# A PAWL for Enhancing Strength and Endurance during Walking Using Interaction Force and Dynamical Information

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## 1. Introduction

PAWL (power assist walking leg) represents a high integration of robotics, information technology, communication, control engineering, signal processing and etc. Today, trends in robotics research are changing from industrial applications to non-industrial applications, such as service robots, medical robots, humanoid robots, personal robots and so on. Human ability to perform physical tasks is limited not only by intelligence, but also by physical strength (Kazerooni, 1990). Our research on robot is using mechanism to augment human muscle and capability of sense during walking; synchronously, it can hold human agility and sense of direct operation. The primary task of this project is to develop a power assist walking support leg (shown in Fig.1) which not only amplifies strength of human legs and enhances endurance during walking, but also reduces user inner force. Power assist system has many potential applications. It can be designed for care-worker, elderly people, nurse,

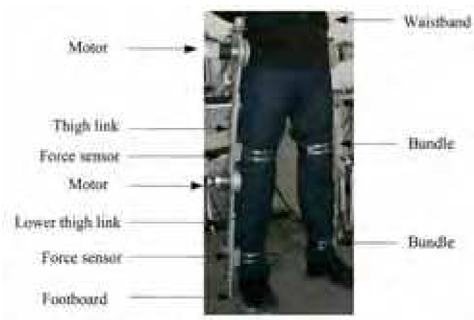


Fig. 1. Power Assist Walking Leg



Source: Climbing & Walking Robots, Towards New Applications, Book edited by Houxiang Zhang,
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soldier, fireman, even for a person with gait disorder (medical rehabilitation system). And it is also expected to have powerful impacts on many applications in the manufacturing, service, and construction industries. In order to utilize PAWL as human locomotion assist apparatus, the PAWL must comply with the locomotion of human legs, i.e. the system in this study is supposed to generate flexible human-like motion without delay. So, the PAWL kinematics must be close to users'. Here, we propose a power assist method using human-robot interaction force. And, the ability of the walking support leg to perform a task depends on the available actuator torque. The direction of the motor rotation is made certain by the user motion based on sensors information, especially the interaction force (between the user and the exoskeleton) and the floor reaction force (FRF). And, the motor rotation actuated by periodic signals should be flexible because the user is in physical contact with the mechanism.

## 2. Related Works of Wearable Power Assist Device

Many projects about a wearable power assist device are developed or developing. Their power assist is distributed to arm, leg, back, and so on. Some representative power assist systems are summarized in this section.

A study of power assist robot was started in 1960s. Hardiman (Makinson, 1971) was the first power assist system. The main purpose of the project is to be used by soldiers, who have to move long-distance with heavy loads. The Hardiman project was a large, full-body exoskeleton weighing 680 kg and controlled using a master-slave system. BLEEX (the Berkeley Lower Extremity Exoskeleton) (Kazerooni et al., 2005; Steger et al., 2006) project has developed an energetically autonomous exoskeleton capable of carrying its own weight plus an external payload. BLEEX has more than 40 sensors and hydraulic actuators, and helps lighten the load for soldier or worker. Currently BLEEX has been demonstrated to support up to 75kg, walk at speeds up to 1.3m/s, and shadow the operator through numerous maneuvers without any human sensing or pre-programmed motions.

In Japan, several universities are developing the power assist system. Kanagawa Institute of Technology has designed a wearable power assist suit (Keijiro et al., 2002; Keijiro et al., 2004) for nurses. The target load is about 60kgf, powered by unique pneumatic actuators controlled by measuring the hardness of the corresponding human muscles. HAL (Kasaoka & Sankai, 2001; Lee & Sankai, 2002; Kawamoto & Kanbe, 2003; Kawamotio & Sankai, 2004; Hayashi et al., 2005) of Tsukuba University was a lightweight power assist device. Its actuators are DC motors at the knee and hip. They use EMG electrodes on human's leg muscles and ground reaction force sensors to estimate a human inner force and motion information. Tohoku University developed a wearable antigravity muscles support system for supporting physically weak person's daily activities (W.W.H-KH2) (Nakamura et al., 2005). The joint support moments are designed based on a part of the gravity term of the necessary joint moment derived by human approximated model.

