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Low-cost and open-source anthropomorphic prosthetics hand using linear actuators

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ABSTRACT

A robust, low cost, open-source, and low power consumption in the research of prosthetics hand is essential. The purpose of this study is to develop a low-cost, open-source anthropomorphic prosthetics hand using linear actuator based on electromyography (EMG) signal control. The main advantages of this proposed method are the low-cost, lightweight and simplicity of controlling the prosthetic hand using only single channel. This is achieved by evaluating the DC motor and exploring number of locations of the EMG signal. The development of prosthetics hand consists of 3D anthropomorphic hand design, active electrodes, microcontroller, and linear actuator. The active electrodes recorded the EMG signal from extensor carpi radialis longus. The built-in EMG amplifier on the electrode amplified the EMG signal. Further, the A/D converter in the Arduino microcontroller converted the analog signal into digital. A filtering process consisted of bandpass and notch filter was performed before it used as a control signal. The linear actuator controlled each finger for flexion and extension motion. In the assessment of the design, the prosthetic hand capable of grasping ten objects. In this study, the cost and weight of the prosthetics hand are 471.99 US$ and 0.531 kg, respectively. This study has demonstrated the design of low cost and open-source of prosthetics hand with reasonable cost and lightweight. Furthermore, this development could be applied to amputee subjects.

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1. INTRODUCTION

Electromyography (EMG) signal is bioelectricity generated by the muscle when there is a contraction [1]. The EMG signal can represent the activity of the human limb [2]. EMG signal quickly can be recorded and manipulated as a control signal. However, the EMG signal is difficult to interpret due to the randomness and stochastic characteristics in nature [3]. Some robotic applications, such as power exoskeleton (upper or lower limb) [4, 5], prosthetics hand [6–8], and teleoperation in telemedicine [2], have used EMG signal as the control signal. In a decade, the study on prosthetic hand has been growing rapidly. An amputee requires the prosthetic hand as a replacement of the lost hand in which could be caused by accident or particular illness. The prosthetic hand could be used as a cosmetic in social life and performed any daily activity. Some manufacturers, such as Bebionic, Ottobock, and Steeper have developed the prosthetics hand with standard functionality; however, the price is too expensive to be bought by people in the developing country. Therefore, the development of prosthetic hand with open source and low cost is still required.

The development of prosthetics hand generally is built based on the main mechanical structure namely prehensor and anthropomorphic hand [9, 10]. The prosthetics hand based on prehension is the first prototype developed by researchers [11]. This type is composed of two main fingers, thumb and index in which resemble a grip. The prosthetic hand based on prehension has two main standards of motion (open and close). In the development of the prosthetics hand based on the prehensor model, some manufacturers added the other three fingers as a cosmetic. The design which based on prehension model is simple to control, using a standard electronic system and low cost to build the mechanical however this type of prosthetics hand has a limitation in the usages. Therefore, some studies tended to develop the prosthetic hand based on anthropomorphic. Cosmetically, the anthropomorphic hand tended to look like a real human hand which consisted of five fingers (thumb, index, middle, ring, and little). This type of hand can perform any complex motion as the human hand. Thus, each artificial finger is required to be controlled individually using a motor (dc or servo motor). Therefore, this type of prosthetic hand has more complex in the electronic system and control algorithm. Cosmetically, this type of artificial hand is more resembles the real hand and able to adapt in daily live and social activity than the prehension one.

