# A DEVELOPMENT OF LOW-COST ACTIVE PROSTHESIS HAND PRINTED BY 3D PRINTER

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## ABSTRACT

This paper proposes the development of a low-cost active prosthesis hand-printed by a 3D printer. The bend sensor connected to the patient elbow is used in this research to control the operation of the prototype. The limitations of this research are the handicap of the patient that needs to have a wrist to the elbow which weighs under 0.5 kilograms. The experiments are divided into 3 sections (i) squeezing force measurement, (ii) object holding experiment, and (iii) battery consumption experiment. The results showed that the low-cost active prosthetic hand has the stability of squeezing force. The average squeezing force at the center of fingers is found to be 16.25 N, and the average squeezing force at the end of fingers (baby finger) is 12.55 N. It also has 1.25 and 1.37 of standard deviation (SD) respectively. Besides, the prototype can pick and hold huge and small objects which has a mass of less than 0.5 kg weight. Moreover, the prototype has low energy consumption around 48.96 Watt-hour. The cost of the equipment without a 3D printer is less than 100 US dollars.

**Keywords:** Prosthetic hand, 3D printer, Bend sensor, Microcontroller

## 1. INTRODUCTION

Presently, In Thailand many people are physically challenged, also due to road rage accidents many people are physically impaired and these accidents are increasing every year. The Department of Empowerment of Persons with Disabilities said that in 2019, Thailand has 1,043,308 (52.38%) male disabled people and 952,459 (47.72%) female disabled people. Most of the disabled people in Thailand have physically impaired people which are 986,583 (49.43%) people [1].

According to physically impaired people in Thailand, most of the physically impaired people is caused by accident such as road accident and machine accident. Most physically impaired people in Thailand risk to be unemployed. So, it can cause serious social problems to their families and government. Moreover, it leads to an economic recession. Therefore, these problems need to be solved urgently to reduce the inequality between disabled people and normal people. It is not only a social problem but also a personal problem. disabled people always suffer when they do their routine activities. Especially in Thailand, public disabled support is not effective. Therefore, disabled people have difficulties to live or travel in public places.

The prosthetic organ is of a very high cost. Disabled people in Thailand cannot afford this equipment. Although Thai researchers themselves develop prosthetic organs to use within the Thai community but still show high cost compared with standard Thai living cost.

Normally, a prosthetic organ costs more especially a prosthetic hand that has a complex mechanism and internal prosthetic organ that need to have compatibility between tissue and prosthetic organ material.

The human hand is very important. Disabled people who lose their hands will be difficult to do their daily activities and make their life difficult. They may also lose their job due to inability. On the other hand, the prosthetic hand is not affordable due to its complex mechanism. This is the reason why this research needs to reduce the cost of prosthetic hand by using a 3D printer.

The 3D printer is the most effective way to reduce the cost of prosthetic organ development because it can create the complex shape of prosthetic parts easily. Moreover, it can be used with many types of filament such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), PETG (Polyethylene terephthalate Glycol-modified), and Flexible filament (TPE/TPU). Each type of these filaments has specific properties that can be selected with appropriate work [2].

Although the 3D printer has many advantages for the development of the prosthetic organ, s limitations. For example, it cannot print some prosthetic internal organs because most filaments don’t have compatibility with human tissue. Moreover, each complex part with high resolution takes a long time to print.

According to prosthetic hand, it can be divided into 2 types which are passive prosthetic hand and active prosthetic hand [3]. A passive prosthetic hand was first developed in 19$^{th}$-century call a “prosthetic hook”. It looks like a metal hook controlled by the shoulder. This prosthetic hand has advantages such as low cost and without battery. On the other hand, it has the disadvantage that it is hard to hold the brittle object. The important disadvantage of this prosthetic hand is its shape. Since it looks like a metal hook, disabled people feel diffidence with normal people. It may cause mental problems to the disabled people who wear this prosthetic hand. Another

