ANALYSIS OF GRASPING MOTION USING A VIRTUAL PROSTHETIC CONTROL SYSTEM

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ABSTRACT
Electromyogram (EMG) signals can be measured from human muscles and can be used to anticipate movements. In fact, many researchers have tried to use these signals as an interface tool for a prosthetic hand. However, most of these studies focused on the discrimination performance of the EMG signals, and only discussed the control method for the prosthetic hand. Evaluation of the operating performance while the operator wore the prosthetic hand was seldom reported. This paper presents the analyses of a grasp motion under two different EMG control methods: ON-OFF Digital Control (Digital) and Dynamic Mode Control (DMC). DMC is able to proportionally control the grasping velocity based on the amplitude of the EMG signal. Digital controls the hand at a uniform rate while the amplitude of the EMG signal is greater than a predefined threshold. We conducted experiments based on a virtual prosthetic control system, and results indicate interesting differences in these control methods.

KEY WORDS
Prosthetics and Orthotics, Rehabilitation Engineering, Robotics, EMG, Interface

1 Introduction
Many researchers have designed EMG-controlled hands for amputees since the concept of Cybernetics by Wiener [1]. The pioneering research regarding the EMG-controlled hand was conducted from the 1960s to the 1980s. Kato et al. at Waseda University developed the Waseda hand that had five fingers controlled by EMG signals [2], and Jeard et al. at MIT proposed the EMG-controlled above-elbow prosthesis [3]. Moreover, the Utah artificial arm was developed by Jacobson et al. at Utah State University [4]. Today, the Otto Bock hand is the most widely used EMG-controlled hand [5]. This prosthesis hand has a powerful grasping force, and is useful for basic daily activities. The Otto Bock hand, however, is cumbersome, and its range of motion is very limited; allowing for only the opening and closing of the hand.

Today, research on EMG-controlled hands continues [6], [7]; however, much of the recent interest is in the discrimination algorithm and its accuracy. Not much discussion has included the evaluation of the operating performance while the prosthetic device is being worn. The control performance during practical applications must be evaluated.

In this paper, we present a novel, virtual prosthetic control system for evaluating and improving the method of operating an EMG-controlled hand. Various control methods are introduced by means of specially designed software. The flexibility and high efficiency of the virtual control system is suitable for prototyping EMG-controlled hands prior to implementing an actual control method into the prosthetic device. In this paper, we present the analysis of a grasping motion under two different EMG control methods, ON-OFF Digital Control (Digital) and Dynamic Mode Control (DMC). These control methods have been adopted by Otto Bock Inc. [5] and are widely used for the EMG-controlled Otto Bock hand. Herein, we introduce the components of the virtual prosthetic control system and discuss the experimental results.

2 Virtual prosthetic control system

2.1 System components
The components of the virtual prosthetic control system are illustrated in Fig. 1. The system consists of an EMG amplifier system (Bagnoli-4, Delsys Inc.), a 3D position sensor system (Isotrack, Polhemus Inc.), a personal computer (Intel(R) Core(TM)2 Duo, 3.00 GHz), and feedback display (FlexScan S2410W, EIZO NANAO Corp.). The 3D position sensor measures the wrist joint position of the operator, and the personal computer simulates the motion of the virtual prosthetic hand based on the recorded EMG signals.

The feedback display, with a screen refresh rate of 20 Hz, shows the virtual prosthetic hand and a target object (actual size). A schematic diagram of the virtual hand and the object is illustrated in Fig. 2. The operator can control the virtual hand using their EMG signals and their upper limb motion. The grasping force between the virtual hand and the target object are calculated during the task. The calculation is currently based only on the static equilibrium of the contact force, and does not consider the dynamics of the both bodies. The dynamics of both the hand and the target object will be introduced in future studies.

The grasping force, the EMG signals, the hand position, and the hand width are recorded onto the hard disk of
the personal computer. It should be noted that in the present study, the 3D position sensor only measures the motion of the hand toward the object, and the EMG signals are only used for opening and closing the hand.

