Proceedings of the 2004 IEEE International Workshop on Robot and Human Interactive Communication
Kurashiki, Okayama Japan September 20-22, 2004

Power Assist Method Based on Phase Sequence Driven by Interaction between Human and Robot Suit

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Abstract

In this paper, we proposed a power assist method for leg based on the autonomous motion driven by the interaction between human and the robot suit, HAL (Hybrid assistive limb) and verified the effectiveness of this method in the experiments in walking. In order to perform walking task autonomically, we used Phase Sequence control which generates a task by transiting some simple basic motions called Phase. A task was divided into some Phases on the basis of the task performed by a normal person. The joint moving modes were categorized into the active, passive and free modes according to the characteristic of the muscle force conditions. The autonomous motion which HAL generates in each Phases were designed according to one of the categorized modes. The floor reaction force and joint angle were adopted as the condition to transit each Phase. The experiments in power assist were performed for normal person. The experiment results showed that the muscle activation level in each Phase were significantly reduced. With this, we confirmed the effectiveness of the proposed assist method.

1 Introduction

Exoskeleton robots have been studied in order to amplify human muscle strength. An exoskeleton consists of an external structure which covers human body parts and has joint parts corresponding to those of human body. The physical contact between the operator and the exoskeleton causes the integration of the operator and the exoskeleton. The exoskeleton directly provides mechanical power for the operator. Recently the exoskeleton for human arms and their control methods have been studied in order to extend human arms' strength in order to reduce the burden imposed on the operator by an external load[1, 2]. On the other hand we have developed the exoskeleton powered suit for lower limb to provide power necessary to perform tasks such as walking, standing up, etc. We have proposed the power assist method using the joint torque estimated based on the myoelectricity signals that reflect the operator's intention[3, 4].

An autonomous motion generated by an exoskeleton robot moves the human's body directly. The human becomes a part of the exoskeleton system and the exoskeleton robot operates the human's body. The exoskeleton robot can take the place of the wearer's body function by performing motion like human autonomically. If the exoskeleton robot has realized the tasks such as walking, standing up and so on, the exoskeleton could be used as a function aid apparatus for gait disorder persons with spinal cord injury. Our research goal is to develop the autonomous motion method of the exoskeleton robot in order to aid human leg motion.

In utilizing the exoskeleton robot as a human motion assist apparatus, the exoskeleton should provide motions like human. We have developed Phase Sequence method, using human motion characteristics, that enables Humanoid robots to generate human-like motions[5]. Phase Sequence is the method to generate tasks such as walking, standing up and so on by transferring some prepared motion elements called Phases. A take is analyzed based on kinematic and biological information and divided into some Phases according to the specific motion intentions like "swing the leg" or "lifting the body". For each task, a sequence of Phases is transformed into the motion for the humanoid robot. As the result, the humanoid robot performs the task motions like human. We attempt to adopt Phase Sequence method to control the

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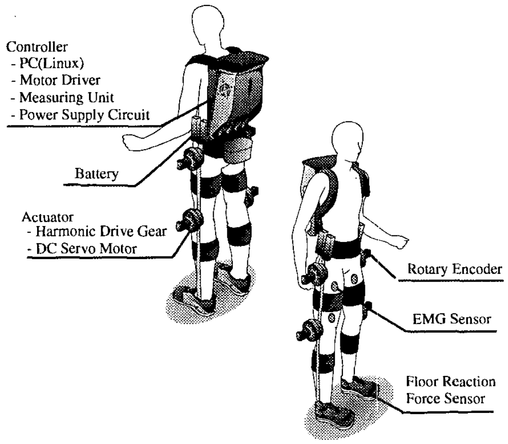

Figure 1: HAL-3 system.

autonomous motions of the exoskeleton robot.

As the wearer and exoskeleton robot are driven by the interaction between human and the exoskeleton robot, we consider that the motion properties generated by the exoskeleton robot accord to that performed by the wearer. The human realizes tasks using a variety of joint motions based on some modes of muscle activity. So we consider that the exoskeleton robot should use to generate motions corresponding to joint the motions based on modes of muscle activity which normal person performs. In this study, we propose the Phase Sequence method based on the modes of muscle activity for autonomous motion of the exoskeleton robot HAL. We divide tasks of going up and down stairs into the Phases according to the joint motion characteristics based on muscle activity. And we realize the motion assist for these tasks by performing and transform Phases using HAL.

