Power Assist System HAL-3 for Gait Disorder Person

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Abstract. We have developed the power assistive suit, HAL (Hybrid Assistive Leg) which provide the self-walking aid for gait disorder persons or aged persons. In this paper, We introduce HAL-3 system, improving HAL-1,2 systems which had developed previously. EMG signal was used as the input information of power assist controller. We propose a calibration method to identify parameters which relates the EMG to joint torque by using HAL-3. We could obtain suitable torque estimated by EMG and realize an apparatus that enables power to be used for walking and standing up according to the intention of the operator.

1 Introduction

At present, people with gait disorder can only move around by wheelchair or by using a wheeled walker. Unfortunately, barriers such as bumps and steps restrict the area that these people have access to. Elderly people who are unable to walk without assistance may lose muscular strength in their legs and become bedridden. Caring for bedridden people entails a large physical burden, and in aging societies such as Japan, this has resulted in a growing perception of this issue as a social problem for the entire community to deal with.

The most effective method ensuring that people do not become bedridden is to provide a way for them to be able to continue walking without assistance from a care-giver. In consideration of this problem, we have developed the *Hybrid Assistive Leg(HAL)* series for such people. The HAL is a walking aid system which capable of allowing the user to problem to movements such as standing up, sitting down, and going up and down stairs[1][2][3][4]. The purposes of this research are to develop HAL-3, to propose a calibration method to identify a constant relating EMG signal to joint torque, and to realize an apparatus that enables power to be used for walking and standing up according to the intention of the operator.

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2 HAL-3 System

HAL-3 system has three parts: skeleton and actuator, controller, and sensor. The schema of HAL-3 system is shown as Fig. 1.

The skeletal system of HAL-3 consists of exoskeletal frame. The exoskeletal frame is combined with the outside of the lower of limb, and transmit the assist force generated by the actuator to the lower of limb. The frame has joint at hip, knee, and foot respectively. The each joint has one degree of freedom, and the restriction is given at the joint mobile angle to ensure the safety of the person and to be correspondent to the movement of the human joint angle. The aluminum alloy and steel are used for the material of exoskeletal frame in consideration of lightness. The actuator system of HAL-3 provides the assist force for knee and hip joints. The actuator have DC-motor and harmonic drive to generate the torques of each joint. The actuator using harmonic drive is packed compactly, has large reduction gear ratio, and drives smoothly.

关节只有一个自由度

谐波减速

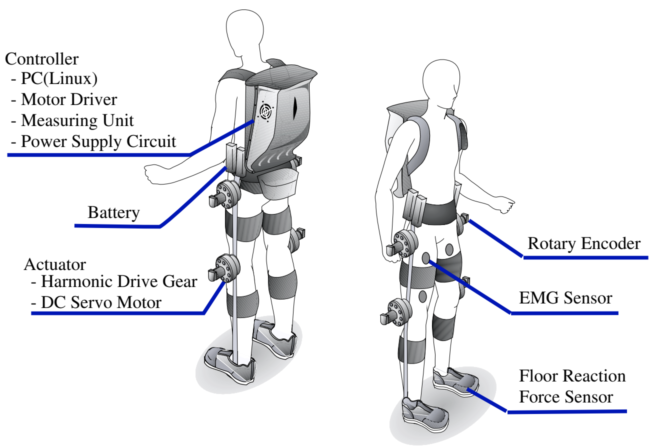


Fig. 1. HAL-3 system configuration. HAL-3 system consists of three parts: skeleton and actuator, controller, and sensor. These parts are developed in pursuit of lightness, compactness and mobility

The control system of HAL-3 is mainly developed by considering mobility because the field of activities of HAL-3 is presumed outdoors like corridors and stairs. So compact type PC as the controller, driver circuits, power supply, and measuring module are packed in the back pack. The real-time processing and the communication using the network are required in the control field. So the operating system of this PC is adapted as Linux which enables the measurement, the control, and the monitoring in real time. Wireless LAN(Local Area Network) card which has 11Mbps transmission speed, A/D(Analog to Digital) converter card which has 64ch(12bit resolution) inputs and D/A(Digital to Analog) which has 8ch outputs(12bit resolution) are selected respectively.

Sensor Systems of HAL-3 are used to detect HAL and operator's condition and estimate the assist force. The rotary encorder are prepared to measure the each joint angle, force sensors are installed in sole of foot to measure the floor reaction force (FRF), and the myoelectricity sensors are attached on the surface of the skin of leg to estimate the muscle activity and the estimated torques for knee and hip joints.