Manuscript received on January 27, 2021; revised on March 7, 2021, accepted on April 8, 2021.
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type of passive prosthetic hand can solve problems of the prosthetic hook. It is designed like a human hand controlled by the wrist. This type of prosthetic is easy to control and to hold the small object, but it cannot hold heavy object [4]. To give more convenience to disabled people, the active prosthetic hand was developed. The active prosthetic hand is a combination between passive prosthetic hand and electronic circuit. This type of prosthetic hand has complex parts and has more function like a human hand. Some brands can be controlled by muscle or electrical activity of the nerves and muscles called an electromyogram (EMG) [5][6]. This prosthetic hand has a very high price that starts from 18,000$ to 150,000$. According to its price, ordinary people especially Thai people cannot afford the active prosthetic hand. Although many researchers try to reduce the cost of an active prosthetic hand, but still cannot be affordable due to the standard of living cost in Thailand.

This paper proposes a low-cost active prosthetic hand using a 3D printer controlled by a bend sensor connected to the elbow. This research mainly aims to reduce the cost of active prosthetic hands that can be affordable to disabled people in Thailand or all other developing countries. The cost of a prototype of this research is lower than 100$. According to the prototype cost, this research can also reduce the inequality between disabled people and normal people in Thailand or other developing countries.

## 2. BASIC CONCEPT

This research can be divided into 3 units which are input unit, control unit, and output unit as shown in Figure 1. The input unit consists of a bend sensor connected to the disabled patient's elbow. After the bend sensor in the input unit is bent by the disabled patient's elbow, the electric signal from the input unit will be sent to the control unit. Then, the control unit will command a servo motor to pull tendons connected to prosthetic fingers. The end of prosthetic fingers has rubber covers to increase friction when holding an object.

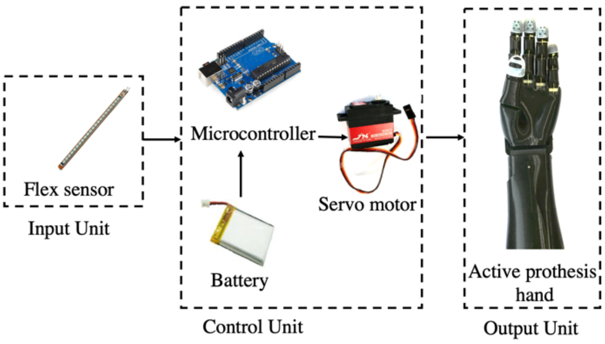


**Figure 1.** Diagram of active prosthetic hand prototype

To develop an active prosthetic hand, there are 5 theories: hand anatomy, 3D printer, servo motor, flex sensor, a microcontroller that are very important to study first.

### 2.1 Hand Anatomy

The human hand has 27 bones divided into 3 sections which are Carpal (8 bones), Metacarpal (5 bones), and Phalanges (14 bones). Phalanges can be divided into Proximal phalanges, Intermediate phalanges, and Distal phalanges [7] shown in Figure 2.

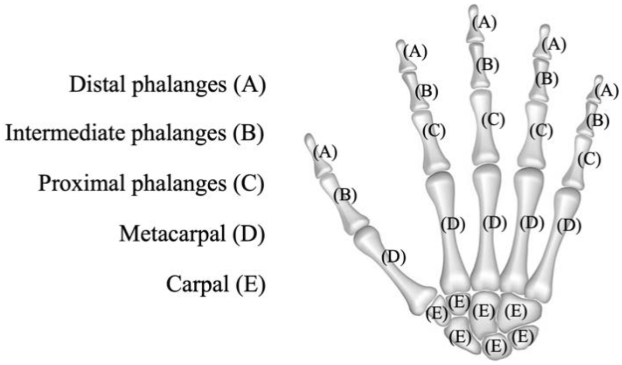


**Figure 2.** Human hand bones

According to Figure 2, Phalanges are divided into 3 Proximal phalanges, Intermediate phalanges, and Distal phalanges are denoted by (A), (B), and (C) respectively. Metacarpal and Carpal are denoted by (D) and (E) respectively.