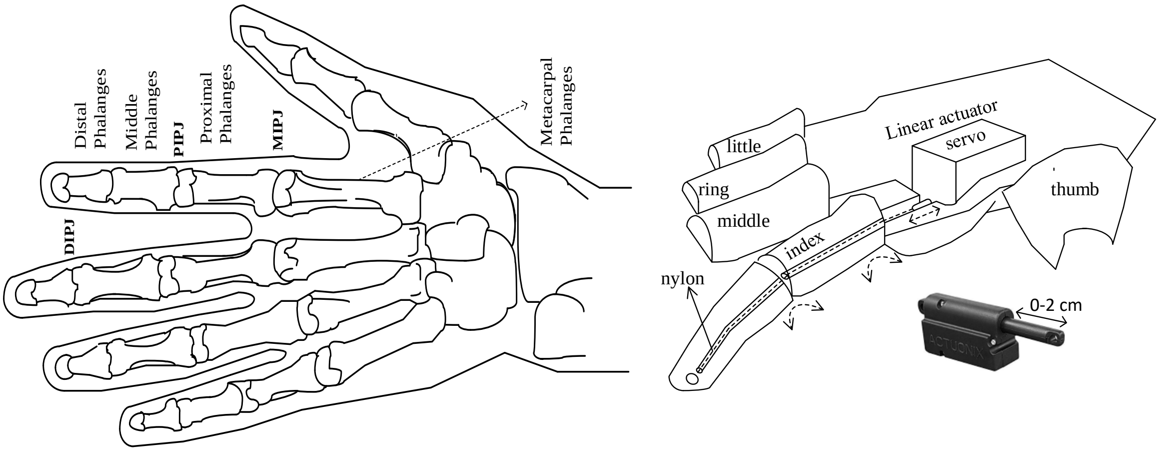
Previous studies developed the prosthetic hand in a sensory system [12–14], focusing on the usage of DC motor, and pattern recognition for EMG signal [15]. Generally, some researchers focused on investigating the type of motor and gear transfer, which used as an actuator of the finger, to obtain low power consumption and more speed. Kasim et al. used DC micro motor in the development of prosthetics hand [16] because the size is small, precise, and fit to be placed on the prosthetic palm. Even though they have equipped with precise gear transfer and encoder, they reported that the usage of micro dc motor is not the best solution to design a prosthetics hand because of the heavyweight and high-power consumption. Geethanjali et al. proposed an anthropomorphic hand using a dc motor [15]. By connecting the finger to the string which connected to the dc motor shaft, the dc motor was able to pull and push with a certain mechanism. Tomczyński developed a prosthetic hand using five miniature dc motor [17]. The resulted design capable to hold an object with various shapes and sizes. To drive the finger, a worm gears were installed on the motor shaft, this is in order to hold the position of the finger without electronic control. However, any gear transfer between motor and shaft will result in a lost power due to the friction resistance. Lenzi proposed a 5-DOF of anthropomorphic prosthesis design which focused on improving the mechatronic design [18]. In the design, they resulted in the weight only 1518 g however the stall current for each motor is still high (4500 mA) and the design was not open-source.

Robust, lightweight, and low power consumption are still the main issue in the development of prosthetics hand. A low cost and open source to build the prosthetics hand will be an added value because other researchers can improve the same design for better performance. As stated in the previous studies that the researchers faced the problem in which concerned about power consumption and weight. Therefore, a new actuator with low power consumption and lightweight was required to design the prosthetic hand. Generally, the previous studies used standard dc motor with a circular motion; thus, it needs a gear transfer to perform a linear motion and driver circuit to drive the dc motor which results in lost power and requires high power consumption. A new linear actuator will be proposed in this study in which there is no gear transfer needed between the motor and the artificial fingers. Furthermore, the device is controlled by pulse width modulation (PWM) such as a servo motor. In order to obtain the product which can be applied by other researchers, the design of anthropomorphic hand from was selected from the open-source of 3D printing from Open Bionics Laboratory. The purpose of this study is to develop a low cost and open-source anthropomorphic hand using a linear actuator using the EMG signal. The contribution of this design is that we resulted in a lightweight of prosthetics hand with low power consumption, open-source, and low-cost. The organization of this paper is as follows: section 2 will present the prosthetic design which composed of the 3D printing process and control circuit. Section 3 presents the result and discussion of this study in which consisted of the resulted prosthetics hand and the EMG signal. Section 4 will show the conclusion of this study.

2. MATERIALS AND METHOD

2.1. The design of the anthropomorphic hand

In this study, the design of the prosthetics hand was based on the anthropomorphic hand. The real bone structure of the hand is shown in Figure 1 (a) [19]. The anthropomorphic hand is composed of five fingers (little, ring, middle, index, and thumb fingers). Each finger consists of distal, middle, and proximal phalanges [19]. The joint related between distal and middle phalanges is called a distal interphalangeal joint (DIP-J). The proximal interphalangeal joint (PIP-J) is a joint connected between the middle and proximal phalanges segment. Further, the joint which related between proximal and metacarpal is called a metacarpal interphalangeal joint (MIP-J). In this study, to minimize the design of the prosthetics hand, the distal and middle phalanges were fixed as one segment for all five fingers. Thus, in this design, one finger is composed of two segments (distal-middle and proximal phalanges). In the mechanical design, a linear actuator is used to drive each artificial finger, as shown in Figure 1 (b). This linear actuator has a 20 mm stroke length. Thus, to build the prosthetics hand, we need five linear actuators. In the design, we placed the actuator in the fixed compartment, and five cm of nylon was used to pull the finger. In this paper, the open-source of prosthetics design was obtained from Open Bionics (https://openbionicslabs.com). The file consisted of STL extension which is palmar and dorsal. The files can be opened using an open-source Blender program (Blender 2.7.9).