3 Estimation of Assist Torque

ENG signal of a muscle relates the torque generated by the muscle. It is effective to estimate the assist force from EMG signal. We need to decide the appropriate parameter relating EMG signal to joint torque. So,we propose a parameter calibration method using HAL–3.

3.1 EMG

EMG(Electro Myogram, myoelectricity) signals imply muscle activity, and are used as the estimation of joint torques. EMG is action potential generated in a muscle as the command signal from motion control system of human is transmitted to the muscle through the motor nerves. The muscle contracts, after EMG signal is generated. So EMG signal can predict the beginning of generation of the muscle strength to predict. The relationship between the joint torque and the processing EMG signal in isometric contractions has been reported to be linear[5]. The joint torque can be estimated by the EMG signal. Therefor, the appropriate assist torque can be estimated by using EMG.

The EMG signals are measured through bipolar skin surface electrodes fixed to prepared skin over muscle. EMG signal is amplified by 10^6 times, and filtered by using low pass filter cutting off at 500 Hz and high pass filter cutting off at 33 Hz to remove the effects by motion artifact. The filtered signal is transferred to PC through A/D converter. And imported signals are filtered again by low pass filter cutting off at 3 Hz to obtain the information of muscle force from spike signals[3].

3.2 Method

We find a joint torque from EMG signals which generate in the extensor and flexor respectively. The joint torques for knee and hip joints are estimated by using the following equations.

$$\hat{\tau}_{knee}(t) = K_1 E_1(t) - K_2 E_2(t) \tag{1}$$

$$\hat{\tau}_{hip}(t) = K_3 E_3(t) - K_4 E_4(t) \tag{2}$$

$\hat{\tau}_{knee}$ is estimated the torque for knee joint, $\hat{\tau}_{hip}$ for hip joint. $E_1,\ldots,E_4$ are EMG signals measured from the surface of the muscles shown in Fig. 2 In equation (1) and (2), the term of the positive means extensor and negative means flexor. $K_1,\ldots,K_4$ are

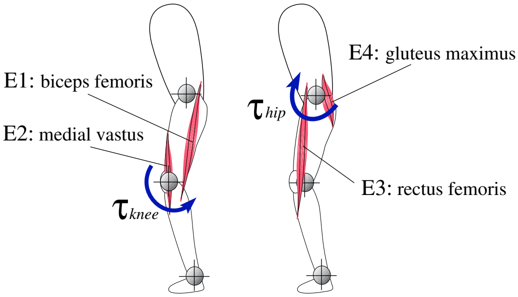


Fig. 2 Represented muscles in EMG measurement. The joint torques are estimated on based of these EMG signals

the parameters relating EMG signals to torques.

3.3 Procedures for Calibration

校准程序

应变计

Previously, the joint torque was measured by strain gauge to identify the parameters relating EMG signals to the joint torques. However, this method is very complex. We propose a parameter calibration method using HAL-3. HAL-3 is used to determine the parameters $K_1,\ldots,K_4$. We assume that each joint torque is generated by only agonist. For instance, to determine the knee flexor parameter K_1, the torque $\tau_m(t)$ as the signal for the calibration is generated by HAL-3 knee actuator. The subject generates the knee joint torque $\tau_{fl}(t)$ in order to match with the added $\tau_m(t)$. The knee joint torque $\tau_{fl}(t)$ is equal to $\tau_m(t)$ generated by the knee actuator because the subject outputs $\tau_{fl}(t)$ to keep the knee joint angle constantly.

通过力矩抵抗的方式进行肌电参数校准

$$\tau_{fl}(t) = \tau_m(t) \tag{3}$$

And the estimated torque calculated from EMG of the flexor is represented as

$$\hat{\tau}_{fl}(t) = K_1 E_1(t) \tag{4}$$

其中K为未知量

The error $e(t)$ between the measured torque $\tau_{fl}(t)$ and the estimated torque $\hat{\tau}_{fl}(t)$ is discretely represented as

$$e(k) = \tau_{fl}(k) - \hat{\tau}_{fl}(k) = \tau_m(k) - \hat{\tau}_{fl}(k) \tag{5}$$

The performance function J can be expressed as

$$\begin{aligned} J = e^2(k) &= \sum_{k=0} (\tau_m(k) - \hat{\tau}_{fl}(k))^2 \\ &= \sum_{k=0} (\tau_m(k) - K_1 E_1(k))^2 \end{aligned} \tag{6}$$

The performance function J can be minimized by setting its derivative with respect to K_1 equal to zero. This yields

$$\frac{dJ}{dK_1} = -2\sum \tau_m(k)E_1(k) + 2K_1 \sum E_1{}^2(k) = 0 \tag{7}$$

Therefore, K_1 can be expressed as

$$K_1 = \sum \tau_m(k)E_1(k) \Big/ \sum E_1{}^2(k) \tag{8}$$

The other parameters, $K_2,\ldots,K_4$ in Eq(1) and (2) are calculated by the least squares method similarly.