In the following Chapter 2, the details of the exoskeleton robot HAL-3 is described, and the task of walking is divided into Phases respectively and Phase-shift Timing for each task is determined. We construct the Phase Sequence control algorithm to generate assist motions. In chapter 3, we experiment on power assists with the Phase Sequence control. In chapter 4, we discus experimental results. In chapter 5, we gives a brief conclusion.

2 HAL-3 system

HAL-3 system is composed of three main parts: skeleton with actuator, controller, and sensor. The schema of HAL-3 system is shown in Fig.1. Exoskeletal frame consists of a three-link, two-joint mechanism with the links corresponding to the hip ,the thigh and the lower thigh, and the joints corresponding to the hip and the knee joints of the human body. The knee joint of the exoskeleton has one degree of freedom. The ankle joint has also one degree of freedom, dorsiflexion-planterflexion. This exoskeleton system attaches to the hip, the thigh, the lower thigh and the foot area of the body. 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. We consider that the ankle joints play a important role in maintaining stability in support phase. The total weight of the skeleton system with the actuators is about 15 Kg. The wearer does not have to bear the weight load of the exoskeleton by riding in the soles 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 wearer. 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). 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 control system of HAL-3 is mainly developed to enhance the mobility because the field of activities of HAL-3 assistance is expected to be like outdoors activities. 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. 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.

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3 Assist method

3.1 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.2.

In the case of rectus femoris, the muscle length is shortened as it's contractive force is generated in active mode (Fig.2(a)). It is mainly based upon the contractile element. In passive mode (Fig.2(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.2(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.

3.2 Phase division

We analyse the motion of a normal person during walking to divide into some Phases according to three modes based on muscle activity and direction of muscle length. The joint angle is assumed to be proportional to muscle length. The muscle activity are estimated from the behavior of myoelectricity signals of the flexor and the extensor. The subject is a normal 28 years old male.

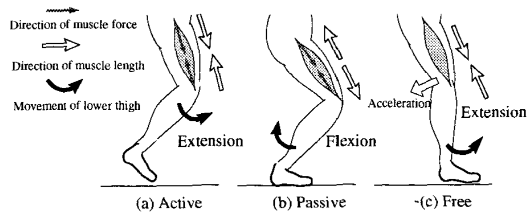

Figure 2: Muscle condition.

Fig.3 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 three phases. Phase 1 is the swing phase that the foot lefts from the ground surface, and the leg swings forward. Phase 2 is the behavior that the leg is slightly lowered in order to contact the foot to the ground surface. Phase 3 is the support phase that the foot stay in contact to the ground surface and the body is supported by the leg.

In Phase 1, 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 forced to move by the inertial force generated by the thigh. Therefore the knee joint works in the free joint mode.

In Phase 2, when the hip is extended slightly and the knee is lifted slightly, the myoelectricity signals at the flexor and the extensor of both joints is generated slightly. Each joint works in free mode.

In Phase 3, 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

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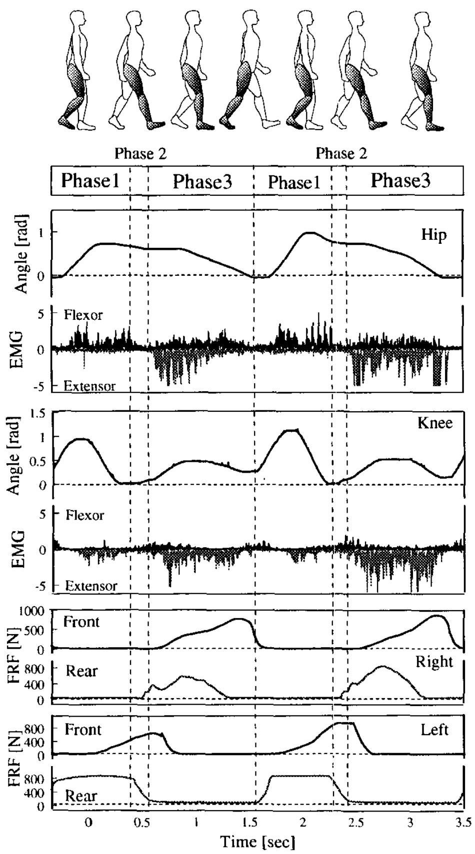


Figure 3: Motion analysis for walking.

