A Force-controlled Three-finger Prosthetic Hand via Three-Dimensional Printing

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Abstract
This paper presents the development of a force-controlled 3D-printed prosthetic hand commanded by surface electromyography. The prosthetic hand used force control to pick up a 600-ml water bottle without any damages. Two experiments were carried out to determine the model of the system. The first one is to determine the relationship between the voltage of electromyography and the handgrip force. The second one is to determine the relationship between the current of DC motor and the water bottle grip force. Feedback control was used to control the gripping force. The prosthetic hand was tested for its gripping water bottles. Percentage of success in holding water bottle with a closed bottle cap is 90% of all brands. With opened bottles, the prosthetic hand cannot hold bottles from one brand, which is made of a soft plastic shell. The remaining brands of water bottle have a percentage of success above 90%.

Keywords: force-controlled, three-finger gripper, three-dimensional printer, surface electromyography

1. Introduction
The three-dimensional printing was widely applied in a variety of fields such as education, automotive industry, engineering, architecture, medical, etc. One of the medical applications is the creation of prosthetic hands to help disabled people. The survey of the National Statistical Office in 2007 found that 43.7 percent of the disabled in Thailand do not have access to the aiding equipment [1]. While the number of disabled people in Thailand increases (from 2017 to 2018). The three-dimensional (3D) printing promises an ability to customize the size to fit with the body of a disabled person. However, the current designs of 3D printed prosthetic hands do not function sufficiently for their needs. This work focuses on the grasping function to help the disabled to hold things in daily life.

In order to gain information from experts in the field of prosthetic hands, we contacted the head of Prosthesis and Orthosis division, Sirindhorn National Medical Rehabilitation Institute to provide the requirements of the prosthetic hand. From his experience, a prosthetic hand using strings and elastics [2] cannot firmly grasp an object, cannot control the grasping force and has a short lifetime.
In addition, objects that the disabled people want to grasp in their daily lives include spoon, fork and plastic water bottle.

The low-cost prosthetic hands using 3D printing were designed with various requirements [3-4]. This research focuses on the design of a prosthetic hand with minimal mechanical movement. The prosthetic hand must handle a 600-ml. plastic water bottle with a firm grip, which prevents damage on the plastic water bottle. In addition, the grasping force must be controlled without extra sensors, but using the signal from the motor itself.

2. Prosthetic hand design
The prosthetic hand was designed specifically to hold water bottles. Therefore, the inside of the finger was designed to be a circular shape (as shown in Figure 1). The gripper has three fingers – two fingers on one side, and one finger on the other side, which moves between the other two fingers in a closing position.

2.1 Grasping Force and Motor Selection
A 12-V worm-gear motor is chosen with a speed of 10 rpm. At such speed, the motor can provide a torque of 722 N-mm. The grasping force places on a plastic water bottle. At 50 mm. away from the motor’s rotation point, as shown in Figure 1. The forces are the same on both sides of the gripper as shown by the free body diagram in Figure 2. Note that the diagram shows only one finger on each side for simplicity, but the summing forces are the same either for one or two fingers on one side.

The grasping force $F$ can be calculated by the motor torque as follows:
The maximum weight, which the gripper can lift up at the maximum grasping force, can be computed by the following equations,

\[ F = \frac{T}{s} = \frac{722}{50} = 14.44 \text{ N} \]

Therefore, the gripper has sufficient force to carry the 600-ml water bottle.

2.2 The Prosthetic hand prototype

A prosthetic hand prototype was designed as shown in Figure 3. It connected with the control devices including Arduino Uno R3, ACS712 current sensor, Myo-Ware Muscle Sensor, L298N dual H-bridge motor controller and Li-Po battery. The control operation will be described in the next section.

![Figure 3. Prosthetic hand prototype](image)

3. The Control System

3.1 The Control Scheme

The control objective is to control the grasping force according to the user’s desired force measured by a Myo-Ware Muscle Sensor to detect the electromyography signal. When the motor starts working and the gripper starts squeezing the water bottle, the value of the current that applies to the motor increases. The automatic control system relies on a current sensor and converts the motor feedback current to the actual force against the water bottle.

Then the microcontroller compares the actual force and the desired force and then feeds the difference to drive the motor as shown in Figure 4.
3.2 Relationship between the Myo-Ware Muscle Sensor and the desired force
To find the relationship between electromyography and the desired gripping force, an electromyography signals and corresponding gripping force were measured and plotted as shown in Figure 5. The electromyography signal was measured by attaching the Myo-Ware Muscle Sensor at a forearm. The gripping force was measured by squeezing a hand dynamometer. The relationship equation between the electromyography signal (x) and gripping force (y) is

\[ f(x) = 198.67x - 18 \]

\[ R^2 = 1 \]

3.3 Relationship between the Motor Current and the Actual Gripping Force
To find the relationship between DC motor current and the actual gripping force of the prosthetic hand, test weights, range 0-600 gram, were hung at the middle of the finger, 50 mm. away from the motor axis. The motor currents were measured with respect to the test weights and plotted on a graph as shown in Figure 6. The relationship equation between the motor current (x) and the gripping force of the prosthetic hand (y) is

\[ y = 29.715x - 0.0435 \]
Figure 6. The relationship between motor currents and actual gripping forces of the prosthetic hand

3.4 Programming
The control system of the prosthetic hand was implemented on Arduino Uno, which is a low-cost microcontroller using C programming language. The control diagram can be shown by the block diagram in Figure 7.

Figure 7. Block diagram of the control system programming
4. The prosthetic hand grasping test

The prosthetic hand was used to grasp plastic water bottles from 9 manufacturers (represented by brands A to I). The dimensions of the plastic water bottles are described in Figure 8 and Table 1.

![Figure 8. Dimensions of plastic water bottle](image)

Table 1. Dimensions of 600-ml plastic water bottle

| Brand | h (mm) | e (mm) | d (mm) |
|-------|--------|--------|--------|
| A     | 225.83 | 0.19   | 63.30  |
| B     | 233.21 | 0.22   | 63.06  |
| C     | 237.10 | 0.29   | 61.06  |
| D     | 233.36 | 0.25   | 63.14  |
| E     | 236.26 | 0.26   | 61.00  |
| F     | 233.45 | 0.24   | 63.10  |
| G     | 232.81 | 0.28   | 64.20  |
| H     | 237.83 | 0.25   | 62.89  |
| I     | 240.20 | 0.23   | 60.69  |

The prosthetic hand was tested to hold the opening water bottles from 9 brands, with 20 repetitions for each brand. The test was considered/regarded as successful if the water bottle was held still and no water was spilt.

![Figure 9. Percentage of success from holding water bottles from 9 brands](image)

From the test, the prosthetic hand can hold 8 brands of opening water bottles with a percentage of more than 90% success in holding water bottles. Brand A failed the test because of the small thickness of the bottle. However, brand A passed the test more than 90% when the water bottle was closed.
5. Conclusion
The prototype of the prosthetic hand-worked according to the objective. It can hold the opening 600-ml plastic water bottles with 8 out of 9 brands. A problem from the force control using the electromyography is that the accumulated fatigue from the contraction of the muscle directly affected the function of the prosthetic hand. While the prosthetic hand holding a water bottle but the value of electromyography is reduced, the prosthetic hand spread the finger immediately causing the failure of holding a water bottle.

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