(a) (b)

Figure 1. (a) The bone structure of the human finger which each finger consisted of distal, middle proximal, and metacarpal phalanges, (b) The design of prosthetic hand using linear actuator which consisted of five artificial fingers and each finger is controlled by the linear actuators

For the 3D printing, we used an application (Ultimaker Cura Version 3.6.0) to print the file into the 3D object. In the application, each file showed the time and materials that will be consumed by the 3D printer. To design the palmar and dorsal objects, the printer required 173 grams and 106 grams, respectively. The estimated time to print the object is 13 hours and 17 minutes, and 6 hours and 26 minutes for palmar and dorsal, respectively. In this study, the material used to print the object is polylactic acid (PLA).

2.2. The linear actuator and controller circuits

In this study, the actuator used to drive the finger is the linear actuator (Actuonix PQ12, servo RC series, Canada). It was different from the previous study, in the development of prosthetics hand, which generally used dc motor to drive the finger, nevertheless in this research we used linear actuator. This design is a modification from the previous design, which used a linear actuator with a dc motor. In this study, the design was implemented the new linear actuator with servo RC series; thus, we do not require any motor driver, but we can drive the linear actuator as a servo motor. This linear actuator consists of three pins, namely VCC (6 volts), PWM with 50 Hz frequency and the on pulse ranged between one and two milliseconds, and GND pin. We selected the linear actuator is due to the lightweight (15 grams) and low power consumption (550 mA on stall current). The comparison of specification among the actuator (dc motor and linear) is shown in Table 1.

Table 1. The specification of the actuators

Specification	Linear actuator PQ12	Maxon EC20	MicroMo 2036
Supply voltage (volts)	6	14.8	14.8
No-load speed	8 (mm/s)	11,569 (rpm)	21,706 (rpm)
Stall torque	45 (N)	23.31 (mNm)	27.13 (mNm)
Stall current (mA)	550	1900	4310
Speed ratio (Hz)	63	36	62
Diameter (mm)	15	21.2	20
Height (mm)	36.5	14	36
Mass (g)	15	22	50

The diagram block of the electronic design is shown in Figure 2. The mainboard to control the prosthetics hand consisted of dry electrodes with built-in EMG amplifier and microcontroller (Arduino Nano). The dry electrode is a reusable electrode that can be used without a pre-gelled. The dry electrodes composed of three bar of metal material. The EMG signal was recorded in bipolar mode on the extensor carpi radialis longus. The placement of the electrode followed the SENIAM rules [20] and the location of the muscle [19]. The built-in amplifier on the electrode will give less noise on the EMG signal because of the position of the electrode is close to the main amplifier. Further, the amplified EMG signal was digitized using a built-in A/D converter in the Arduino Nano microcontroller. In order to minimize the circuit size, the filtering process was conducted in the microcontroller using a digital bandpass filter. In accordance with the EMG signal, the specification of the bandpass filter is 20 to 500 Hz and second-order Butterworth [21]. A notch filter of 50 Hz was also built in the microcontroller. This notch filter is used to reduce the effect of interference noise from the power line. Before the EMG signal can be used as a signal control, the EMG signal was rectified and extracted using mean absolute value (MAV) [22]. The decision to open and close the prosthetic hand is depended on the level of the EMG contraction, whether the EMG amplitude exceeded the pre-defined threshold value or not. All of the five linear actuator PQ12 (servo series) are connected to the Arduino Nano pin (five pins).

