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

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***Abstract* – A power assist walking leg is designed for enhancing strength and endurance during walking, it can be also applied to one whose legs are injured or who has difficulty in walking because of aging, paralysis and amputation. In this paper, we intend to introduce a concept of power assist walking support system and its fundamental control strategy using the information of human-robot interaction force. The whole system must be simple for user, i.e. the user can manipulate the walking support system easily. In order to make the system work smoothly, it must understand the user's intent through human-robot interaction force and the joint angle. Therefore, we propose tentatively a strategy using human-robot interaction force between the assist walking exoskeleton and human legs. Correlative experimental results show the effectiveness of the control strategies.**

Index Terms - PAWL. Moment of Inertia. Force/Velocity.

I. INTRODUCTION

Robots represent 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's ability to perform physical tasks is limited not only by intelligence, but also by physical strength [1]. 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 objective of this project is to develop a power assist walking support leg (PAWL) 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, soldier, fireman, even for a person with gait disorder (medical rehabilitation system). And it also is 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 primarily 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 fusion, 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.

In this paper, related works are summarized in the next section. Conceptual design and necessary calculation of joint torques on PAWL are shown in section III. It is necessary that the device becomes smaller and lighter in order to reduce loads. In Section IV, the dynamic behavior of the PAWL and human is analyzed, which is designed for reducing the user inner force or increasing the strength. In section V, experiment apparatus is introduced. And then, the experimental results and the future work are depicted in section VI.

II. RELATED WORKS OF WEARABLE POWER ASSIST DEVICE

Many projects about a wearable power assist device are developed or developing. Their target portions of assisting are 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 [2] 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) [3-5] 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 1.3 m/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 [6] [7] for nurses. The target load is about 60kgf, powered by unique pneumatic actuators controlled by measuring the hardness of the corresponding

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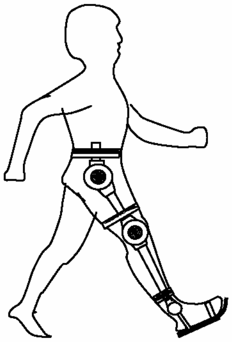


Fig.1 Conceptual Sketch of PAWL

human muscles. HAL [8-12] 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) [13]. 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 human's, but it does not include all the DOF of human legs. And, the PAWL degrees of freedom are all purely rotary joints. To make the system work smoothly and taken 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.

III. 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 human's. The PAWL is to be attached directly to the bilateral side of human legs. Fig. 1 shows the conceptual sketch of PAWL. It also can be said that PAWL will become a part of human body or human body is a part of PAWL. Here, we have designed six degrees of freedom and four-link on each unilateral exoskeleton's leg. The links correspond to the hip, the thigh, the lower leg and foot, and the degrees of freedom per leg:

- 3 degrees of freedom at the hip,
- 1 degree of freedom at the knee,
- 1 degree of freedom at the ankle,
- 1 degree of freedom at the metatarsophalangeal.

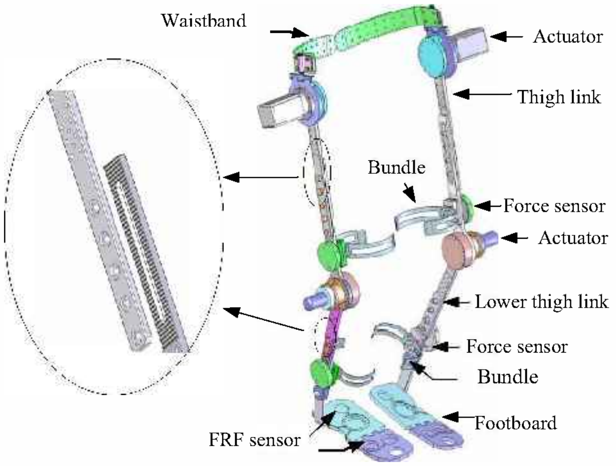


Fig.2 Configuration of the robot suit PAWL

Here, the all degrees of freedom are rotary. For absolute safety, every joint range is also limited to prevent its hyperextension through mechanics design and pre-programmed software design. To avoid the motion collision between the exoskeleton frame and the user, the designed joint axes and human joint axes must be on an identical axis. So, the length of the exoskeleton links can be adjusted to satisfy the real length of user thigh and lower thigh. So, we have designed the exoskeleton links which length can be changed in a certain range as shown in Fig.2.

