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Predictive Control Estimating Operator's Intention for Stepping-up Motion by Exo-Sckeleton Type Power Assist System HAL

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Abstract

Generally, the operator's force signal is utilized in the case of the power assist. However, the operator must keep always providing the force in order to obtain the force signal. We have developed an exo-skeleton type power assist system, HAL (Hybrid Assistive Leg) for the walking aid. The purposes of this study are 1)to estimate the operator's action in the initial stage of the motion, 2)to propose the method for realizing the power assist corresponding to the operator's motion. We include the following mechanism into HAL system ; 1) the mechanism which estimate the reference input of the bend angle of a joint by using myoelectricity, 2) the mechanism which autonomously generates the motion using phase sequence. For optional steps, experiments were performed to realize the stepping-up motion which reflects the intention of the operator. As the result, HAL started the autonomous motion immediately when the operator intended to start the motion, and stepping-up motion which reflected the intention of the operator was able to be achieved, even if the operator hardly generated the power.

1 Introduction

It is difficult for a person with disability in his lower body to do a stepping-up and down motion, like as walking at stairs etc.. And, the barrier free is not fully popularized under the present condition. Therefore, it is indispensable to realize a stepping-up and -down motion.

We have developed an exo-skeleton type power assist system, HAL (Hybrid Assistive Leg) for walking aid (Fig. 1.1).

The research about such power assist system was studied and challenged by Vukobratovic et al[1]. However, with technology of those days, the performance of a motor and the electronic technology of a drive system were inadequate. Therefore, the torque and speed for power assist were not able to be generated to each joint. And, the size of system was large. Moreover, there was no advanced digitization technology. Myoelectricity has not been transformed into torque.

In order to perform the power assist which was adapted for an operator, the followings are required; 1) sufficient torque, 2) sufficient speed, 3) nonlinear processing, 4) parameter tuning, 5) virtual torque computation using myoelectricity.

More important point is to realize power assist control which predict operator's motion. It is desirable to realize power assist more quickly than the operator's motion.

In our HAL project, the following are used : Myoelectricity-force transform method for estimating the operator's force, and the method of Phase Sequence which efficiently generates a series of motion.

The purposes of this research are 1) to propose and develop the method which estimates the operator's action using myoelectricity(EMG) in the initial stage of the motion, 2) to realize the power assist based on the Phase Sequence method and the proposed predict method for the stepping-up motion, and 3) to confirm the effectiveness of this predictive control method estimating the operator's intention for stepping-up motion by using HAL

2 HAL

2.1 HAL System

HAL developed in our project is the exo-skeleton type power assistant system.

HAL has four joints (a hip joint and a knee joint on either side). Each joint is 1 DOF (degree of a freedom).

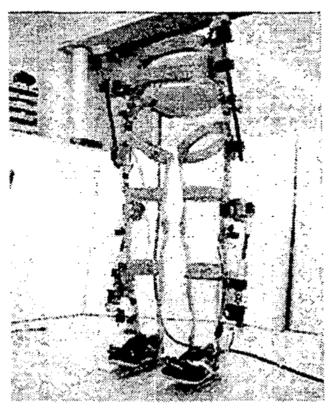

Fig.1.1 HAL-1

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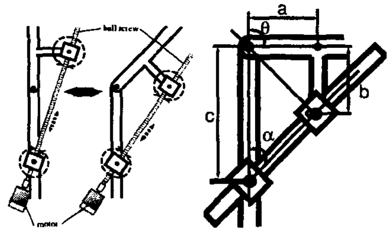

Fig.2.1 Actuator movement (left) and parameter of the mechanism (right)

And, the movable range of each joint is the almost same as a human.

In order to generate torque to each joint, the mechanism of a DC motor and a ball screw is adopted. The attachment metal which is fixing the bearing unit of the ball screw can rotate to the frame of HAL. Therefore, the rectilinear motion of the ball screw is changed into the rotary motion of a joint shaft (Fig.2.1(left)). For the ball screw mechanism, it is unique that the backlash is very small and mechanically large torque can be generated.