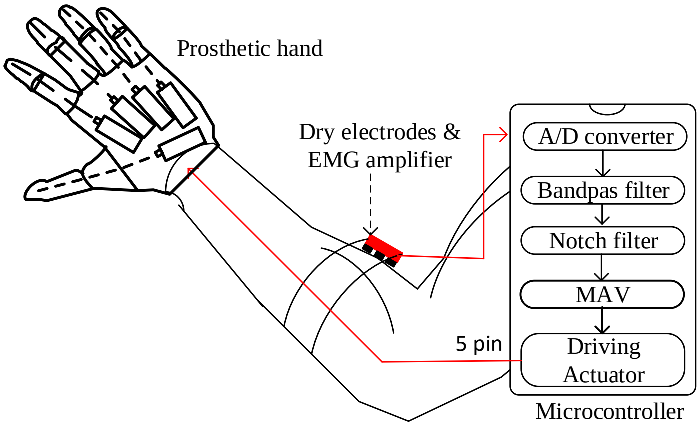


Figure 2. Design of electronics control to drive the prosthetics hand

3. RESULTS

In this work, we present the development of the anthropomorphic prosthetic hand using a linear actuator. The 3D printing is an open-source design from Bebionic Laboratory. We modify on the linear actuator part, previously the design is based on standard dc motor control but in this paper, we used the linear actuator with servo type. Thus, there was no motor driver required to drive the linear actuator. Consequently, this will reduce the power consumption and space for the hardware.

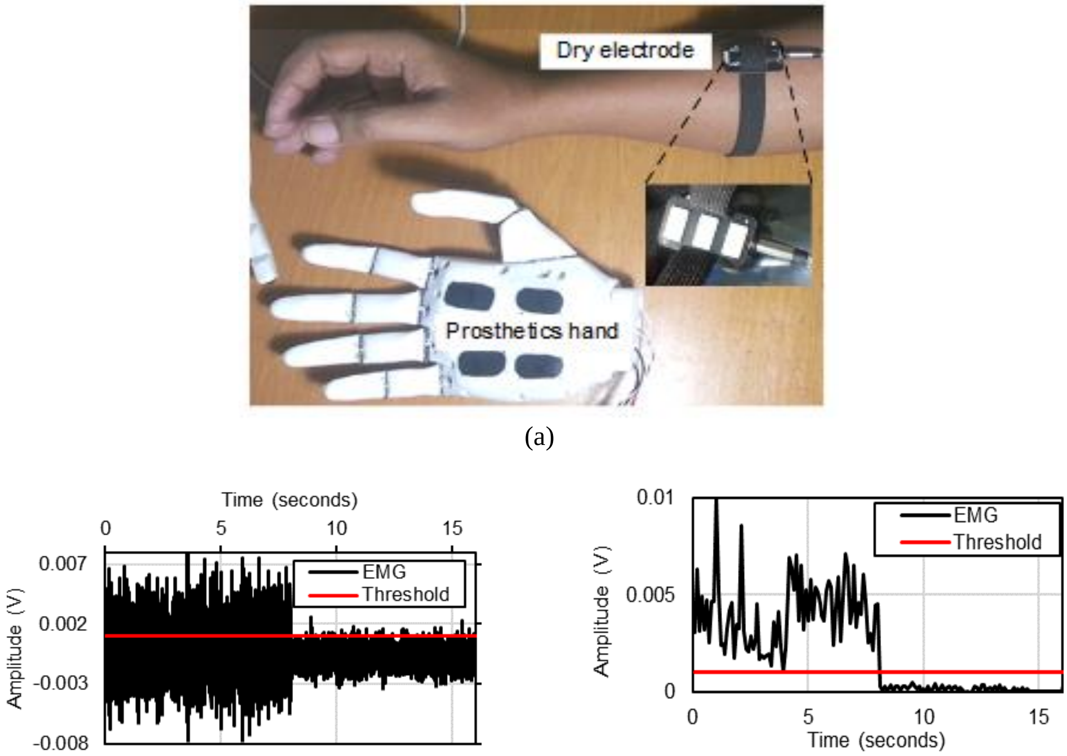
3.1. The anthropomorphic hand

The resulted anthropomorphic hand was in accordance with the adult human hand. The width and high on the palmar side were 90 mm and 120 mm, respectively. The maximum width and high, in which including the finger, were 200 mm and 170 mm, respectively. The photograph of the palmar and dorsal side of the artificial hand were shown in Figure 3. The material used for 3D printing is PLA. Because of the PIP and MIP joint in the 3D printing design was easily broken. Then, in this study, we modified the PIP and MIP joint from the previous design by separating the finger into two-part. To connect between the segment, we placed a leather sheet as a joint. In order to finger in the extension position, a rubber material was located on the PIP and MIP joint, thus after the flexion position, the finger will pull to the extension position. Finally, five linear actuators were placed on the compartment on the dorsal side. As shown in Figure 3 (a), the linear actuator was located firmly in the dorsal thus it can pull and release the finger for flexion and extension motion.