Fig.2 shows 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 [14], we can obtain the segments relative weight of human body. Here, the person is premised 80 kg. 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. And the segments weight of human lower limb is shown in table 2. Considering the safety to user, the motion range of the exoskeleton joint must be restricted according with human each joint's (shown in Table 3). That is, the joint range of PAWL should not go over the corresponding range of human's. 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

Table 1 Weight of each link

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

Table2 Weight of segments per leg

Segments	Percent(%)	Weight(g)
Thigh(M_1)	14.19	11352
Low Thigh (M_2)	3.67	2936
Foot(M_3)	1.48	1184

Table 3 Human joint ranges of motion

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°

motor power in order to avoid the unexpected accident.

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 force caused from the motion difference between PAWL and the user. And they contact directly with human leg through bundles. Floor reaction force (FRF) 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 sensors fusion is used to understand human intent. So, the sensors must have the properties of high stability, sensitivity and accuracy. Furthermore, the PAWL motion should be prompt. 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 θ_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.

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

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

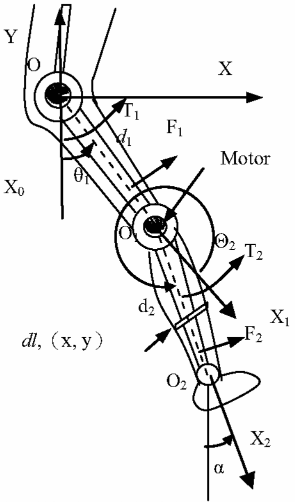


Fig.3 Simplified model of the human-robot system

Where

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

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

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

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

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

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

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

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

$$D_1 = \left(\frac{1}{2}m_1 + \frac{1}{2}M_1 + m_{c2} + m_2 + M_2 + m_f\right)g d_1 \sin\theta_1 + \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)g d_2 \sin(\theta_1 + \theta_2)$$

$$D_2 = \left(\frac{1}{2}m_2 + \frac{1}{2}\mathrm{M}_2 + m_f\right)g d_2 \sin(\theta_1 + \theta_2)$$

We can also simplify the equation (1) to static body mechanics. Based on the equation (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.

IV. DYNAMIC MODEL AND CONTROL STRATEGY

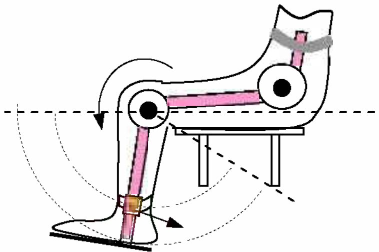
A. Dynamic behavior of the PAWL and human

The behavior of walking support machines must be simple for users [1]. So, the system should be worn easily; and, its sensors should not be placed directly on the user body.

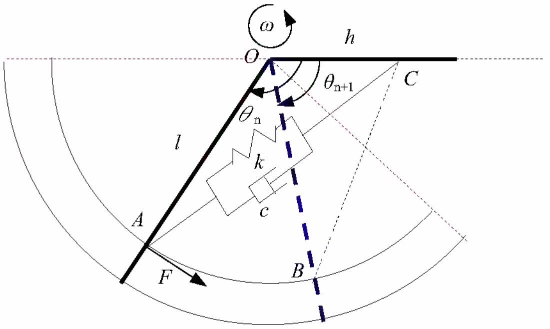
In order to use PAWL as a human power assistant, we should consider when and how to make the power assist robot to provide assist to user. The analyses focus on the dynamics and control of human-robot interaction in the sense of the transfer of power and information. Sensor systems are equipped on PAWL 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 joints' rotation. 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 work 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 mass-spring-viscidity system [15], we can show a configuration of the human-robot system (shown in Fig. 4).