Each finger has 4 joints. The 1$^{st}$ joint located between Carpal and Metacarpal is called Carpometacarpal joint (CMC). The 2$^{nd}$ joint located between Metacarpal and Proximal phalanges is called Metacarpophalangeal joint (MCP). The 3$^{rd}$ joint located between Proximal phalanges and Intermediate phalanges is called Proximal interphalangeal (PIP). The 4$^{th}$ joint located between Intermediate phalanges and Distal phalanges is called Distal interphalangeal (DIP) [7].

The CMC joint is fixed by a ligament. It can be slightly moved. The main function of CMC joint is to increase the stability when an object is held.

The MPC joint can flex to 90 degree approximately and extend to 20-30 degree from normal position. The MPC joint is the only one joint that can turn around in frontal plane to make abduction and adduction of each finger. The limitation of MPC joint turning is 45 - 60 degrees [7].

*2.1.1 Pollex Amputation*

Pollex is a very important finger comparing to the other fingers. The hand's abilities lose 40% approximately when pollex is amputated. The loss ability of opposition, lateral pinch, and abduction can be seen.

*2.2.2 Index finger amputation*

Index finger amputation will lose 20% of hand abilities. The accuracy of picking reduces when the index finger is amputated at the Proximal interphalangeal (PIP) level. Moreover, the remained index finger will obstruct the cooperation between the pollex and middle finger.

*2.2.3 Middle finger amputation*

Middle finger amputation will lose 20% of hand abilities same as index finger amputation. The middle finger uses to hold an object tightly. Moreover, it works mutually with pollex and index fingers.

*2.2.4 Ring finger amputation*

Ring finger amputation will lose 10% of hand abilities

*2.2.5 Little finger amputation*

Little finger amputation will lose 10% of hand abilities. The function of the little finger is to help other fingers when holding the huge object.

### 2.2 3D Printer

The 3D printer is a very favorite device for many inventors. It can print specific parts with fast and save time. In 2011, 3D printer was first used to create the rapid prototype. Then, it was developed continuously. Now, it has many models and printing techniques.

Stereolithography Apparatus (SLA) patented by Chuck Hull [8] is one of the 3d printing techniques. The principle of SLA starts from liquid polymer heated by ultraviolet laser. The container of liquid polymer move vertically while printing to create a workpiece layer. Each layer of liquid polymer is turned into a solid by a UV laser. If the workpiece has a complicated shape, it is necessary to use “support” to brace the workpiece. The support will be removed after printing successfully. Workpiece from this printing technique is strong like plastic and has high resolution [8].

The Stereolithography Apparatus (SLA) technique was developed to micro stereolithography technique that is suitable for the very small workpiece. This technique called poly jet uses a small resin injector to inject resin to support with UV light at the same time. The injected resin becomes solid immediately. This technique needs a huge container to contain the whole system.

The most favorite technique of 3D printing is called the extrusion processes. This technique has a low cost. The filament will be heated to a liquid state. Then, it will arrange with many layers called “fused deposition modeling (FDM)”. The object surface created by this technique is not smooth. Therefore, it needs to scrub its surface before use. The hardness of this technique depends on filament material such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) that ABS is stronger than PLA.

### 2.3 Servomotor

Servomotor is a motor that can be controlled its movement such as speed, angle and position. It normally uses to control the operation of the machine such as speed, torque, and position. The control accuracy depends on the type of servo motor.

There are 2 types of servomotor: AC servomotor and DC servomotor. Normally, AC servo motor is used in high-frequency use. Besides, servomotor can be divided by its structure which is brushed and brushless servomotor. The brushed servomotor has a winding in the rotor and permanent magnets on the stator. To achieve motor torque, carbon brushes and a mechanical commutator provide a current path through the windings. On the other hand, the brushless servomotor is suited for work due to their high efficiency and reliability, low torque, and linear speed-torque relationship.