2.2 Prosthetic hand control methods

The two EMG control methods used in the present study (Digital and DMC) can be flexibly changed using the associated software. DMC is able to proportionally control the grasping velocity based on the amplitude of the EMG signal. Digital controls the hand at a uniform rate while the amplitude of the EMG signal is greater than a predefined threshold. These types of control methods have been adopted by Otto Bock Inc. and are widely used for their EMG-controlled Otto Bock hand (Fig. 3). The specifications of the Otto Bock hand are listed in Table 1. The parameters of the developed virtual hand in the present study are configured based on these values.

Two electrodes placed on the extensor and flexor muscles are used for the control, each one corresponding to the opening and closing motion. The EMG signals are sampled at a frequency of 1 kHz, rectified and then filtered using a digital low-pass filter with a cut-off frequency of 2 Hz. The smooth envelope signals are subsequently re-sampled at a frequency of 20 Hz and defined as $EMG(t)$. Here, $t$ indicates the re-sampled time. For the Digital control, the hand moves at a uniform rate while $EMG(t)$ is greater than a predefined threshold. The velocity of the DMC hand is proportionally controlled by the amplitude of $EMG(t)$. The proportional velocity is defined as:

$$V(t) = \frac{EMG(t) - a}{EMG_{max}} \times (V_{max} - V_{min}) + V_{min},$$

(1)

where $V(t)$ indicates the proportional velocity at $t$, $a$, $V_{max}$, $V_{min}$ indicate the predefined threshold and the maximum and minimum velocity of the hand, respectively. If $EMG(t)$ is not over $a$, the hand does not move ($V(t) = 0$). The opening and closing motion is selected corresponding to the electrode that records the EMG that is above the predefined threshold.

3 Experimental Setup

Experiments were conducted in order to evaluate the operating performance under the Digital and DMC control


<table>
<thead>
<tr>
<th>Specifications of OttoBock hands</th>
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<tbody>
<tr>
<td>1. Digital type (Size: 7 1/4)</td>
</tr>
<tr>
<td>Operating voltage [V] 6/7.2</td>
</tr>
<tr>
<td>Opening width [mm] 100</td>
</tr>
<tr>
<td>Velocity [mm/sec] 110</td>
</tr>
<tr>
<td>Grasp force [N] 80</td>
</tr>
<tr>
<td>Weight [g] 457</td>
</tr>
<tr>
<td>2. DMC type (Size: 7 1/4)</td>
</tr>
<tr>
<td>Operating voltage [V] 6/7.2</td>
</tr>
<tr>
<td>Opening width [mm] 100</td>
</tr>
<tr>
<td>Proportional Velocity [mm/sec] 15-130</td>
</tr>
<tr>
<td>Proportional grasp force [N] 0-90</td>
</tr>
<tr>
<td>Weight [g] 457</td>
</tr>
</tbody>
</table>

methods. Informed consent was obtained from three subjects (male; age range: 30-39 years) prior to participation in the experiments. Subjects also participated in 4 days of training before experimentation, with less than 2 days between each training session.

At the sound of a start signal, through the use of their recorded EMG signals and upper limb movements, subjects approached and grasped the target object. Fifteen trials were conducted for each EMG control method. A real-world experiment identical to the virtual environment was also conducted. Subjects were asked to grasp a real target object 15 times using their hand, and the trajectory of the wrist joint was recorded during the real-world grasping motion. In both the virtual and real-world experiments, the distance between the initial hand position and the target object was 0.25 m, and the width of the object was 0.06 m. The electrodes were placed on the extensor carpi ulnaris (ECU) muscle and the flexor carpi radialis (FCR) muscle. The extension and flexion motion of the wrist joint was used for the opening and closing motion of the EMG-controlled hand, respectively.

Two kinds of operations were analyzed during the experiments, i.e., the EMG operation and the upper limb movements. Subjects were required to simultaneously open and close the hand as well as approach to the object. Subjects were prohibited from executing these two operations in sequence and were also prohibited from repeating the operation halfway through the trial.