The parameters of the mechanism are shown in FIg.2.1. In this prototype model HAL-1, a and b were set to 8 [cm] and c was set to 16 [cm] (Fig.2.1 (right)) from the relation between the shape of frame and the attachment position.

$$(c-b)^2 + a^2 = c^2 - \left(a^2 + b^2\right) \leftrightarrow bc = a^2 + b^2$$

$$c = \frac{\left(a^2 + b^2\right)}{b}$$

Using such a mechanism shown Fig2.1, the relation

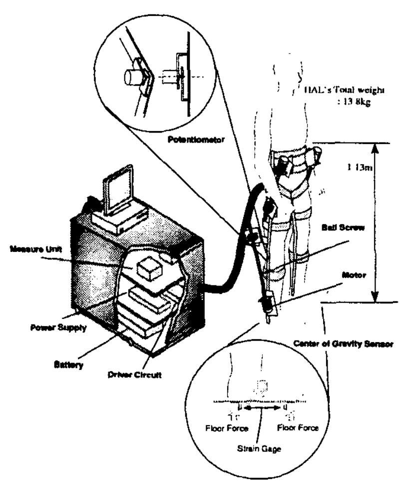

Fig.2.2 HAL system

between the rotational frequency of a motor (N) and the angular velocity of a joint (ω) is expressed as follows,

$$\omega = \frac{l}{\sqrt{a^2 + b^2}} \cdot \frac{N}{60} \cdot \frac{360}{2\pi} \times 10^{-1} [deg/sec] \cdots\cdots\cdots\cdots (1)$$

ω *: angular velocity of joint [deg/sec]*
N *: rotational frequency of motor [rpm]*
l *: lead of ball screw*

The relation between torque of a motor T(kgf-cm) and the joint torque F(kgf-cm) is expressed as follows,

$$F = 2\pi\eta l^{-1} \sqrt{a^2 + b^2} \cdot T \times 10^{-1} [kgf \cdot cm] \cdots\cdots\cdots\cdots (2)$$

η: *efficiency*

Based on the analysis results of human's motion, specification required for each joint is decided (Table.2.1).

Table.2.1

	maximum angle [rad]	maximum angular velocity [rad/sec]	maximum torque around joint [kgf-cm]
hip joint	2.2	3.8	700
knee joint	2.5	5.0	800

To satisfy the specification shown Table 2.1, motor's rotational frequency and torque was calculated from a formula (1) and (2). Consequently, it became rotational frequency of a motor about 2000 (rpm), and torque 10 (kgf-cm). The specification of HAL-1 is shown in Table.2.2.

Table.2.2

rated angular velocity [rad/sec]	maximum angular velocity [rad/sec]	rated torque [kgf-cm]	maximum torque [kgf-cm]
9.5	15.8	242	2300

In order to know HAL and an operator's condition, it has an angle sensor (potentiometer), a pressure sensor of a sole (a strain gauge, amplifier), and the myoelectricity sensor (electrode, amplifier, filter). The pressure sensor of a sole measures the center of gravity (COG). position from the load balance of front and rear. And, grounding condition of a sole is also detected (Fig. 2.2).

2.2 Myoelectricity

Muscles generate action potential when a man moves. These action potential that it is measured by the electrode on the surface of the skin are said as the myoelectricity. By using this myoelectricity, all motions of man is measurable as an electric signal.

When performing the power assist, it is necessary to know an operator's intention. the myoelectricity is closely

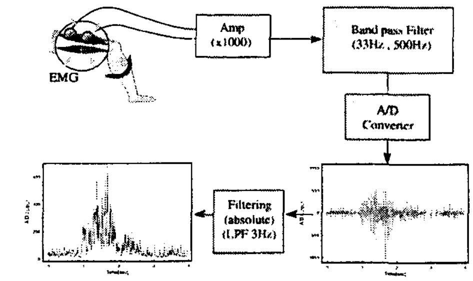

Fig.2.3 Outline of EMG measuering

related to muscular power. It is measurable just before taking out power. Therefore, in this research, the myoelectricity is used as the method for estimating an operator's intention.

