2 Estimation method of position

To estimate the operator's position which reflects the operator's next motion, the joint angle is measured after the grounding is used. For example, when the right leg is grounded and the right knee joint angle attain the threshold preset as 0.3[rad] by the pre-experiment, the current position is determined as the standing position, and when the hip and the knee joint of the grounded legs are extended, the operator's position is determined as the standing position.

3.3.3 Estimation method of motion

Figure 4(a),(b),(c),(d) shows the flowchart of estimation method of position (Figure 4(a)), standing up (Figure 4(b)), starting to walk (Figure 4(c)), and walking and stopping walking (Figure 4(d)) in Phase Sequence where,

R_{rh}:Right hip angle	R_{rk}:Right knee angle
R_{lh}:Left hip angle	R_{lk}:Left knee angle
FRF_{rf}:FRF right front	FRF_{rr}:FRF right rear
FRF_{lf}:FRF left front	FRF_{lr}:FRF left rear

The threshold for the recognition was decided by using the result of analysis. Figure 4(b),(c),(d) show each Phase of the operator's motion which was recognized by HAL. In Figure 4.(b), f_{s1} and f_{s2} were represented respectively as the threshold when upper body begins to bend forward and the threshold when hip and knee joint begins to extend. The start of standing up motion was recognized as Phase 2. In Figure 4(c), f_{w1} represented the threshold which was FRF of front sole in supporting leg at the time of the operator starts walking. In Figure 4(d), f_{W2} represented the threshold which was FRF of front sole in supporting leg at the time of the operator stops walking, and f_{W3} represented the threshold when operator's foot contacts on the ground surface while walking. For example, when the operator starts walking, he is standing, and then the FRF value of front sole in right leg is larger than f_{W1}. We decided that the operator started walking.

4 Experimental verification

The experiments for power assist control and the recognition method described are performed with Phase Sequence. In these experiments, power assist was performed for active movement in each Phase. The assist torque in each active movement is adjusted by trial and error. The assist torque is generated in a rectangular wave pattern[3]. Each threshold of FRF for Phase shift and recognition are determined adequately from the exoskeletal 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.

4.1 Power assist control

4.1.1 Walking

The experimental results for walking motion are shown in Figure 5. Thresholds for FRF at the front and rear part of each foot for Phase shift were set as 560[N] and 80[N] respectively. The assist torques of hip joint in Phase 1 and Phase 2 were 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 Phase 1 and Phase 2 relative to the normal walking (Figure 5). This power assist would be realized corresponding with the operator's intention.

4.1.2 Standing up

Thresholds for Phase shift needed to transit from Phase 1 to Phase 2 and from Phase 2 to Phase 3 were set as 50[N] and 290[N] respectively. The assist torque of hip and knee joint in Phase 1 were 12[N] respectively. That of Phase 2 were 16[N]. Figure 6 shows the exoskeleton performance on the left leg while standing up. The amplitude of myoelectricity signals of the left hip flexor and the knee extensor are respectively reduced in Phase 1, and the both of extensors are reduced in Phase 2 relative to the normal standing up. As Phase 2 is changed into Phase 3, the hip joint angle did not indicate smooth Phase transition comparing to the normal standing up (Figure 6). It would be attributable to the rapid direction change of

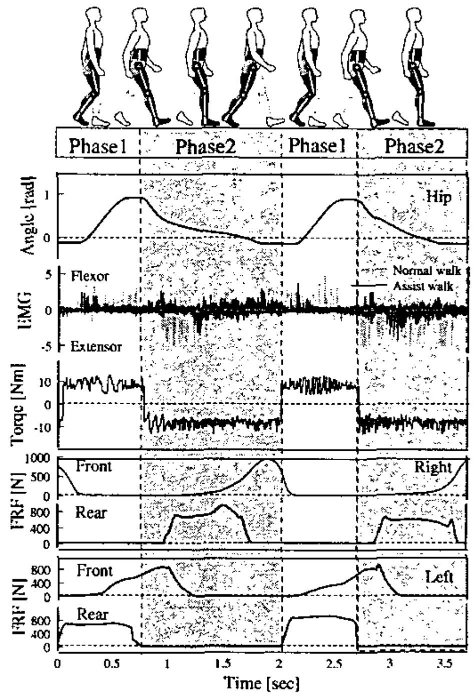

Figure 5: *Power assist performances by using Phase Sequence controller while walking.*

the assist torque while changing from the flexion to the extension of hip joint due to the rectangular wave as the assist torque pattern in each Phase. However, this power assist processes satisfied the operator. We got the comment from the operator that he obtained the comfortable and smooth power assist according to the operator's intention. Therefore, It is important to focus on the timing (or switching) of the assist torque rather than the trajectory or the pattern of joint angles in order to perform the adequate power assist.