4 Results

Results of a subject controlling the virtual prosthetic hand using upper limb movements and EMG signals are shown in Fig. 4(a) and (b). The hand position and width are shown in Fig. 4(a). The approach and opening and closing motions were performed simultaneously during the task. The muscular contraction rates of the ECU and FCR muscles are shown in Fig. 4(b). As shown in this figure, the subject proportionally controlled the grasping velocity based on the muscular contraction rates. The following were calculated during the experiments: 1) Total operating time, 2) Maximum grasping force, 3) Hand opening and closing velocity, 4) EMG operating time, 5) Integrated EMG signals, 6) Movement trajectories. The analysis of these parameters is introduced in the following sections.

4.1 Operating performance

The total operating time is shown in Fig. 5; and clearly shows that the Digital and DMC hand take considerably longer to conduct the task compared to the actual human hand. The results of the DMC hand were a little longer than the Digital hand, with a significance level of 1% ($p < 0.01$). The maximum grasping force obtained during the task is shown in Fig. 6. The grasping force was calculated based on a predefined elasticity coefficient of 8000 N/m. A large force was observed during use of the Digital hand, though the subjects were instructed to grasp the object using a small force. Conversely, a small grasping force was observed when subjects used the DMC hand.
4.2 Prosthetic control ability

The velocities for the opening and closing motions of the virtual hand are shown in Fig. 7. It should be noted that the velocity of the Digital hand, a uniform 0.11 m/sec, is provided for reference. As shown in Fig. 7, the driving velocity between the opening and the closing motions definitely changed while using the DMC hand. Specifically, the opening velocity was fast, and the closing velocity was slow. The velocity of the DMC hand was relatively slow compared to the Digital hand, because the overall velocity of the DMC hand contained slow velocities at both the start and the finish of the grasping motion.

The operating time for the EMG control is shown in Fig. 8. There was no difference in the DMC results between the opening and closing motion, but the closing time was clearly shorter than the opening time in the case of the Digital hand. These results suggest that the subject might control the Digital hand motion based on the operating time period because the velocity of this hand cannot be changed. This figure also shows that the DMC hand had a longer operating time compared to the Digital hand.

The integrated EMG signals are shown in Fig. 9. Subjects tended to generate more EMG signals during the opening operation because the hand was completely closed at the start of the experiment. The integrated EMG signals of the DMC hand were greater than those of the Digital hand, with a significance level 1\% (p < 0.01). Results suggest that the DMC hand requires more EMG signals than the Digital hand in order to control the hand motion with a greater velocity.

4.3 Cooperation between the EMG operation and the upper limb movement

Finally, we examined the trajectory of the hand movement and its width during the grasping task. The mean values for all subjects and trials are shown in Fig 10. The time base was normalized by the total operating time, and data were plotted every 10\%. The width of the Digital hand was much greater than the width of the object, while the width of the DMC hand was controlled according to the object width. The velocity of the DMC hand gradually decreased before contact with the target object, and this hand stopped at the appropriate position. The Digital hand rapidly moved even in close proximity to the object, and subsequently compressed it. As also shown in Fig. 10, the DMC hand approached that target object earlier than the Digital hand. The results show that the DMC hand grasped the object slowly and carefully.

The hand width and the distance to the object during the task are shown in Figs. 11 and 12, respectively. The time base was normalized by the total operating time, and data were plotted every 10\%. The approach of the human hand is plotted for comparison in Fig. 12. As for hand
5 Conclusion

In the present study, we developed a virtual prosthetic control system, and analyzed a grasping motion under two different EMG control methods. The control methods were simulated according to the ON-OFF Digital Control method and the Dynamic Mode Control method, which are widely used for EMG-controlled prosthetic hands. Three subjects participated in experiments involving a grasping task in a virtual environment. In order to compare the EMG control methods, the operating performance, prosthetic control ability, and cooperation between the EMG control and upper limb movements were analyzed. The experimental results clearly indicate an interesting difference in these control methods. Also, the trajectory of hand movements was influenced by the performance of the EMG control method. In future studies, we would like to conduct experiments using many subjects, including amputees, and attempt to develop a new EMG control method based on these analysis results.

This research was partially supported by a Grant-in-Aid for Young Scientists [(B), 21700591, 2009] from the Ministry of Education, Science, Sports and Culture.

References