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.

As explained above, Fig.4 shows the joint part, direction and torque mode in each Phase for walking.

3.3 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 wearer's intention. If the Phase generated by HAL does not accord to the Phase which the wearer intends, HAL may provide unnecessary load to the wearer and the wearer would feel uncomfortable. In this section, we determine Phase-shift Timing 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 left floor reaction force for Phase-shift Timing of the right leg. During walking the right leg swings (Phase 1 starts), when the rear part of the left foot contacts with the ground surface (Fig.3). 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 Phase 1. Phase 2 starts when 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 Phase 2. Phase 3 starts when the right foot contracts with the ground surface. At this time, we should be able to detect FRF at the rear part of right foot and this detection can be used as an indication for the start of Phase 3.

Based on these characteristics of FRF, we set thresholds for FRF at the front and rear part of the left foot and rear part of the right foot(V_{lf}, V_{lr}, V_{rr}) which indicate the ground contact. If the FRF value at the front part of the left foot (f_{lf}) exceeds the threshold of the FRF at the front part of the left foot (V_{lf}) during Phase 1, Phase 1 shifts to Phase 2. Subsequently if the FRF value at the rear part of the right foot (f_{rr}) exceeds the threshold of the FRF at the rear part of the right foot (V_{rr}), Phase 2 shifts to Phase 3. If the FRF value at the rear part of the left foot (f_{lr}) exceeds the threshold of the FRF at the rear part of the left foot (V_{lr}), Phase 3 shifts to Phase 1.

We use the same method to determine the Phase-shift Timing of the left leg based on the FRF of the right foot. The flow chart of Phase Sequence in walking power assist for right leg is shown as Fig.5.

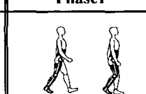
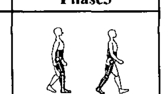
	Phase1		Phase2		Phase3	
						
Joint	Direction	Mode	Direction	Mode	Direction	Mode
Hip	Flexion	Active	Extension	Free	Extension	Active
Knee	Flexion ↓ Extension	Free	Flexion	Free	Flexion ↓ Extension	Passive

Figure 4: Joint torque modes for walking motion.

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each Phase is defined using the average myoelectricity signal.

$$A = \frac{1}{T_p}\int_{t_s}^{t_s+T_p} E(t)dt \tag{1}$$

where, $E(t)$ is myoelectricity signal. t_s and T_p represent the start time and the period of each Phase. The effect of the power assist is evaluated by the comparison between the muscle's activation level with and without power assist. The wearer is a normal 28 years old male.

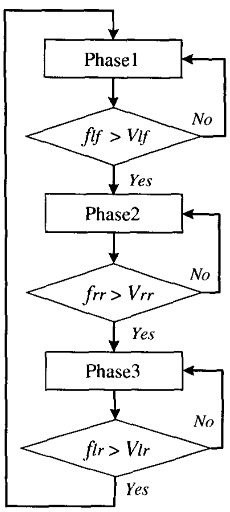

Figure 5: Phase Sequence control argolism for walking power assist of right leg.

4 Experiment

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 Protocol

The power assist experiments described in this section are performed with the Phase Sequence control defined in Chapter 3. The assist torque pattern of each Phase is shown in Table 1.

In case of Phase 1, the assist torque of the active mode in hip joint is generated as constant torques in the direction of the flexion and the assist torque of the free mode in knee joint is generated as the torque needed to compensate the inertia force of the exoskeleton's lower thigh in order to perform the movement of the wearer's lower thigh like a pendulum comfortably. In case of free mode for both joints in Phase 2, the assist torques are not generated. In case of Phase 3, the assist torque for active mode in hip joint is generated as constant torques in the direction of the extension, and for passive mode in knee joint is controlled by PD controller based on the knee joint angle and velocity. The assist torque parameters for each mode was adjusted on the wearer's feedback suggestions.

It is considered the assisted muscle's activation level of the adequate power assist motion is reduced comparing to the activation level of the motion without the power assist. The muscle's activation level during

4.2 Result

In this experiment, the parameters in Table 1 are set as $\tau_{hip1} = 12[N]$, $\beta = 0.8$, $\tau_{hip3} = 4[N]$, $K_p = 7$ and $K_p = 0$ respectively. Thresholds of FRF for Phase shift in Fig. 5 are set as are set as $V_{lf} = 640[N]$, $V_{rr} = 180[N]$ $V_{lr} = 180[N]$ respectively.