### 2.4 Flex Sensor

Flex sensors sometimes called bend sensors can measure the amount of deflection or bending. Normally, this sensor is in contact with the surface. The resistance of the sensor element is varied by deflection or bending the surface. Since the electrical resistance is directly proportional to the bending angle, it can use as a goniometer. Flex sensor sometimes called a flexible potentiometer.

**Figure 3.** Flex sensor

### 2.5 Microcontroller

Microcontroller normally works like a computer. It consists of Ports, CPU and RAM. It can work in both digital and analog. Arduino is a basic microcontroller board because it can be developed by open source. It has cross-platform system that can be developed by many operating system [9]. There are many types of Arduino microcontroller board depending on applied work.


**Figure 4.** Arduino microcontroller board

## 3. PROTOTYPE DESIGN

The proposed prototype is started by designing a prosthetic hand using 3D solid modeling software. The prototype is designed according to human hand structure, strength, adjustable and lightweight. Each part of the prototype prosthesis hand is shown as follows:

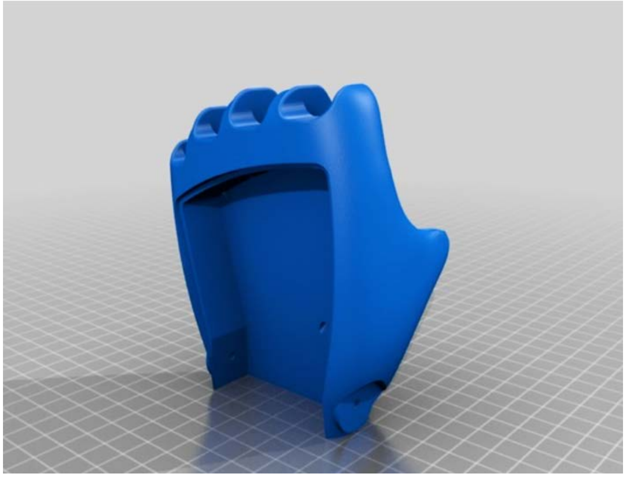

**Figure 5.** Prototype palm design

According to Figure 5, at the back of the palm, it has space for tendons connected between each finger and servomotor. At the wrist, it needs space to install a servomotor as shown in figure 6. Each finger part is designs are as shown in figure 7.

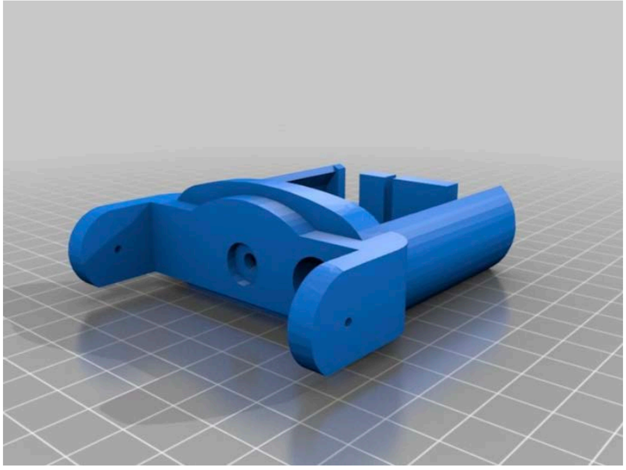

**Figure 6.** Prototype wrist design

According to figure 7, each part of the finger has a notch to connect. To connect each finger part, the connectors made from flex filament are used. These connectors have flex property printed by a 3D printer to make the finger moving. The finger connectors are shown in figure 8.

**Figure 7.** Prototype finger design

**Figure 8.** Finger part connectors

After designing all parts of the prosthesis hand prototype, all parts are printed by a 3D printer. Part of the palm, wrist, and fingers is printed by the normal filament. Part of the finger connectors is printed by flex filament.

## 4. PROTOTYPE ASSEMBLY

To assemble the prototype, each part of the finger is first connected. The assembly of each finger is shown in figure 9.