The robot that we proposed is for assisting activities of daily life through decreasing human inner force / increasing human strength. So, the system must have many DOFs like humans. And, the PAWL DOFs are all purely rotary joints. To make the system work smoothly and toted easily, the control scheme must be effective and the weight of the whole system should be light. Aluminium alloy are used as the main material for the exoskeletal frame in consideration of lightness.

### 3. Conceptual Design and Calculation of Necessary Joint Torques

PAWL is composed of five main parts: lower exoskeletons, actuators, controllers, sensors, and power unit. By matching human degrees of freedom and limb lengths, PAWL must have the necessary degrees of freedom and its segments length equal human legs' in order to satisfy human normal walking. This means that for different operators to wear the exoskeleton, almost all the exoskeleton limbs must be highly adjustable, even for the waistband. In order to make the exoskeleton work smoothly and safety, the PAWL must have the kinematics which is similar to man. The PAWL is to be attached directly to the bilateral side of human legs. Fig.1 shows the hybrid system of human-PAWL. It can be said that PAWL will become a part of human body or human body is a part of PAWL.
The PAWL that we proposed is for assisting activities of daily life without affecting the user to walk normally. So, the system has many DOFs like humans, however, it is impossible to include all the DOFs of human legs in consideration of design and control complexities. Here, our mechanical structure consists of a 12 DOFs mechanism (6 DOFs for each leg). And, all joints of PAWL are rotary structure. The hip structure has 3 DOFs in total. They perform function of flexion/extension, abduction/adduction and internal rotation /external rotation. At the knee joint, there is 1 DOF, which perform the flexion/extension. 1 DOF at the ankle permits dorsiflexion/planter flexion and 1 DOF at the metatarsophalangeal joint for flexion/extension.
Comparing to other joint motion, the flexion/extension of hip and knee is the most important to normal walking and its energy consumption is also most. So, only the motion of flexion/extension at hip and knee is currently powered. To make the system work smoothly and move easily, besides the validity of the control strategy, the weight of the whole system should be light. Here, aluminium alloy are mainly used as the material for the exoskeletal frame in consideration of lightness. To avoid the motion collision between the WPAL exoskeleton and the user, the designed joint axes and human joint axes must be on an identical axis. So, the length of PAWL exoskeleton is designed to be changed according to the real length of user thigh and lower leg as shown Fig.2.