Figure 6 shows the hip and knee joint angles, myoelectricity signals and assist torques for hip and knee joint, and FRF in the front and rear parts of both feet during walking with power assist. The relation between the hip and knee joint angles and the assist torques indicate smooth Phase shift. Figure 7 shows the the averages and standard deviations of the muscle's activation levels at the hip flexor in Phase 1 and the hip extensor in Phase 3, during the tenth steps of the right leg with and without power assist respectively. It is obvious that the muscle's activation levels with the power assist are reduced compare to that without power assist.

5 Discussion

The hip and knee angle joints with power assist as shown in Fig.6 were similar to that of motions without power assist as shown in Fig.3. It is obvious that Phases for the task is successfully transited and the task are realized. And the activation levels of the muscles assisted in each mode was significantly reduced relative to the activation levels without the assistance (Fig..7). This fact indicates that the autonomous mo-

Table 1: Assist torque for each Phase.

	Hip joint	Knee joint
Phase 1	τ_{hip1}(cost.)	$-\beta\ddot{\theta}_{hip}$
Phase 2	0	0
Phase 3	τ_{hip3}(cost.)	$K_p\theta_{knee} + K_d\dot{\theta}_{knee}$

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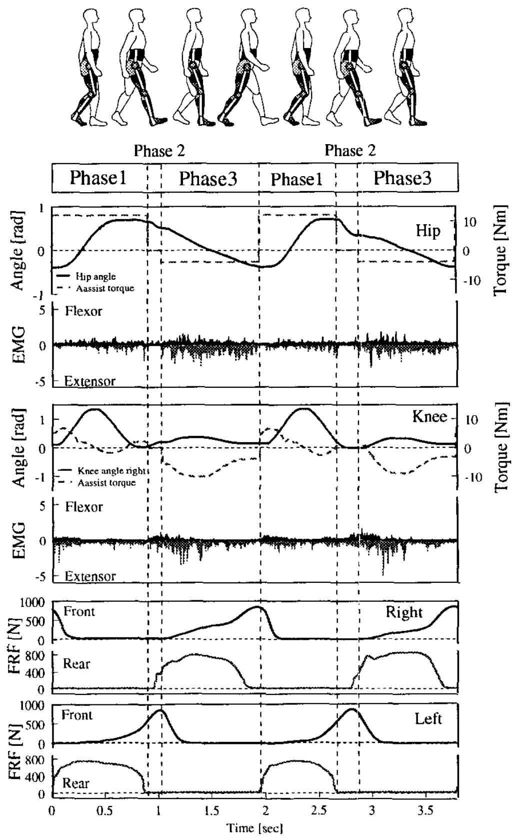

Figure 6: Power assit walking by using Phase Sequence.

tions generated by an exoskeleton robot move the human's leg. Therefore we confirmed the Phase Sequence method based on the modes of muscle activity is effective as a assist method by using autonomous motion of the exoskeleton robot HAL-3.

6 Conclusion

In this research we proposed an assist method on the basis of autonomous motion driven by the interaction between human and the robot suit. In order to perform walking task autonomically, we used Phase Sequence control which generates a task by transiting some simple basic motions called Phase. Task was divided into some Phases during the task performed by a normal person. The joint moving mode were categorized into the active, passive and free modes based on the characteristic of the muscle force conditions.

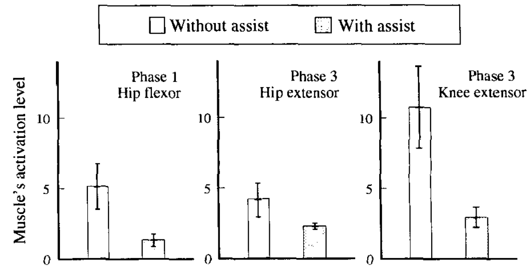

Figure 7: Comparison of the muscle activaton level with and without power assit.

The autonomous motion which HAL generates in each Phases were designed according to one of the categorized modes. The floor reaction forces were adopted to transit each Phase. The experiments in power assist were performed by using the autonomous motion. The experiment results showed that the muscle activation level in each Phase were reduced. With this, we confirmed the effectiveness of the proposed assist method.

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