DEVELOPMENT OF BIOMIMETIC HAND PROSTHESIS WITH MORE POWERFUL MOTOR

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Abstract: A biomimetic myoelectric hand prosthesis consisting of electromyogram (EMG) signal processing units, a microprocessor-based DC motor servo system and a one-degree-of-freedom end effector have been developed. The finger angle and compliance of this prosthesis can be voluntarily controlled with EMG signals. Basic functions of the human neuromuscular control system are realized by using position control, force feedback and variable gain modulated by EMG signal amplitude. An amputee subject was able to easily grasp a soft object after a short training period.

Introduction

Powered hand prostheses are used to replace the functions of a lost natural hand. Most of the commercial prosthetic hands in clinical use are controlled by myoelectric signals (electromyogram, EMG), and are referred to as myoelectric hands [1-4].

There are two types of voluntary control system of the myoelectric hands: on-off (known confusingly as “digital”) and analog. In a ‘digital’ control system, when the amplitude of the EMG signals exceeds a threshold determines when the fingers open or close, the velocity is fixed. One of the best-known digital systems is the MYOBOCK System Electric Hand by Otto Bock Orthopedic Industry [5].

In analog control systems, the rectified and smoothed EMG (RSEMG) signals are used as control signals. Two types of analog control system have been reported: proportional and compliant. In a proportional control system, the velocity of the opening or closing of the hand increases with increasing difference in RSEMG between the flexor and extensor muscles.

A compliance control system allows users to voluntarily control both the finger angle and the compliance. Skeletal muscles have well-known viscous and elastic properties [6], and the dynamic properties of both the muscle itself and the stretch reflex are not fixed but change depending upon the activation level of muscle contraction [7]. These properties play an important role in maintaining posture and controlling limb movements as well as in absorbing mechanical impact exerted on the limb. A prosthetic hand that restores these lost functions should allow the user to easily grasp both soft and hard objects by controlling the compliance of the hand.

Based on the above considerations, the biomimetic myoelectric hand is designed to mimic the basic functions of the neuromuscular control system of human finger muscles [8, 9]. In a previous study, it was found that two limb absent subjects were able to voluntarily control with the hand and so grasp soft objects [9]. However, the power of the DC motor of the prosthesis did not provide sufficient control of compliance to allow practical use of the hand.

The purpose of the present study was to develop an

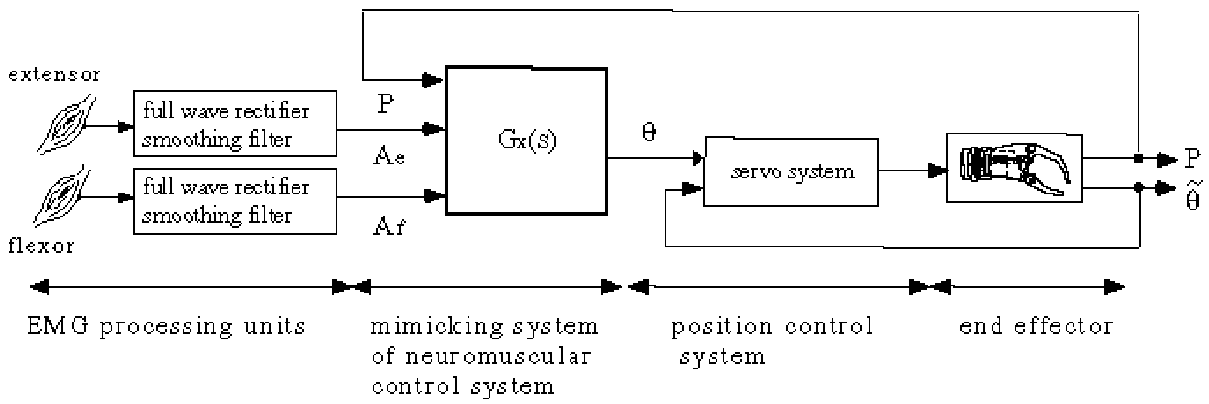

Figure 1 Block diagram of the biomimetic hand. Angle and stiffness are controlled with EMG signals of flexor and extensor muscles.

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improved version of the hand that uses a more powerful DC motor (6 watt) and a recently developed advanced microprocessor unit (MPU). Once again it was found that the users were able to voluntarily control the finger angle and the compliance and grasp soft objects.

Biomimetic Myoelectric Hand Controller

Figure 1 shows a block diagram of the biomimetic myoelectric hand. The hand consists of EMG processing units, a system to emulate the neuromuscular control system, a position control system and an end effector.