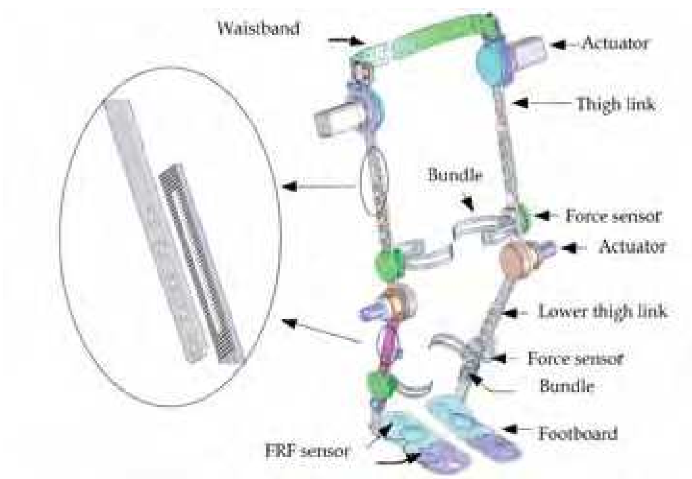



Fig. 2. Configuration of the robot suit

Fig.1 and Fig.2 also show the fundamental configuration of PAWL. The actuator used in PAWL is DC servomotor attached with a harmonic drive gear, which provide assist force for knee and hip joints. Here, MAXON DC servomotor and reducer are selected for PAWL actuators by analysing the dynamic model of human body and the exoskeleton. The direction of the interaction force decides the rotation direction of the manipulator. And the motor clockwise/anti-clockwise rotation achieves the flexion/extension of human leg. According to (Zheng, 2002), we can obtain the relative weight of human body segments, especially lower limb. Aluminium alloy is mainly used as the material for the exoskeleton frame in consideration of lightness. Table 1 shows the weight of the main links. Considering the safety to user, the motion range of the exoskeleton joint must be restricted according with human each joint's (shown in Table 2). That is, the joint range of PAWL should not go over the corresponding range of human. So, we restrict the joint motion range of PAWL during mechanical design. And, it is also insured against maximum by pre-programmed software. The maximum velocity of actuator is limited by software, too. Furthermore, there is a close-at-hand emergency switch to shut off the motor power in order to avoid the unexpected accident.

| Objects(unilateral) | Weight [g] | Material |
|---|---|---|
| Waistband | 390.69 | Stainless steel |
| Thigh Link ($m_1$) | 769.97 | Duralumin |
| Lower Thigh Link ($m_2$) | 371.42 | Duralumin |
| Foot Board ($m_3$) | 755.55 | Duralumin |

Table 1. Weight of each link

| | | |
|---|---|---|
| Hip Joint | Flexion | 120° |
| | Extension | 10° |
| | Abduction | 45° |
| | Adduction | 30° |
| | Internal rotation | 45° |
| | External rotation | 45° |
| Knee Joint | Extension to flexion | 135° |
| Ankle Joint | Dorsiflexion | 20° |
| | Planter flexion | 50° |
| Metatarsophalangeal Joint | Flexion | 45° |
| | Extension | 70° |

Table 2. Human joint ranges of motion

Many sensors are used to detect the conditions of the PAWL and user. The two two-dimension force sensors are equipped on thigh and lower thigh respectively per exoskeleton leg, which detect the interaction force caused from the motion difference between PAWL and the user. And they contact directly with human leg through bundles. FRF (Floor reaction force) sensors are developed to measure FRF which are generated in front and rear parts of the footboard. Rotary encoders are used to measure the hip and knee joint angles. The multi-sensors information is used to understand human motion intent. So, the sensors must have the properties of high stability, sensitivity and accuracy. Furthermore, the PAWL motion should be prompt and smooth. Otherwise, the PAWL will be a payload to the user. Using Lagrange method, we can work out the necessary joint torque for lifting up the user leg and the exoskeleton itself. The simplified model is shown in Fig.3. In this simplified model, we assumed that all links and segments of human lower limbs are rigid and the mass distribution of each link or limb is uniform. The lengths of the links are indicated by the symbol $d_i$, $m_i$ denotes mass of links, $M_i$ denotes mass of human lower limbs and $\theta_i$ denotes the angle of joints, $m_f$ denotes the total mass of user foot and the aluminum alloy footboard, i.e. $m_f = m_3 + M_3$. Besides, the motors mounted on the hip and knee joint respectively have masses (include the mass of harmonic gear reducer) $m_{c1}$ and $m_{c2}$, and the friction of joint and gearing is ignored.

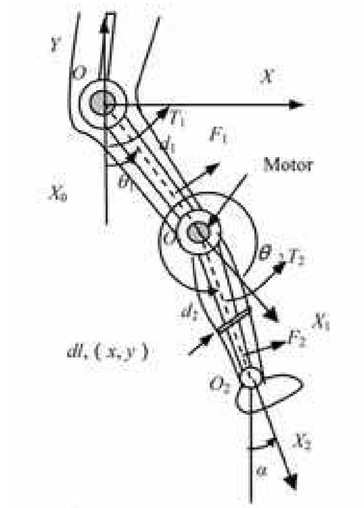



Fig. 3. Simplified model of the human-robot system

Using the derivative and the partial derivative knowledge, we can derive the hip torque $T_1$ and the knee torque $T_2$.