(a) Configuration of the PAWL-human model



(b) Bone-muscle model

Fig. 4 Configuration of the human-robot

A simplified configuration of user's lower leg equipped with PAWL is shown in Fig.4. (a), and Fig.4. (b) shows a sketch map of the bone-muscle dynamic model. 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.

In the above simplified model, we ignore the disturbance which maybe caused by the friction of joints. The dynamics for the bone-muscle of user are represented by (2).

$$M = I\beta = I\dot{\omega} = I\ddot{\theta} \tag{2}$$

where

M Torque generated by muscle [N·m],
I Moment of inertia of the lower thigh [kg·m^2],
β Angle acceleration of knee joint [rad/s^2],
ω Angle speed of knee joint [rad/s],
θ Angle of knee joint [rad].

Torque generated by muscle can be expressed by the force (f_{muscle}) generated by muscle flexion and extension.

$$M = \vec{f}_{muscle} \bullet \vec{l} = f_{muscle} \cdot l \cdot \sin\angle OAC \tag{3}$$

where

$$\sin\angle OAC = \sin\theta_n \cdot \frac{h}{\left(h^2 + l^2 - 2hl\cos\theta_n\right)^{1/2}} \tag{4}$$

$$f_{muscle} = m\ddot{x} + c\dot{x} + kx \tag{5}$$

where x denotes the variable of muscle length during its flexion and extension. The variable x to the muscle are calculated by

$$x = \left(h^2 + l^2 - 2hl\cos\theta_n\right)^{1/2} - \left(h^2 + l^2 - 2hl\cos\theta_{n+1}\right)^{1/2} \tag{6}$$

Equation (5) shows a dynamic equation that stands on the mass-spring-viscidity model. In fact, it is difficult to obtain the exact value of k, c and m. The main reason is that human body is a complex system.

In order to make PAWL provide power assist for user during walking, we must amend the equation (2). Here, except for the moment of inertia of user lower thigh, the moment of inertia of exoskeleton link itself must be included in the equation (2), i.e. the moment of inertia of user thigh should be regarded as a part of PAWL. Therefore, the user limb is not only the generator of force giving out but also a load to PAWL. Additionally, a torque assist ratio μ (factor) is to be added to the equation (2). Now a new equation is given as follows:

$$M_{muscle} + \mu \cdot M_{exoskeleton} = \left(I_{thigh} + I_{link}\right) \cdot \dot{\omega} \tag{7}$$

I_{link} to the exoskeleton can be calculated by the rotation inertia formula:

$$I = \sum m_i r_i^2 \tag{8}$$

I_{thigh} to human leg can be estimated by equation [10]:

$$I_i = B_0 + B_1 X_1 + B_2 X_2 \tag{9}$$

Table 4 Coefficient of dual regression equation about rotation inertia

Segments	Inertia index	B_0	B_1	B_2
Thigh	Ix	-3705.377	4.284	28.621
	Iy	-3664.889	5.549	28.078
	Iz	65.270	7.165	-1.461
Lower thigh	Ix	-301.044	2.990	2.012
	Iy	-299.164	2.930	2.009
	Iz	-17.776	0.792	-0.033

where

X_1 Weight of user [Kg],

X_2 Height of user [cm],

I_x The rotation inertia circling frontal axis [Kg·cm^2],

I_y The rotation inertia circling sagittal axis [Kg·cm^2],

I_z The rotation inertia circling vertical axis [Kg·cm^2].

And, table 4 partly shows the coefficient of dual regression equation about rotation inertia based on weight and height of human body.