EMG processing units

Output of the EMG processing units is roughly related to the contractile force of the muscle. The outputs of the flexor and extensor are denoted by A_f and A_e, respectively. The model in Figure 2 expresses the contractile force $A^*(t)$ as a function of EMG signal $e(t)$, where $r(t)$ is the output of a full wave rectifier and $H(j\omega)$ is the output of a smoothing filter. A parametric filter $H(j\omega)$ was needed for the prosthetic hand.

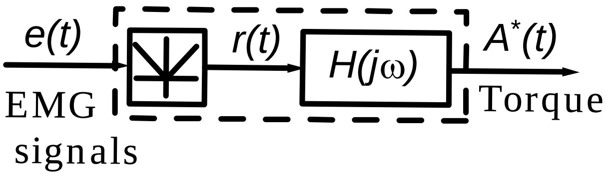

Figure 2 Configuration of EMG processing unit.

The smoothing filter was designed as follows. First, the three healthy subjects were asked to perform voluntary isometric contraction to measure EMG signals $e(t)$ and the isometric torque $A(t)$. Then, the filter $H(j\omega)$ was calculated as follows:

$$H(j\omega) = G_{rA}(j\omega)/G_{rr}(j\omega) \qquad (9)$$

where $G_{rr}(j\omega)$ is the auto-spectral density function of $r(t)$, and $G_{rA}(j\omega)$ is the cross-spectral density function of $r(t)$ and $A(t)$. Next, transfer functions of the smoothing filter $H(s)$ were calculated from different criteria. Finally, an optimal transfer function was selected from among these transfer functions by examining performance of the finger angle control. We selected filter (A) as the optimal filter, using the following equation:

$$H(j\omega) = \frac{K_n \omega_n}{s^2 + 2\zeta\omega_n s + \omega_n{}^2} \qquad (10)$$

Where,
$K_n = 30.1 Nm/mV, \quad \omega_n = 15.5/s, \quad \zeta\omega_n = 13.2/s.$

Figure 3 shows one of the results of the measured isometric torque and the estimated one. The subjects changed the torque almost triangularly at a certain frequency. The estimated torque was almost same as measured torque.

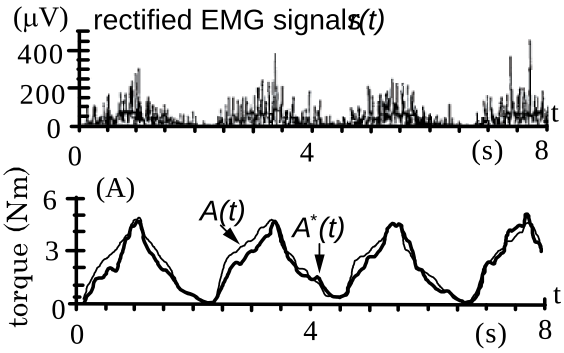

Figure 3 Rectified EMG signals of the extensor muscle and isometric force. Thin line $A(t)$ is the measured force. Solid line is force curves, $A^*(t)$, obtained using the smoothing filters.

System to emulate the neuromuscular control system

In order to emulate the neuromuscular control of the finger, the desired finger angle is calculated, based on simplified dynamics of a neuromuscular control system, which consists of the flexor and extensor muscles. The angle of the joint is denoted by $\theta(t)$, and the torque around the joint by $P(t)$. We define the joint output torque $P(t)$ as the difference between torque of the flexor $A_f(t)$ and torque of the extensor $A_e(t)$, when the joint is maintained at the angle $\theta(t)=0$. Assuming that when the joint angle changes from $\theta(t)=0$, torque is added depending on the muscle length; this implies that the torque is due to the viscous and elastic properties of the muscles and the stretch reflex. Denoting this relation by the transfer function $G_x(s)$, the dynamic equation of the neuromuscular control system is expressed as follows:

$$\theta(s) = \{A_f(s) + A_e(s) - P(s)\}/G_x(s) \qquad (1)$$

Although the dynamics of this system are complicated by nonlinearities and time delays, as the first step, we express $G_v(s)$ in the simplest form by referring tension responses of the muscle to stretch [8].

$$G_x(s) = K\frac{1+\tau_1 s}{1+\tau_2 s} \qquad (2)$$

$$K = K_0 + a(A_f + A_e) \qquad (3)$$

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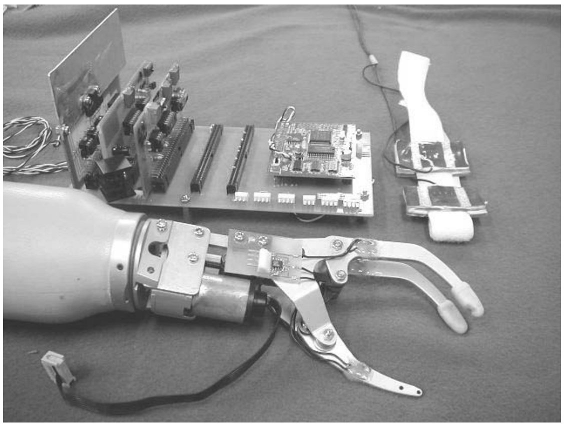

Figure 4 Photograph of the developed Biomimetic Prosthetic Hand.