The measurement process of myoelectricity is shown in Fig.2.3.

2.3 Phase Sequence

In this research, as the control method of motion, Phase Sequence is adopted. The motion of a walk, a standing-up, etc. was realized using this method.

Phase Sequence is the method for realizing the various motions of human (Task(Fig.2.4)). The Task is divided into some units (Phase(Fig.2.4)).

Sensing information is,

$$angle = (a_0, a_1, a_2, a_3, \dot{a}_0, \dot{a}_1, \dot{a}_2, \dot{a}_3)$$
$$ground = (COG_R, COG_L)$$

$a_0 = a_{rh}$: *Right hip* $\quad a_1 = a_{lh}$: *Left hip*

$a_2 = a_{rk}$: *Right knee* $\quad a_3 = a_{lk}$: *Left knee*

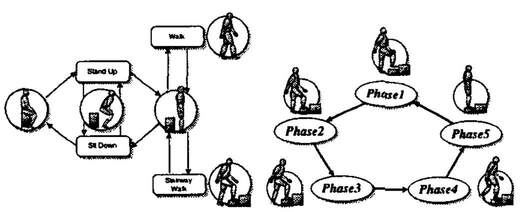

Fig.2.4 Image of Task(left) and Phase(right : step up motion)

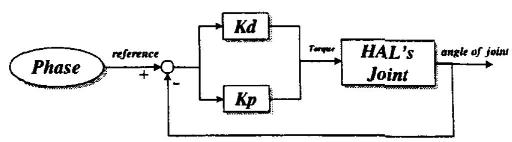

Fig.2.5 Joint control system

COG_R : *Right foot's center of gravity*
COG_L : *Left foot's center of gravity*

The next Phase (n_phase) is determined from HAL and the operator's condition.

$$n\_phase = f(angle, ground, Phase)$$

The Phase consists of motion of each joint.

$$Phase = (motion_{if}, \cdots)$$
$$motion_{ij} = Kp_j(R_{ij} - a_j) + Kd_j(DR_{ij} - \dot{a}_j)$$

R,DR : *reference input* $\quad$ Kp,Kd : *feedback gain*

Kp and Kd has been decided in order to reduce the discomfort of the operator, and torque is given to a joint as shown in Fig.2.5.

3 Stepping-up motion by Phase Sequence

3.1 Analysis of stepping-up motion

A man's stepping-up motion is analyzed.

The direction of the joint angle in this research is shown in Fig.3.1. The joint angle of a standing posture was set to 0 [rad].

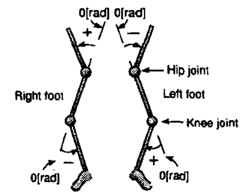

Fig.3.1 Derection of joint rotation

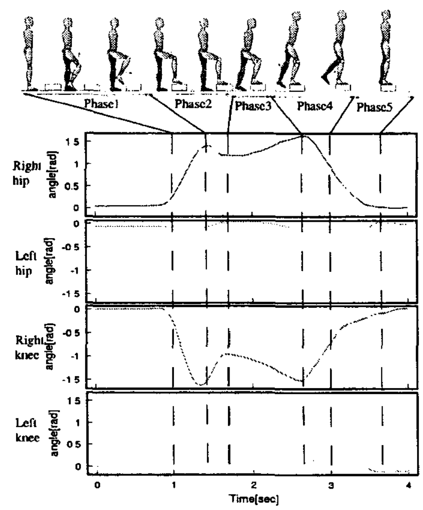

Fig.3.2 Angle variation of each joint

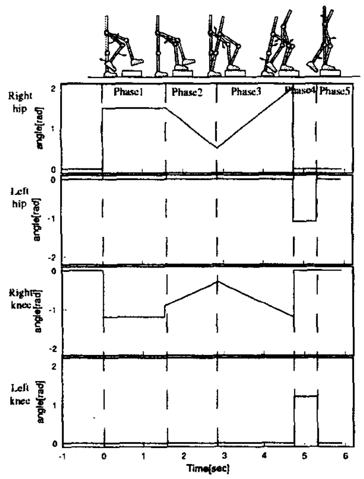

Fig.3.3 HAL's reference corresponding to each Phase

Transition of each joint angle is shown in Fig.3.2.