3.2. The performance of the prosthetics hand

The EMG signal was recorded using dry electrodes from extensor carpi radialis longus (Figure 3 (a)), which [19] responsible in the open and close motion of the finger. The representation of the EMG signal, whenever the hand in the position of close and open, is shown in Figures 3 (b) and (c). The EMG signal showed higher activity when the muscle performed a contraction (from 0 to 8 seconds). Furthermore, the EMG signal showed a lower activity when the muscle in a relaxed position (from 8 to 16 seconds).

The prosthetics hand was tested to grasp some objects found in daily life. The grasping power was measured using load cell which normally measured based on the weight in kg or converted in Newton (N). The average force to grasp the object is 20.00 ± 0.81 Newton. In the assessment, the design was controlled using five potentiometers through the Arduino microcontroller and single-channel EMG signal. Figure 4 represents the capability of the design to hold some objects used in daily life. The fingers of prosthetic were also able to move individually as shown in Figure 5.



(a)

(b) (c)

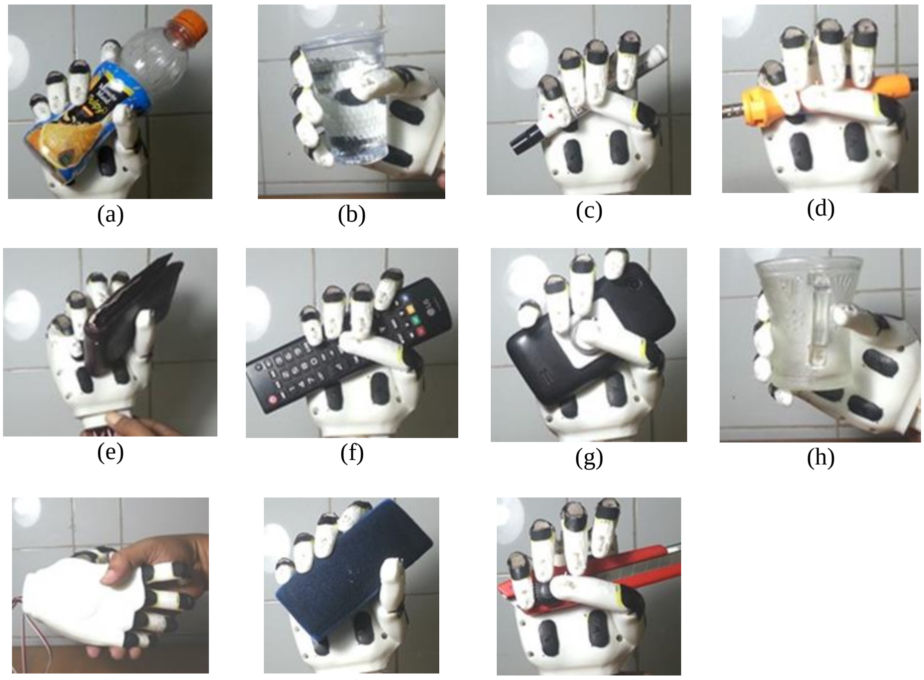
Figure 3. (a) The placement of the dry electrode with armband to record the EMG signal, (b) EMG signal which collected from extensor carpi radialis longus, and (c) The processing EMG signal using mean absolute value (MAV)

3.3. The weight and cost of materials

The material used to build the prosthetic hand is shown in Table 2. 3D printing can be found at the local 3D printing services. The total weight and cost of the prosthetic design are 531 grams and 471.99 US$, respectively. The material to build the prosthetic hand can be obtained at the local market, except for the linear actuator and the dry electrodes.

Table 2. The materials of prosthetics hand

No.	Part	Weight (grams)	Cost (US $)
1	3D printing service	279	48.10
2	Linear actuator PQ12 (5x)	75	350
3	Arduino NANO	7	1.66
4	Arduino NANO socket	20	1.73
5	Dry electrodes plus amplifier	50	37.50
6	Battery 6V (4000 mA)	100	33.00
	Total	531	471.99