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 & D_{212} \\ D_{221} & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \end{bmatrix} + \begin{bmatrix} D_{311} & D_{312} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_2 \dot{\theta}_1 \end{bmatrix} + \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \tag{1}$$

Where

$$D_{11} = \left( \frac{1}{3} m_1 + \frac{1}{3} \mathrm{M}_1 + m_{c2} + m_2 + \mathrm{M}_2 + m_f \right) d_1^2 + \left( \frac{1}{3} m_2 + \frac{1}{3} \mathrm{M}_2 + m_f \right) d_2^2$$
$$+ 2 \left( \frac{1}{2} m_2 + \frac{1}{2} \mathrm{M}_2 + m_f \right) d_1 d_2 \cos \theta_2 \ddot{\theta}_1$$

$$D_{12} = \left( \frac{1}{3} m_2 + \frac{1}{3} \mathrm{M}_2 + m_f \right) d_2^2 + \left( \frac{1}{2} m_2 + \frac{1}{2} \mathrm{M}_2 + m_f \right) d_1 d_2 \cos \theta_2$$

$$D_{21} = \left(\frac{1}{3}m_2 + \frac{1}{3}\mathrm{M}_2 + m_f\right)d_2^2 + \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)d_1 d_2 \cos\theta_2$$

$$D_{22} = \left(\frac{1}{3}m_2 + \frac{1}{3}\mathrm{M}_2 + m_f\right)d_2^2$$

$$D_{212} = -\left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)d_1 d_2 \sin\theta_2$$

$$D_{221} = \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)d_1 d_2 \sin\theta_2$$

$$D_{311} = -\left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)d_1 d_2 \sin\theta_2$$

$$D_{312} = -\left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)d_1 d_2 \sin\theta_2$$

$$D_1 = \left(\frac{1}{2}m_1 + \frac{1}{2}M_1 + m_{c2} + m_2 + M_2 + m_f\right)gd_1 \sin\theta_1 + \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)gd_2 \sin(\theta_1 + \theta_2)$$

$$D_2 = \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)gd_2 \sin(\theta_1 + \theta_2)$$

We can also simplify the Eq. (1) to static body mechanics. Based on the Eq. (1), we can estimate the necessary output torque of the motors. It is well known that the torque is important to motors decided. Here, the weight of force sensors is not taken into account in the above model.

## 4. Dynamic Model and Control Strategy

### 4.1 Dynamic behavior of the PAWL and human

The behavior of walking support machines must be simple for user. So, the system should be worn easily; and, its sensors should not be placed directly on the user body.

In order to use PAWL as a human power assistant, we should consider when and how to make the power assist leg to provide assist to user. The analyses focus on the dynamics and control of human-robot interaction in the sense of the transfer of power and information. Sensor systems are equipped on PAWL to detect the motion information of the PAWL and user. Force sensors are used to measure the interaction force between the PAWL and user (the force caused from the motion difference between the walking support robot and human, all feedback forces are assumed to be on the sagittal plane). Encoders provide the pose of the low limbs (angle of the hip joint and knee joint). According to the information of the encoder, we can obtain the velocity of the joint. Motion intention may be rightly made certain by sensors fusion and calculated joint torque, and has to be directly transmitted to the control system.

It's well known that interaction force is produced between two or more objects when they are in contact. Contact force is an important piece of information that shows their interaction

state to some extent. Because the user is in physical contact with the exoskeleton, the power assist walking support leg kinematics must be close to human leg kinematics.
Using a simplified model, we can establish a model named mass-spring-viscidity system (shown in Fig. 4 (a)), which can be used as the interaction description. A simplified configuration of user's lower leg equipped with PAWL is shown in Fig.4 (b). In order to found effective control strategy, firstly, we analyze the dynamic characteristics of the bone-muscle model. At the fore, we assume that the mechanism system is rigid, *m* denotes the mass of lower thigh; *k* and *c* denote the coefficient of muscle spring and viscidity respectively.