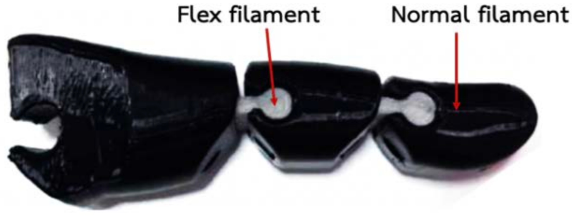


**Figure 9.** Each finger part connected by a connector printed by flex filament

Each finger is connected to the palm with the tendon tightly. Then, the palm is connected to the wrist. Finally, all tendons are connected to the servomotor. The 8 kilograms of the maximum load of the servomotor is used in this research.

Moreover, a rubber cover is used to cover at the end of each finger to increase friction when holding an object. The overall assembly is shown in figure 10.

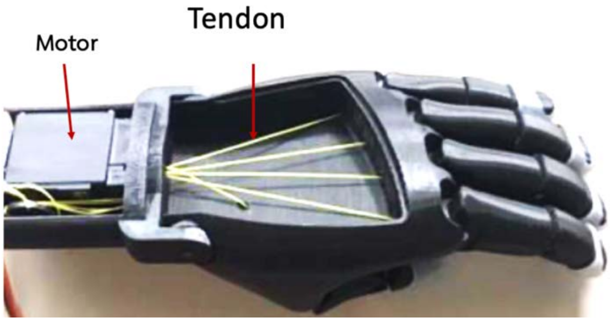


**Figure 10.** Overall assembly of the prototype

## 5. EXPERIMENT

The experiment of this research can be divided into 3 parts which are squeezing force measurement, object holding experiment, and battery consumption experiment. Each detail of the experiments will be described in the following subsections.

### 5.1 Squeezing force measurement

The squeezing force measurement is to show how much the squeezing force of the prototype. In this experiment, a squeezing force meter was used to measure the squeezing force of the prototype. The squeezing force meter is shown in figure 11.

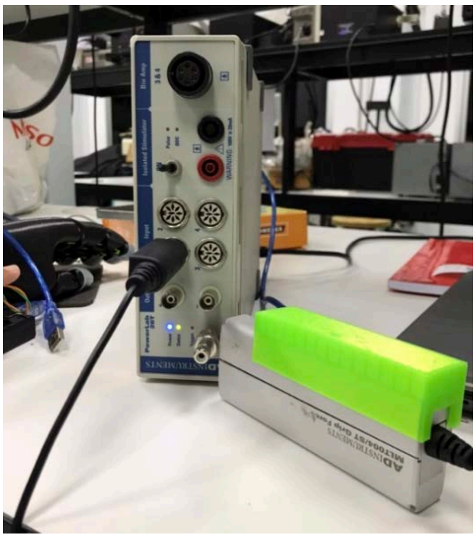

**Figure 11.** Squeezing force meter

The data received by squeezing force was sent to a computer to process received data to measure the squeezing force in newton (N).

The squeezing force experiment is divided into 2 positions. (1) center squeezing measurement and (2) end squeezing measurement. In each measurement, the prototype needs to hold the squeezing force meter for 60 seconds. Each measurement was measured 5 times. Then, the average and standard deviation (SD) were calculated.

According to the center squeezing measurement, the squeezing force meter was located at the center of a prosthetic hand. The squeezing force meter contacted to the center of all fingers shown in figure 12.

**Figure 12.** Center squeezing measurement

The result of the center squeezing measurement is shown as follows in the table.1:

| Number of Experiment | 1st time | 2nd time | 3rd time | 4th time | 5th time |
|---|---|---|---|---|---|
| Grip force (N) | 15.50 | 16.50 | 17.50 | 17.25 | 14.50 |
| Average | 16.25 N | | | | |
| Standard deviation | 1.25 | | | | |

**Table.1.** Result of center squeezing measurement

Normally, for picking an object, the targeted object will be contacted at the end of fingers. Therefore, it is necessary to know the force at the end of all fingers while picking an object. The end squeezing measurement will show how much force at the end of the prototype fingers.