A man's stepping-up motion can be divided the five motions from a change in angle of each joint.

Phase1 : leg raising
Phase2 : step-upping
Phase3 : weight motion
Phase4 : hind legs raising
Phase5 : erection

3.2 Control method of stepping-up motion

A stepping-up motion is controlled by using Phase Sequence. The reference input of each Phase and the Phase shift timing is examined.

The reference input of each Phase is shown in Fig.3.3. Reference trajectory input of each Phase is decided from a motion of human.

Phase1 (leg raising) :

$R_{rh} = 1.5[rad]$ $\quad R_{lh} = 0.0[rad]$

$R_{rk} = 1.2[rad]$ $\quad R_{lk} = 0.0[rad]$

Phase2 : (weight movement) :

$R_{rh} = R_{rh} - At[rad]$ $\quad R_{lh} = 0.0[rad]$

$R_{rk} = R_{rk} + At[rad]$ $\quad R_{lk} = 0.0[rad]$

Phase3 (weight movement) :

$R_{rh} = R_{rh} + Bt[rad]$ $\quad R_{lh} = 0.0[rad]$

$R_{rk} = R_{rk} - Bt[rad]$ $\quad R_{lk} = 0.0[rad]$

Phase4 (hind legs raising) :

$R_{rh} = 0.0[rad]$ $\quad R_{lh} = 1.1[rad]$

$R_{rk} = 0.0[rad]$ $\quad R_{lk} = 1.1[rad]$

Phase5 (erection) :

$R_{rh} = 0.0[rad]$ $\quad R_{lh} = 0.0[rad]$

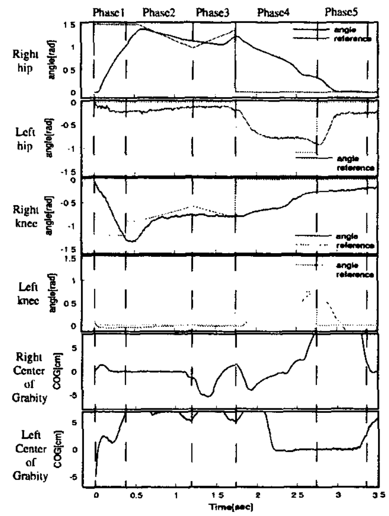

Fig.3.4 Anglar displacement of each joint and reference input. (The step of the height is 10cm) : the time of Phase when it moved was shown with dashed line.

$R_{rk} = 0.0[rad]$ $\quad R_{lk} = 0.0[rad]$

R_{rh}: *Right hip* $\quad R_{lh}$: *Left hip*

R_{rk}: *Right knee* $\quad R_{lk}$: *Left knee*

A, B: *Coefficient* $\quad t$: *time*

A and B is decided from a motion of human.

Next, phase transition timing is decided as follows,

Phase1 $\Rightarrow$ Phase 2

$a_{rh} = R_{rh} \cap a_{rk} = R_{rk}$

Phase 2 $\Rightarrow$ Phase 3

$COG_R < -3[cm]$ (The center of gravity is at the back)

Phase3 $\Rightarrow$ Phase 4

$COG_R > 3[cm]$ (the center of gravity is at the front)

Phase4 $\Rightarrow$ Phase 5

$a_{lh} = R_{lh} \cap a_{lk} = R_{lk}$

3.4 Results and Discussion

The result of an experiment are shown in Fig3.4. Each graphs show the transition of the angle and the reference input of each joint. The measuring data of COG of right and left are also indicated in Fig.3.4.