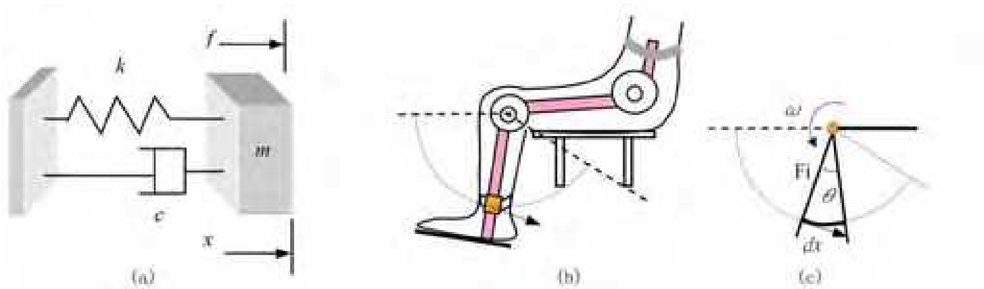


Fig. 4. Simplified model hybrid system

In the above simplified model, we ignore the disturbance which maybe caused by the friction of bearings and gears. It is described with the following differential equation

$$f = m\ddot{x} + c\dot{x} + kx \tag{2}$$

where

| | |
|---|---|
| $f$ | composition of forces, [N], |
| $m$ | mass of exoskeleton, [kg], |
| $x$ | position of exoskeleton, [m], |
| $\dot{x}$ | velocity of exoskeleton, [m/s], |
| $\ddot{x}$ | acceleration of exoskeleton, [m/s$^2$], |
| $c$ | viscidity coefficient of interface, |
| $k$ | stiffness coefficient of interface. |

Acceleration and velocity have another expression:

$$\ddot{x} = \frac{v_{n+1} - v_n}{dt} \quad , \quad \dot{x} = v_n \tag{3}$$

Substituting Eqs. (3) for (2), we obtain

$$v_{n+1} = \frac{dt}{m}\left(f_n - cv_n - kdx_n\right) + v_n \tag{4}$$

From Fig. 4 (c), we can obtain

$$v_n = \omega_n \cdot r \quad , \quad dx_n \doteq r \cdot d\theta_n = r\omega_n \cdot dt \tag{5}$$

$d\theta_n$ and $w_n$ can be obtained by the information of encoder.
Considering the system controlled by PC periodically (control cycle time is indicated by the symbol *T*), *dt* can be approximately described with time *T*. That is

$$dt \doteq T \tag{6}$$

On inserting Eqs. (5), (6) into Eq. (4), we can obtain

$$\omega_{n+1} = \frac{T}{mr}\left(f_n - c\omega_n r - kr\omega_n T\right) + \omega_n = \frac{T}{mr} f_n + \left(1 - \frac{cT}{m} - \frac{kT^2}{m}\right) w_n \tag{7}$$

Because PAWL is a part of human body or human body is a part of PAWL, we must amend the Eq. (7). Here, except for the weight of the exoskeleton link, the weight of the user lower thigh must be included in the Eq. (7), i.e. the weight of the user thigh should be regarded as a part of the PAWL. Therefore, the user limb is not only the subject-body of force giving out but object-body of load to PAWL. Referring to (Zheng, 2002), we can obtain the segments relative weight of human body. Now a revised equation is given as follows:

$$\begin{aligned} \omega_{n+1} &= \frac{T}{(m + M)r}\left(f_n - c\,\omega_n r - kr\,\omega_n T\right) + \omega_n \\ &= \frac{T}{(m + M)r} f_n + \left(1 - \frac{cT}{(m + M)} - \frac{kT^2}{(m + M)}\right)\omega_n = \alpha f_n + \beta\omega_n \end{aligned} \tag{8}$$

Where

$$\alpha = \frac{T}{(m + M)r} \;,\; \beta = 1 - \frac{cT}{(m + M)} - \frac{kT^2}{(m + M)}$$

The operator $w_{n+1}$ and $w_n$ are the output angular speed of reducer in the equations mentioned above.
Eq. (8) shows an approach that stands on the interaction force. In fact, it is difficult to obtain the exact value of $\alpha$ and $\beta$. The main reason is that the weight of segments of the human lower limb can not be measured accurately, and the coefficient $k$ and $c$ are not obtained accurately. We also found the thigh model according to the same rules as before. The Eq. (8) is very important to found the control strategy of the system. Here, each individual motor is controlled by a local controller with the velocity control scheme illustrated in Fig.5. The velocity is controlled by a simple PID feedback controller on all joints.