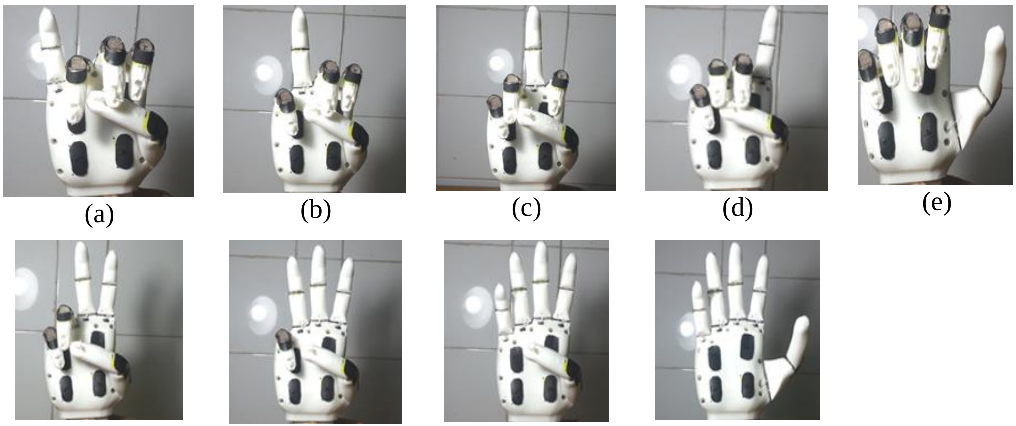


(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k)

Figure 4. The number of objects which can be held by the prosthetics hand: (a) bottle, (b) plastic glass, (c) marker, (d) iron solder, (e) wallet, (f) remote control, (g) mobile phone, (h) glass water, (i) hand shake, (j) whiteboard eraser, (k) cutter



(a) (b) (c) (d) (e)

(f) (g) (h) (i)

Figure 5. The motions which can be performed by the prosthetics hand using five potentiometers: (a) little, (b) ring, (c) middle, (d) index, (e) thumb, (f) index and middle, (g) index, middle and ring, (h) all fingers

4. DISCUSSION

In this study, we have developed an anthropomorphic prosthetics hand with a PLA material that has been used by previous studies [7, 14, 23]. This material is the most common material in 3D printing because it has a low melting temperature, inexpensive and fairly strong. In this work, the material cost to build the prosthetic hand is 279 grams. However, in the original design, the joint between middle and proximal phalanges (PIP) (and between proximal and metacarpal phalanges [MIP]) are easily broken, thus in this design, we placed a leather sheet at the joint. A rubber material was also placed in this joint (PIP and MIP) to pull the finger in the extension position. The design of the prosthetic hand was capable of holding eleven objects which used in daily life. In order to avoid a slip, four sheets of rubber were placed on the palmar side. In the experiment, the five fingers of the prosthetic hand can hold the object firmly without any slip. Each finger was able to hold the object with the mean force of 20.40± 1.02 N (mean ± standard deviation). Thus, in future work, we suggested using this design to be applied to amputee subjects. Furthermore, each finger of the prosthetics hand can be controlled individually as shown in .ure 5 by using five potentiometers.

A low cost and open-source prosthetic hand have been developed in this work which required the cost of 471.99 US$ for a single right hand. Mostly, the cost to build this prosthetics hand was consumed for the linear actuators (350 US$). Therefore, in future work, a new actuator with a low cost was required to be proposed. The other related studies, which concerned the development of the prosthetic hand, reported some various results and costs. Akhtar et al. developed a prosthetic hand for the amputee, which required a cost of 553.06 US$ [9]. In the design, mostly the cost of materials was used to buy the dc motor. Other studies, about the prosthetics hand, was proposed by Krausz et al. They designed an open-source prosthetic hand with six degrees of freedom with the cost of 2,221 US$ [24]. Even though they obtained a good prosthetics hand but the cost is expensive, which mostly used to buy the gear head and dc motors.

In this study, the proposed prosthetic hand, which used a linear actuator with servo control, proved that the design is a low cost, lightweight, and open source. The EMG signal has demonstrated the ability to control the hand smoothly. However, the single channel of the EMG signal can control in two motion (grasp and open hand). In future work, the EMG signal (single channel) will be used to control more than two movements. The activity of the EMG signal depends on some physical condition, such as the position of the electrodes, sweat, and muscle fatigue [25, 26]. Therefore, these parameters were required to be considered in the development of the prosthetics hand.

5. CONCLUSION

In this work, we presented the development of low-cost and open-source anthropomorphic prosthetics hand. The weight and cost to build the anthropomorphic hand were 531 grams and 471.99 US$, respectively. The contribution of this study is that the prosthetics hand was driven using the linear actuator, which has low power consumption and lightweight. The second contribution is that the prosthetics hand can be controlled using a single channel EMG to grasp eleven difference objects. Furthermore, this prosthetics hand development has low noise when it was operated. The prosthetic hand can be applied to amputees for cosmetic purposes and help in daily activity. The limitation of this work is that the EMG signal controlled the five fingers simultaneously. In future work, a real-time embedded pattern recognition should be proposed to control each finger individually.

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