According to the end squeezing measurement, the squeezing force meter was located at the end of the prosthetic hand. The squeezing force meter contacted to the end of all fingers shown in figure 13.

The result of the center squeezing measurement is shown in table.2.

**Figure 13.** End squeezing measurement

| Number of Experiment | 1st time | 2nd time | 3rd time | 4th time | 5th time |
|---|---|---|---|---|---|
| Grip force (N) | 11.00 | 11.75 | 12.00 | 14.00 | 14.00 |
| Average | 12.55 N | | | | |
| Standard deviation | 1.37 | | | | |

**Table.2.** Result of end squeezing measurement

According to the result of the squeezing force experiment, it can be plotted to compare the force between center squeezing measurement and end squeezing measurement. The resulting graph (Figure.14) is shown as follows:

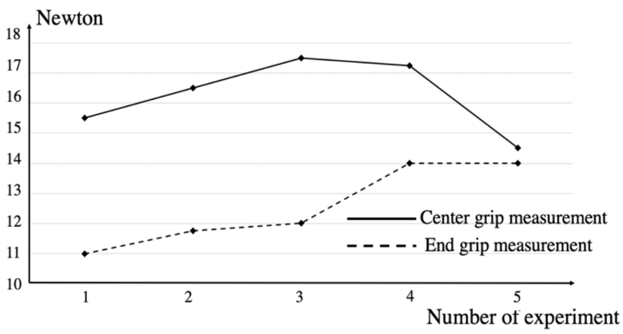


**Figure 14.** Squeezing force between center squeezing measurement and end squeezing measurement

### 5.2 Object holding experiment

This experiment describes picking and holding 10 Yale-CMU-Berkeley (YCB) objects [10] that widely facilitate benchmarking in robotic manipulation, prosthetic design, and rehabilitation research. The 10 YCB objects used in this research can be divided into 5 groups which are huge/light object, small/light object, huge/heavy object, small/heavy object, and flat object. Each object has under 5 kilograms of its weight. In this research, each type of this object is shown in the following figure.

| Huge/ light object | Small/ light object | Huge/ heavy object | Small/ heavy object | Flat object |
|---|---|---|---|---|
| toilet paper roll | glass (empty) | sparkling water can (full) | mobile phone | spoon |
| water bottle (empty) | small box (empty) | water bottle (full) | apple | bottle cap |

**Table.3.** Objects used for holding an experiment

According to Table.3, each object needs to be picked and held for 2 minutes. The objects that can be picked and held for 2 minutes by the prototype will be denoted by “pass”. The objects that cannot be picked or held for 2 minutes will be denoted by “fail”. Each object was tested 5 times. The result of this experiment is shown in Table.4.

| Objects | 1st time | 2nd time | 3rd time | 4th time | 5th time |
|---|---|---|---|---|---|
| toilet paper roll | pass | pass | pass | pass | pass |
| glass (empty) | pass | pass | pass | pass | pass |
| sparkling water can (full) | pass | pass | pass | pass | pass |
| water bottle (empty) | pass | pass | pass | pass | pass |
| water bottle (full) | pass | pass | pass | pass | pass |
| mobile phone | fail | fail | fail | fail | fail |
| spoon | fail | fail | fail | fail | fail |
| bottle cap | fail | fail | fail | fail | fail |
| small box (empty) | pass | pass | pass | pass | pass |
| apple | pass | pass | pass | pass | pass |

**Table.4.** Result of object holding experiment

According to the table.4, The objects with flat shapes such as a spoon, bottle cap, and mobile phone are the limitation of this research. The object with huge size having many areas of contact with the prototype can pass the assignment of the experiment.