The Phase shifts smoothly, and each joint angle follow the reference input. The operator has not carried out an impossible motion beyond the necessity, because transition of joint angle is the almost same motion as the actual human (Fig.3.2).

4 The method for estimating reference input of joint angle using myoelectricity

4.1 Measuring experiment

A measuring experiment is performed to examine relations between the bend angle of the hip joint and the myoelectricity of the rectus femoris muscle.

An electrode is put on the rectus femoris muscle, and a leg raising motion is performed.

The myoelectricity until 300msec from the myoelectricity start is integrated. Relations between the value which integrated with the myoelectricity, and the bend angle of the hip joint is shown in Fig.4.1.

$$(x,y) = (\textit{Joint angle}[\mathrm{rad}], \int_T^{T+300msec} EMG(t)dt)$$

$$y = B + Ax$$

$$A = \frac{n \times \sum xy - \sum x \times \sum x}{n \times \sum x^2 - (\sum x)^2}$$

$$B = \frac{\sum y - A \times \sum x}{n}$$

$$\alpha = \frac{1}{A} \qquad \beta = B$$

n : *The number of the samples*

4.2 Method for estimating reference input

From the measuring experiment result, the operator's intention can be estimated. The reference input is estimated by using myoelectricity. A method of calculating reference input (estimated reference input) by integrating with the value of myoelectricity until 300msec from the myoelectricity start is proposed. Bend angle is proportional to the integrated value of the myoelectricity.

$$r = \alpha\left(\int_T^{T+300msec} EMG(t)dt - \beta\right)$$

r : *Estimated reference input*

T : *The time of the myoelectricity start*

EMG(t) : *myoelectricity*

α, β : *Coefficient*

The estimated reference input is decided in 300msec from the myoelectricity start by this method. In the meantime, a joint doesn't move. But, by the person's leg raising motion, a joint begins to bend before 300msec from myoelectricity generation. Therefore, a suitable reference input (temporary virtual reference input) is set until estimated reference input is decided. It becomes possible to begin to bend a joint before 300msec.

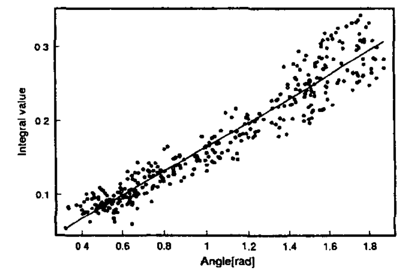

Fig.4.1 Relation of EMG integrated value and bend angle

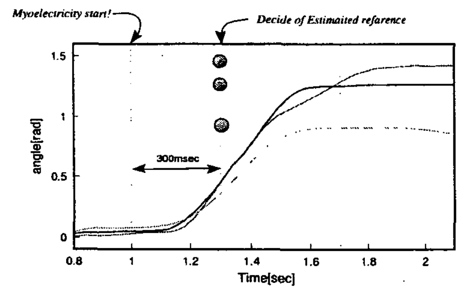

Fig.4.2 Estimated refernce and angle of joint

4.3 Experiment

Targets are given to the operator so that the hip joint angle may become 1.0 rad, 1.25 rad, 1.5 rad.

4.4 Results and Discussion

Before the estimated reference input is decided, a joint begins to move according to temporary virtual reference input which is given by HAL controller (Fig.4.2).

The estimated reference input calculated from myoelectricity becomes almost the same as the target (Fig.4.2). From this fact, the bend angle of joint is able to estimate by using myoelectricity.

5 Stepping-up motion by using estimated reference input

5.1 Control Method

The stepping-up motion by Phase Sequence (3 chapter) and the estimated reference input by the myoelectricity (4 chapter) are combined to realize the stepping-up power assist motion for different height step. As a concrete method, the fixed reference input of the right hip joint of Phase1 in 3 chapter is moved by the estimated reference input calculated from the myoelectricity.