4.2 Recognition of operator's condition

The experiment in a sequence of motion which consisted of standing up and walking were performed by Phase Sequence based on recognition method mentioned above. Figure 7 shows the joint angle, FRF, and Task. Task is the condition of the operator which was recognized by HAL. The relationships between each Task and the operator's condition are defined as

Task0:Standing posture
Task1:Sitting posture
Task2:Walking motion
Task3:Standing up motion

In recognition method, f_{S1} and f_{S2} were represented the threshold which was same value as the threshold

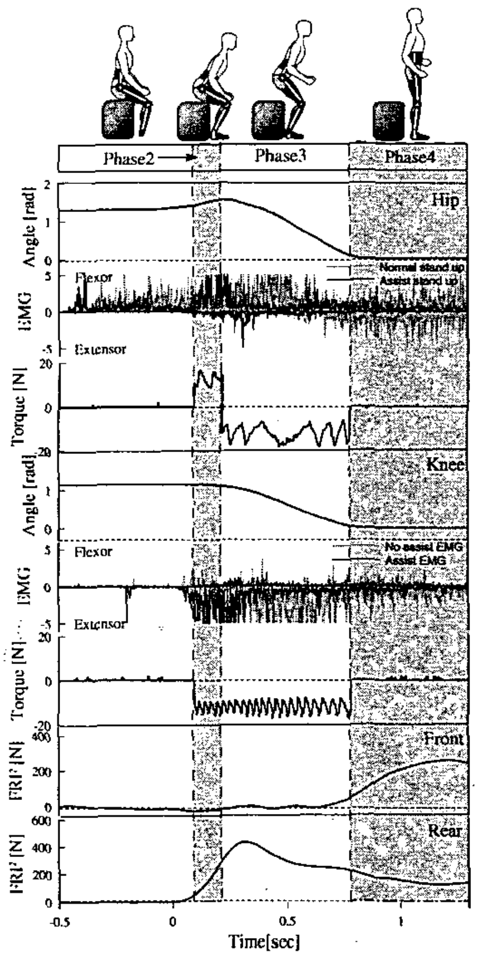

Figure 6: *Power assist performances by using Phase Sequence controller while standing up.*

of power assist for standing up at Phase 2 and Phase 3 respectively. f_{W1} was set as 250[N], and f_{W2} and f_{W3} were represented the threshold which was same value as the threshold of power assist for walking. In Figure 7, Tasks transits smoothly based on the joint angle and FRF. So the recognition system was able to cognize the start of operator's motion, and end of operator's motion.

5 Conclusion

This research proposed the method for recognition of operator's condition and the control method to realize the power assist which reflected operator's intention by grasping the interaction between operator's intention and the information of motion. Phase Sequence control was adopted to realize these methods. In Phase Sequence, standing up and walking tasks

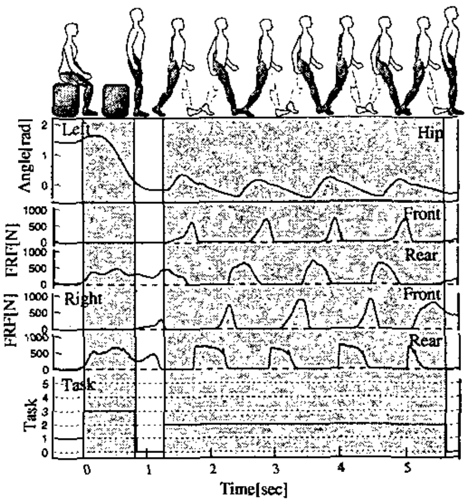

Figure 7: *Recognition method for a sequence of motions which consisted of standing up and walking.*

were analyzed with a focus on the relation between myoelectricity and FRF to divide tasks into some Phases for power assist. The recognition method were applied for a sequence of motions which consisted of standing up and walking. The experimental results showed the effective power assist which reflected operator's intention, and recognized operator's condition. As future work, we will also allow to develop control algorithm based on another parametor or programing technique which determines assist torque and transition level of each Phases for various operators.

References

[1] J. Okamura, H. Tanaka, Y. Sankai, "EMG-based Prototype Powered Assistive System for Walking Aid", Proc of ASIAR'99, pp.229, 1999

[2] Takao Nakai, Suwoong Lee, Hiroaki Kawamoto, Yoshiyuki Sankai, "Development of Power Assistive Leg for Walking Aid using EMG and Linux", ASIAR2001, Bangkok, Thai, pp.295-299, 2001

[3] H. Kawamoto,Y. Sankai, "Comfortable Power Assist Control Method for Walking Aid by HAL-3", Proc. of IEEE SMC, CD-ROM, 2002

[4] M.Vukobratovic,A.Tuneski," General Mathematical Model of Multiple Manipulators: Cooperative Compliant Manipulation on Dynamical Environment", Mechanism and Machine Theory, u stampi, 1997