Because the whole system is periodically controlled by PC (sampling time is indicated by the symbol T), dt can be described approximately with sampling time T. That is

$$dt \doteq T \tag{10}$$

Angle acceleration can be expressed in discrete equation.

$$\dot{\omega} = (\omega_{n+1} - \omega_n)/dt \tag{11}$$

On inserting equation (10) and (11) into equation (7), we can obtain

$$\omega_{n+1} = \frac{M_{muscle} + \mu \cdot M_{exoskeleton}}{I_{thigh} + I_{link}} \cdot T + \omega_n \tag{12}$$

$$M_{exoskeleton} = F \cdot l \tag{13}$$

The operator ω_{n+1} and ω_n are the output angular speed of reducer in the equations mentioned above. It can be obtained by the information of encoder. In order to make PAWL provide power assist for user, an inequality (14) is satisfied as follows:

$$\mu > 1 \tag{14}$$

From above equation, we can calculate theoretically the percentage of power assist:

$$P_{ower} = (\mu - 1)/\mu \tag{15}$$

Due to the imprecise segment moment of inertia, equation (15) can not be regarded as a final power assist evaluating standard to the PAWL. Therefore, an effective evaluating method must be designed.

B. Control strategy

Fig.5 shows the 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 equation (12), a force/velocity control scheme was proposed to provide the exoskeleton with mechanisms to coordinate with human operator. The basic control system of the PAWL consists of five parts: control unit, actuator, transmission/executor, human-robot interaction and sensor system.

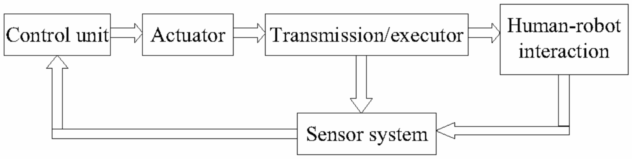


Fig.5 Control Scheme

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.

V. EXPERIMENT APPARATUS

We have conducted experiments to demonstrate and verify the force/velocity method. Due to the force sensors of PAWL are still in processing, here, we select force measure robot as the experiment platform in our laboratory (shown in Fig. 6). We use the existing experimental platform to simulate the interaction condition between human lower thigh and PAWL.

In our experiments, the force sensors and manipulator are used to verify the proposed control strategy. Force sensor placed on the link is used to measure the interaction force between the experimental manipulator and human forearm. Additionally, PUMA560 in our laboratory can also act as the experiment platform.

VI. EXPERIMENTS RESULT AND FUTURE WORK

Fig.7 shows the result of the experiment. We can find that the value of angle speed fluctuates according to the interaction force. It only indicates that the system can run automatically according with the user based on the interaction force between PAWL and user. In fact, we hope that the mechanism should provide much more power for user, so the sensitivity of the force sensor must be good. However, if we improve the sensitivity of the sensors, the uncertain disturbance will be added to the control system. Additionally, the direction of the interaction force decides the rotation direction of the motor, and it also reflects the forearm supination or pronation.

Fig.6 Experimental platform

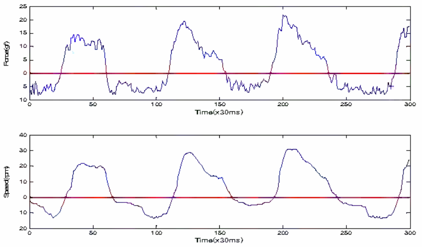


Fig. 7 The response to the experimental platform (force and speed)

The work presented is developing a mechanism, with the main goal of decreasing human inner force / increasing human strength during a certain activities or for special groups, such as succour, care-worker, elderly people, soldier and fireman. 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 s power for user without any accident.

An evaluation method of power assist will be proof-test validate. Here, we may use sensors to detect the exerting muscle forces of legs. First, we detect the exerting muscle forces of user legs in normal walk, without PAWL, a series of data we will get. Then, we will get another series of data when user wears PAWL. From comparing the two series of data, we may get the percentage of power assist. The muscle exerting forces of user legs can be detected by the EMG electrodes, muscle hardness sensors, and so on.

Current works on PAWL include processing force sensors, perfecting design architecture, constructing the whole exoskeleton dynamic model, validating the control method and evaluation method of power assist. In addition, the approaches using hybrid position/force control scheme and predictive control scheme will be verified experimentally. Some works have been finished as shown in Fig.8.

ACKNOWLEDGMENT

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Fig. 8 The primary profile of the PAWL

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