Because of the squeezing force is shown in table.2, the prototype can hold the object with under 500 gm of its weight. It is not only a squeezing force, but a rubber cover is also important for holding an object. Friction force created by rubber cover at the contact between prototype and object can improve holding ability. The example of experiments conducted successfully and failure observed in the experiment are shown in figure 15 and 16


**Figure 15.** Success of object holding experiment


**Figure 16.** Fail of object holding experiment

**5.3 Battery consumption experiment**

This experiment is to test the efficiency of battery consumption. This research uses a 5-volt rechargeable lithium-ion battery with 10,000 mA of its capacities connected by USB cable to microcontroller and servomotor directly. The battery used in this experiment has an ON/OFF switch and status display showing battery percentage.

In this experiment, starting at 100% or fully charged battery, the prototype needs to hold the object for 36 hours without turning it off. The result is shown in the following figure 17.

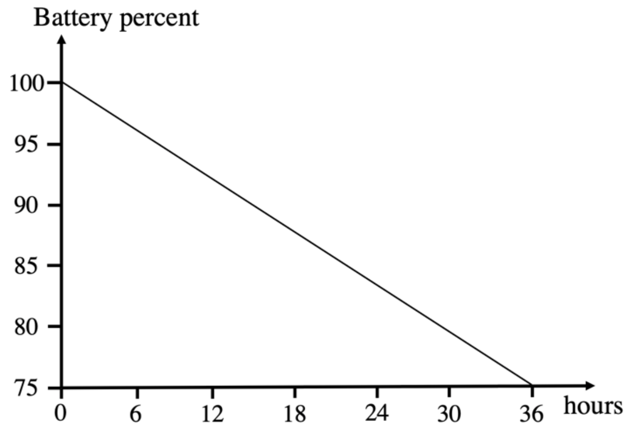


**Figure 17.** The result of battery consumption experiment

According to figure 17, after holding the object for 36 hours, battery percent showed 75%. Therefore, the average battery consumption of the prototype is 69.44 mA/hour. Besides, it can be calculated into energy consumption as 48.96 Watt-hour.

## 6. DISCUSSION

According to the squeezing force measurement, the result showed that squeezing at the center of fingers gained higher squeezing force than squeezing at the end of fingers. Therefore, this active prosthesis hand should grab the object at the center of the finger for the heavy object while using. For light objects, squeezing at the end of the finger is possible to perform. The standard deviation (SD) of center squeezing force and end squeezing force which is found to be 1.25 and 1.37 respectively which confirms that the prototype can perform stable squeezing force.

In the object holding experiment, the prototype cannot pick and hold small and flat objects because it can perform only 2 gestures which are close hand and open hand. To solve this problem, the prosthesis hand needs to do more gestures, but it will affect its production cost. Another problem-solution is to modify the target object. For example, make the spoon handle larger to pick and hold easily.

The battery consumption experiment shows that the prototype with 10,000 mA of the battery can surely operate for more than 1 day on a single charge. To reduce battery weight, users can use lower battery capacity. Not only it reduces batter weight, but it also reduces battery cost.

Moreover, the limitations of this research are to make sure the handicap of the patient needs to have a wrist to elbow and the object weight that needs to have under 0.5 kilogram. Finally, the price of equipment without a 3D printer is lower than 100 US dollars.

## 7. CONCLUSION

The research is to develop a low-cost active prosthesis hand-printed by using a 3D printer. The bend sensor connected to the elbow is used to control the operation of the active prosthesis hand. The limitations of this research can be applied to the handicapped patients who have a wrist to elbow and the object weight that need to have under 0.5 kilogram. The results showed that of low-cost active prosthesis hand has the stability of squeezing force. The average of squeezing force at the center of fingers is 16.25 N, and the average squeezing force at the end of fingers is 12.55 N. It also has 1.25 and 1.37 of standard deviation (SD) respectively. The prototype can pick and hold huge and small objects that have a lower mass of 0.5 kg of its weight. Moreover, the prototype has low energy consumption which is 48.96 Watt-hour.

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