3.4 Protocols for Calibration

协议，草案

To obtain the parameters relating EMG signals to the joint torque, we explain the experimental protocols. The subject is normal 22 years old male. To measure the EMG of knee flexor and extensor, the subject sits with the hip held at near 90° to the upper body. The subject maintains the knee at near 90° against the knee actuator torque $\tau_m(t)$ (See Fig. 3). In the same way, to measure the EMG of the hip flexor and extensor, the subject keep upright standing posture. The subject maintains hip joint at 0°against the hip actuator $\tau_m(t)$. The reference torque $\tau_m(t)$ is made to increase from 8[Nm] to 32[Nm] in every 8[Nm] and is generated as a rectangular wave in the ten second period.

3.5 Evaluation

The parameters calculated for flexor and extensor of each joint is shown in Table 1. For the right leg, the torque estimated using calculated parameters and the reference torque generated by actuator are shown in Fig. 4

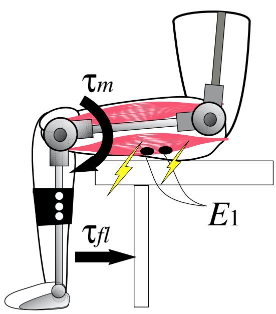
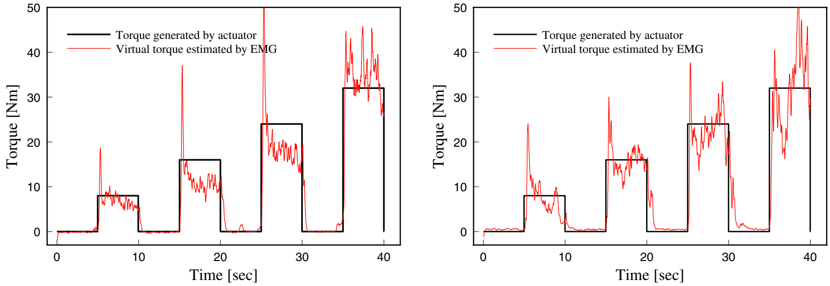


Fig. 3. System configuration of calibration to obtain the parameters by using HAL-3. In case of finding the knee flexor parameter K_1, the subject generates $\tau_{fl}(t)$ by biceps femoris in order to match with $\tau_m(t)$ derived by the knee actuator of HAL-3. K_1 is calculated from eq.(8) using the measured EMG signal E_1

For the extensor and the flexor of each joint, the EMG would be almost proportional to the torque generated by the actuator. Immediately the torque is generated by the actuator, EMG increases in spike like. The subject relaxes, while the torque is not generated. As the torque $\tau_m(t)$ is formed, the joint angle is slightly moved over the desired angle which is maintained in calibration. The subject needs to generate the relatively large torque to bring back the desired angle. Therefore, the relatively large EMG is produced. After this spike, EMG is maintained at the constant value according to the actuator torque $\tau_m(t)$.

Table 1. The values for each parameters calculated by calibration method using HAL-3

Parameter	$K1$	$K2$	$K3$	$K4$
Right leg	3.1133	2.8412	3.6481	4.8901
Left leg	4.5742	2.4446	3.2213	6.9093



(a) Right knee flexor (b) Right hip flexor

Fig. 4. Torque–EMG relationship resulting from calibration for flexor of the right knee and hip. The reference torque driven by HAL3 corresponds to the amplitude of the EMG of representative muscle

4 Power Assist Control

The experiments in walking and standing up are performed by using HAL-3. The assisted torques are estimated according to EMG signals generated in each motion.