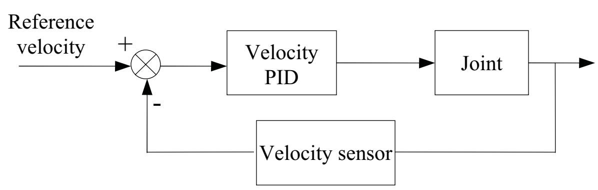



Fig. 5. PID velocity control Scheme

### 4.2 Control strategy

Fig.6 shows the dynamical control scheme of PAWL. The basic control demand of the PAWL rests on the notion that the control strategy must make the user comfortable, and ensure that the PAWL can provide power assist for the user. Based on Eq. (8), a pseudo-compliance control scheme was proposed to provide the exoskeleton with mechanisms to coordinate with human operator.

It is important that the system has ability to adapt itself to the gait of many human. And the system must have fine sensitivity in response to all movements.

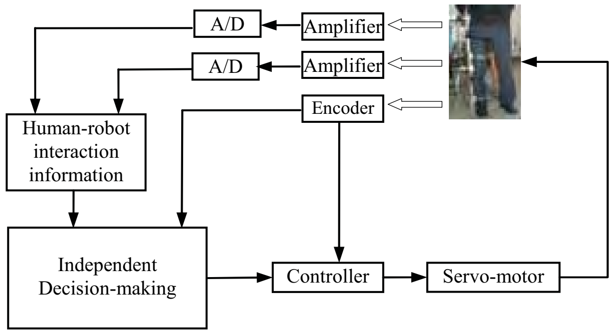
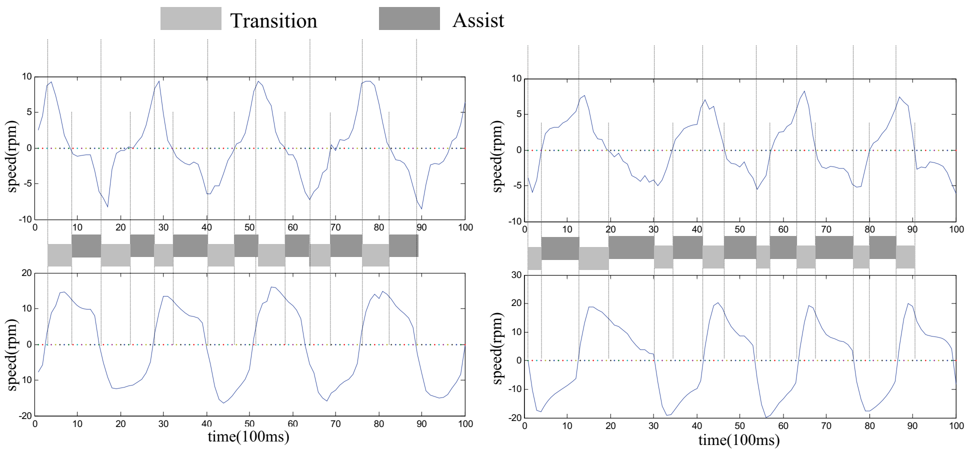



Fig. 6. PAWL dynamical control scheme

## 5. Experiments Result and Future Work

We have conducted experiments to demonstrate and verify the pseudo-compliance control method. Fig.6 shows the right side of PAWL. We use this experimental platform to permit human-robot walking. And we also obtain the interaction information between human lower limb and PAWL.




(a). the right thigh

(b). the right calf

Fig. 7. Output response to experiment

In our experiments, the force sensors and dextral PAWL are used to verify the proposed control strategy. Force sensor fixed on the links is used to measure the interaction force between the experimental exoskeleton and human leg. Here, the sensors of FRF are not used in this experiment because the FRF sensor still processing. And, the software is designed especially for the experiment PAWL.
The work presented is developing a mechanism with the main goal of decreasing human inner force/increasing human strength. And human is in physical contact with PAWL in the sense of transfer mechanical power and information signals. Because of this unique interface, control of PAWL can be accomplished without any type of keyboard, switch and joystick. The final goal of our research is to develop a smart system which can support power for user without any accident.
Fig.7 shows the result of the single hybrid leg experiment. Two phases are in the each motion process of flexion/extension. In fact, we hope that the mechanism should provide much more power for user, so we should shorten the time of transition phase, and lengthen the time of assist. The judgement of user motion intention will be very important to improve the performance of power assist. The percentage of assist can be changed through regulating the coefficient of *m*, *k* and *c*. And, the coefficient of *m*, *k* and *c* (i.e. *a*, *β*) can also make the output velocity smoothness as shown in Fig. 8 (b).