Figure 5 Photograph of the handling of a soft object with the prosthesis.

where τ_1 and τ_2 are time constants, K is gain (stiffness). The values K_0=0.1 Nm/rad, α=0.98 /rad, τ_1=0.12 s and τ_2=0.25 s were used for human finger muscles, where K_0 represents the resting state [8].

Position control system and an end effector

Figure 4 shows the developed myoelectric hand. The end effector consisted of a thumb, index and middle finger, which opened or closed simultaneously. The torque *P(s)* applied to the fingers was measured with strain gauges attached to each finger. Both the neuromuscular control emulator and the servo controller (proportional and differential [PD] controller) of the position control system in Fig. 1 were installed in the digital servo system. We selected a MPU (H8-3067/F, HITACHI) that provides fast calculation and real time control, and selected a high power DC motor (A-max 22 mm, 6 watts, Maxon) that provides fast mechanical response.

Myoelectric Control Experiments

Myoelectric control experiments were conducted with the prosthetic hand developed in the present study, to determine whether the users were able to grasp soft objects. The experiments were conducted with an a limb absent subject, who gave informed consent. The EMG signals were picked up from m. flexor carpi radialis and m. extensor carpi ulnaris, respectively.

A prosthesis user grasped a soft object (a cream puff) with the prosthetic hand. Both of the subject's hands had been amputated below the elbow. He used the MYOBOCK System Electric Hand (on-off type) until about 5 years ago, and has since been using a body powered split hook. In a previous laboratory study, he participated in experiments using another prosthetic hand we had developed.

First, the subject participated in preparatory testing of the control of the prosthetic hand (finger angle) for about 10 minutes. Then, the object grasping experiment was conducted. The object was placed on a desk, and the subject was asked to grasp it, lift it up and place it back on the desk. The experimental setup is shown in Fig. 5.

Time profiles of the experiments are shown in Fig. 6. At the first stage, the finger was opened to about 70 degrees, and was then closed on the object in about 1s (indicated by arrow (A)). The subject grasped the object at time A and released it at time B. The results indicated that the subject could grasp the soft object easily and smoothly with the prosthetic hand.

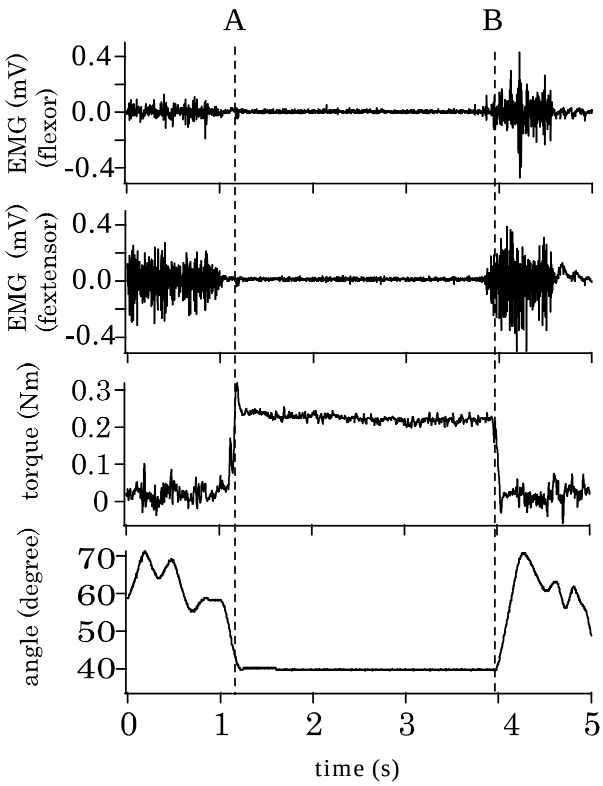

Figure 6. Time profiles of the handling of a soft object shown in Fig. 3

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Conclusions

In this paper, a biomimetic myoelectric hand was described and a controller that it allows voluntary control of compliance was demonstrated.

1. A biomimetic myoelectric hand prsothesis has been developed. It was consisted of electromyogram (EMG) signal processing units, a microprocessor-based DC motor servo system and a one-degree-of-freedom
2. It has been shown that an amputee subject can easily grasp a soft object after a short period of training.

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