4.1 Method

The subject is normal 22 years old male. To measure the EMG signals, the skin surface electrodes are fixed to prepared skin over of the represented muscles (See Fig. 2), and he wears HAL-3. The each parameters are obtained by the parameter calibration method which is shown in the preceding chapter. In the assistance of

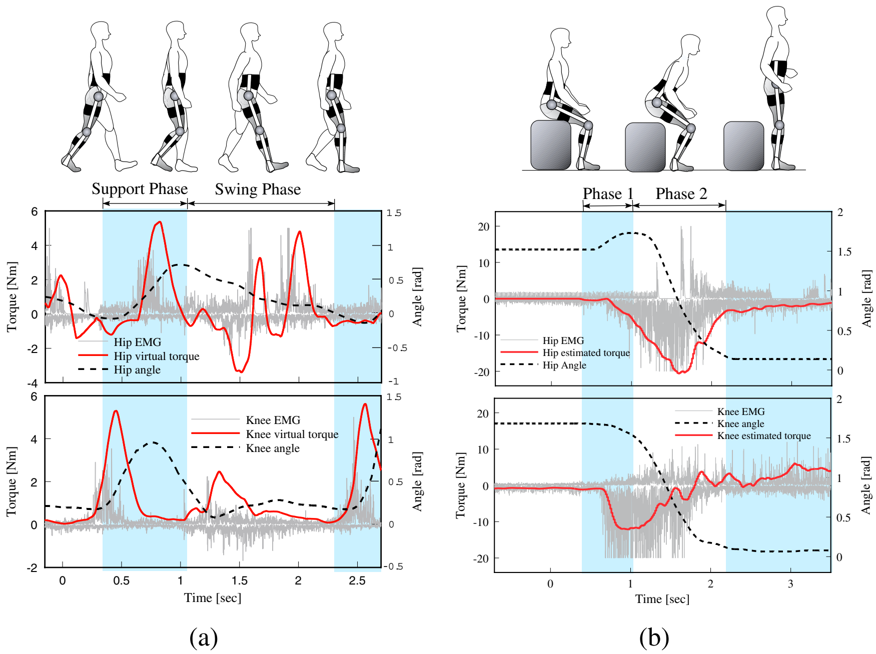


Fig. 5. *EMG*, *the estimated torque* and *the angle* for right hip and knee joints respectively, while power assist of HAL-3 is performed in walking(a) and standing up(b)

walking, the subject begins to walk from the initial condition of the standing posture. In standing up, the subject begins to stand up from the initial condition that the subject sits on the chair which is approximately 40cm high, and maintains the knee and hip joints at near 90°.

4.2 Result and Consideration

Figure 5 shows the estimated torques, the joint angles, and the EMG signals for hip and knee joint in walking and standing up. We divide the motion assisted by HAL-3 into phases corresponding to the particularities of the motion, and evaluate the assistance condition of each phase.

Walking. The motion of walking is mainly divided into two phases, *the support phase* and *the swing phase*. The support phase is the behavior that foot contacts on the ground surface and the body is supported. The swing phase is the behavior that the foot gets from the ground surface, and the leg swings forward.

Figure 5(a) shows that the power assist of HAL-3 is performed in walking. In the support phase, EMG signals are generated at the flexor of hip and the extensor of knee. The walking in the support phase is assisted according to the operator's intention by the suitable estimated torque. In the swing phase, the inappropriate estimated torque calculated by EMG signals of hip extensor is generated. It is considered that the hip extensor works to stop the leg swinging forward too much.

Standing Up. The motion of standing up is mainly divided into two phases, *phase 1*, *phase 2*. The phase 1 is the behavior that the center of gravity of the body is moved into the region where the center of gravity is stably maintained at the standing posture. The phase 2 is the behavior that the upper body is lifted by extending knee and hip joint.

Figure 5(b) shows that the power assist of HAL-3 is performed in standing up. In phase 1, EMG signals begin to generate at the extensor of the both hip and knee, and EMG signals of extensor of knee are large. It means that operator moves the center of gravity of his body into the stable region, as the knee joint gets the large toque. In phase 2, the estimated torque of knee diereses. Contrary, the torque of hip increases. So the large hip torque is generated to lift his upper body. Therefore HAL -3 realizes the aid of standing up in correspond the operator's intention.

5 Conclusion

To provide the walking for gait disorder persons, we developed HAL-3 in the consideration of lightness, compactness and mobility. EMG signals were used as a control signal of HAL-3. We proposed the calibration method of the parameters relating EMG signals of the representative muscles to the joint torques for knee and hip joints using HAL-3. The power assist of HAL-3 was realized according to the operator's intention in walking and standing up. The power assist on based EMG by HAL-3 was regarded as essential to aid the basic motion. In the near future we will apply the more sophisticated HAL-3 for gait disorder persons.

问题：
1.按照这样的校准方式，理论上人体的力矩都由外骨骼产生，那么人体肌肉不应该收缩？
或者说人体与外骨骼个提供百分之五十的力矩？
2.有助力无无助下肌电信号的变化时怎样的？

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