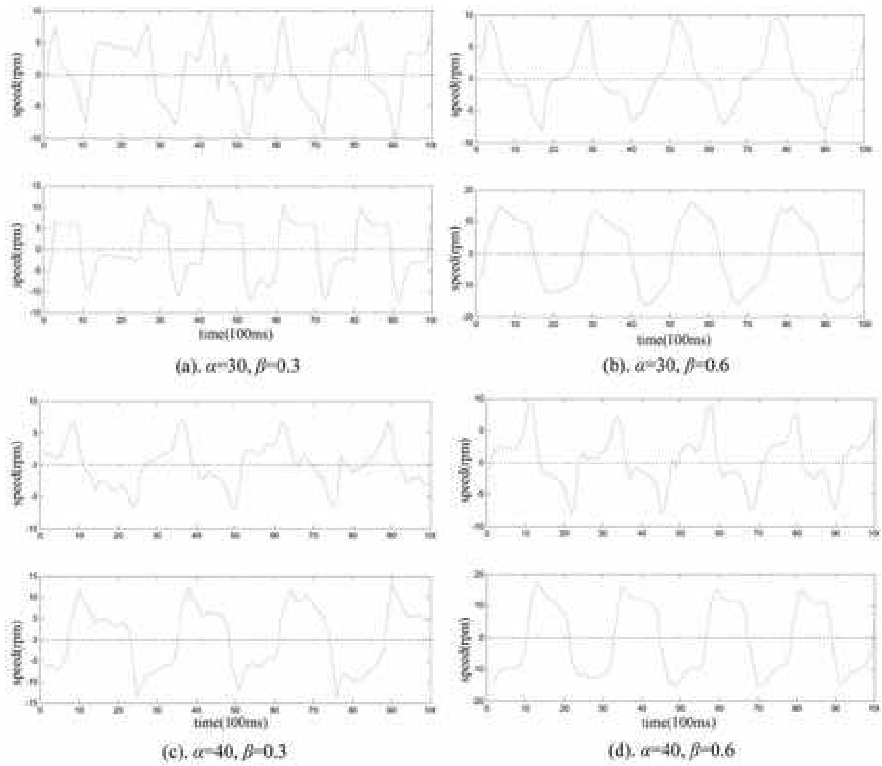


Fig. 8. Response to different coefficient

There is still significant work remaining. Through the calculation of the process of transition and assist, we may get the percentage of power assist from PAWL, and furthermore, we may found a certain relationship between the value of power assist support for user and the coefficient of *m*, *k* and *c*.
Current works on PAWL include developing FRF sensors, increasing sensor stability and sensitivity, improving the system control and sensing system and developing evaluation method of power assist supply. PAWL robot represents a high integration of robotics, information technology, communication, control engineering, signal processing and etc. Hopefully with continued improvement to the system performance, the PAWL will become a practical system for human power augmentation.

## 6. Acknowledgment

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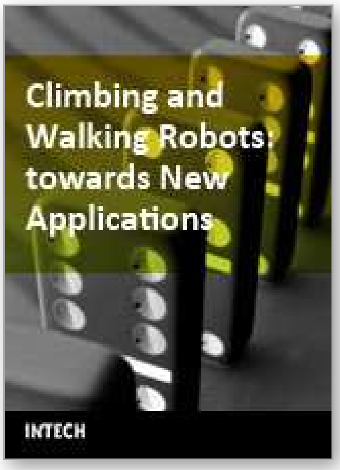
Climbing and
Walking Robots:
towards New
Applications
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