The experiment of the stepping-up motion which doesn't depend on the height is performed. The step of the

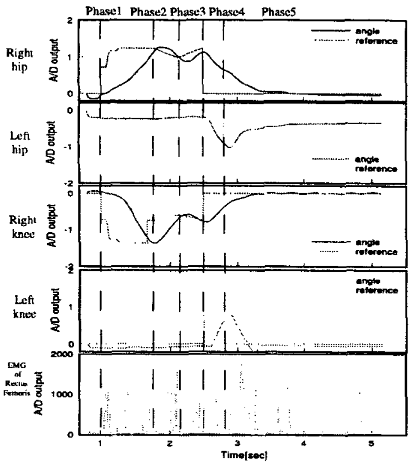

Fig.5.1 Angle variation of each joint and reference(10cm)

height of 10cm and 15cm is prepared. The myoelectricity of the rectus femoris muscle is measured.

5.2 Results and Discussion

The change of each joint angle and the change of the reference input and the myoelectricity are shown in Fig.5.1 (10cm) and Fig.5.2 (15cm).

The estimated reference input of Phase1 changed in proportion to the height of the step (Fig.5.1, Fig.5.2 (Phase1)) by the operator's intention. Therefore, the stepping-up motion by using the estimated reference input was realized.

The myoelectricity with the power assist is compared with the myoelectricity without power assist (Fig.5.1,Fig.5.3). It is understood that the myoelectricity with the power assist is small. From this result, the burden of the operator is reduced by proposed method.

6 Conclusion

Analysing the stepping-up motion of human, 1) the motion was able to be divided to create the Phase Sequence, 2) the reference input and Phase transition timing were decided. From those results, the stepping-up motion by Phase Sequence by using HAL.

Next, the myoelectricity was analyzed, and the method for estimating the reference input of the bend angle of the joint was proposed, and by using this method, the operator's action estimate in the initial stage of the motion.

These two methods were combined, and For optional steps, experiments were performed to realize the stepping-up motion which reflects the intention of the operator. As the result, HAL started the autonomous motion immediately when the operator intended to start the motion, and stepping-up motion which reflected the intention of the operator was able to be achieved, even if the operator hardly generated the power. and the validity of this research was able to be confirmed.

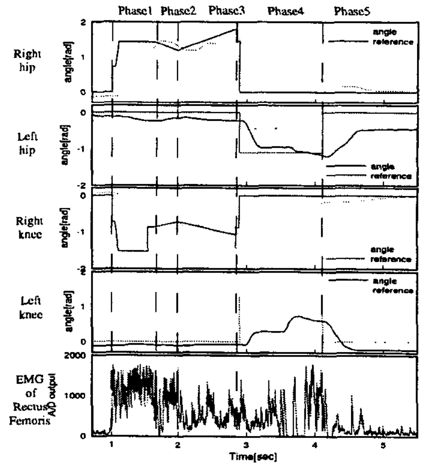

Fig.5.2 angle variation of each joint and reference(15cm)

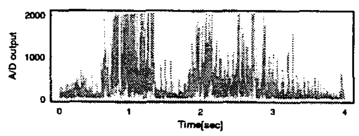

Fig.5.3 EMG without power assist(10cm)

We plan to realize the various daily motion (climbing-up and -down, stepping-up and -down, obstacle avoidance, etc.) by using proposed method in this research

7 Reference

[1]Vukobratovic M., et al., "Further Development of Active Anthropomorphic Exoskeletons", Pro. of the 4th Int. Symposium on External Control of Human Extremities, Dubrovnik, 1972.

[2]G.yoshino, Y.Sankai, H.Moriyama, K.sakamoto : "The Motion Control of Link Robot by Phase Sequence" , RSJ (Annual conference), vol.14.3 pp.977-978,1996

[3]Junpei Okamura, Hiroshi Tanaka, Yoshiyuki Sankai, "EMG-based Prototype Powered Assistive System for Walking Aid", Proc of ASIA'99, pp.229-234,1999

[4]Masami Itoh, "Motion Control at Living body and Robot", The Society of Instrument and Control Engineer (SICE)