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Original article

Myoelectric prosthetic hand with a proprioceptive feedback system

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ABSTRACT

Design of a myoelectric prosthetic hand that satisfies the expectations of those who unfortunately lost a hand is discussed in this paper. That is to perform and look as close as a human hand, and to have a proprioceptive feedback in order to improve their quality of life. Linkage mechanisms are designed to replicate the trajectory of the human hand. Distinct seven grip patterns enable the prosthetic hand to manipulate different amputee needs. Kinematics and dynamics analysis are performed to estimate the required input motor torques, and to determine the hand force capabilities. The user controls the hand with the electromyography signal coming from the arm. The feedback system is then designed to reduce the relying of prosthetic users on visual or audible feedback. This system is divided into four separate categories: force sensing, feeling the temperature, motion sensing, and the final feedback allows the user to monitor and control the hand via an android application. Tests show that the suggested prosthetic hand is able to perform the required grip patterns correctly, and the hand can handle different objects in a wide range.

1. Introduction

During 1960s, many researchers investigated the field of prosthetics because of drug *thalidomide*. It was widely used as analgesic. It slows down limbs development in the fetus (Weir, 2016). By the year 2012, over 1,700,000 amputees are living in the United States of America only and 185,000 people are discharged yearly from the hospital with amputation, for several factors such as infection, trauma, accidents, vascular disease, tumors, and infectious diseases (Bhuvaneswar et al., 2007). This adds a real need to enhance prosthetics to meet their needs through investigating more smart prosthetic hand using linkage mechanisms in this paper. Consequently, researchers focus on four directions through enhancing the prosthetic hand: mechanisms, actuators, sensing, and control.

Mechanisms complexity incarnates in the human hand. It performs very complex tasks with more than 21 degrees of freedom. It uses an effectual combination of mechanisms, sensors, actuators, and control activities. For grasping technique, Napier derived all the hand movement from two major different motion patterns, which he called "precision grip" and "power grip" (Napier, 1956). Bicchi presented a comprehensive depiction and analysis of most relevant researches within the 20th century (Bicchi, 2000).

A hand with regular five fingers including 13 independent degrees of freedom moved by flexible fluidic actuators was able to generate 12 N for the whole hand is presented in (Schulz et al., 2001). Three fingers under actuated hand using pulleys and strings system is proposed in (Massa et al., 2002). Design and analysis of a prosthetic hand having three fingers with a six DOFs that is able to generate a grasping force of 30 N is introduced (Carrozza et al., 2002). Two grip patterns were discussed using

Micro actuators along with hall-effect position sensors actuate the controlled joints. A one motor prosthetic hand using EMG-based control along with the fabrication process is presented in (Carrozza et al., 2005). EMG signal conditioning using low cost technique is discussed in (Sharmila et al., 2016). A three motor prosthetic hand with self-adaptable grasp pattern controlled through EMG signal is introduced in (Huang et al., 2006).

Testing the method of deep learning over intact subjects and amputees, show that surface electromyography requires the architecture of the net, and the optimization parameters (Atzori et al., 2016). The design of a controller based on intuitive gesture recognition and a custom control strategy is used for a wearable,

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prosthetic hand (Benatti et. al., 2017). Following user preferences for improvements in electric powered prosthetic hands; greater finger movement, and less visual attention are the concluded as long-term considerations (Atkins et. al., 1996). These two aspirations are considered in designing the proposed prosthetic hand herein.

Investigating most of the previous prosthetic hand specifications, leads to two possible research gaps in them. First is to introduce temperature sensing to the hand to prevent and accidental ingestion of extremely hot beverages or food. Second is to eliminate the need for visual tracking for the hand especially when handling fragile materials to control prosthetic hand force.

The rest of this paper is organized as follows; Section 2 discusses the mechanical mechanisms for fingers. Grip patterns are presented in Section 3. Dynamic analysis for one finger in power grip pattern is analyzed using Matlab- Simulink in Section 4. Section 5 discusses control and proprioceptive feedback systems along with electronic PCB design.

2. Finger linkage design

The mechanical design of the Smart bionic hand is performed via the use of free hand sketches and Solidworks CAD software. Each part requires cautious model with thorough information and precise dimensions as possible. When dealing with such limited space the accuracy of small components and all moving parts are priorities.

The index finger is the first theme for the whole design procedure. The human hand is then investigated visually whilst grasping and handling different objects. Through vigilantly investigating the fingertip, it is observed that the final knuckle joint rotates a little. Therefore the first simplification through considering the fingertip as one link with the final knuckle fixed somewhat bent over.

Previous robotic hands demonstrated a linked finger motion using tiny cables and pulleys. Complicated design along with simple maintenance is the main disadvantages. Usually, they have low efficiency and high backlash (Light and Chappell, 2000).

Tighten high strength cables in minute spaces is an additional problem. On the other hand, simple mechanical linkages are extremely robust and reliable. Link withstands both tension and compression, allowing application of active force during both the closing and opening regimes. Linkage mechanisms are simple to install and maintain. Therefore, the four bar mechanism moves the four fingers to replicate the human fingers trajectories, Fig. 1.

The thumb differs from the other four fingers as it has four degree of freedom; two knuckle joint in it and two in the palm. However, for simplification the proposed design considers only two degrees of freedom that are in the palm, Fig. 2.

Once the mechanism architecture is chosen, the next step is choosing joint operation method. RC servomotors are the simplest option for this application. They are widely available in multiple sizes and power options. For the index, middle, ring and small Finger, a two bar linkage will connect the finger and the corresponding servo motor, to form a four bar mechanism used to drive each finger.

The four-bar linkage is by far the simplest movable closed chain single degree of freedom mechanism. It consists of four bodies, called crank, coupler, rocker and the frame. This design aspect allows the minimum number of parts. When the motor rotates clockwise, the crank pushes the coupler to close the finger toward the palm and vice avers, Fig. 3.

The drive train of thumb is dissimilar to the other fingers; it rotates about two different axis perpendiculars to each other that make the two degrees of freedom. A motor inside the hand actuates the first rotation (open/close); the other rotation is manually operated via under actuated joint.

The thumb motor position is different from the other fingers; the axis of rotation of the servo is parallel to the first axis of the rotation and perpendicular to the other (open/close) of the thumb. A new drive train is designed to withstand the two different rotations without affecting each other. For this mechanism, a six bar linkage is then chosen to drive the thumb.

The six-bar linkage is also one degree-of-freedom mechanism that is constructed from six links and seven joints. When the motor rotates counter clockwise the mechanism is pulled downward to close the thumb, and vice versa, Fig. 4.

3. Grip patterns

Distinct seven grip patterns enable the proposed prosthetic hand to manipulate almost everything that the amputee needs for daily actions like eating, opening doors, typing, carrying bags, and switching the lights. Open palm pattern presents an effectual method of manipulating dishes. Moreover, when hand is not in use the open palm configuration plays a role in giving the hand a normal and realistic appearance, Fig. 5.

In others daily activities like pressing small or convoluted buttons, typing on a keyboard, and pressing a doorbell, the pointed index finger is used. The index finger is in an open position, the

Fig. 1. Architecture for the four fingers.

Fig. 2. The thumb architecture.

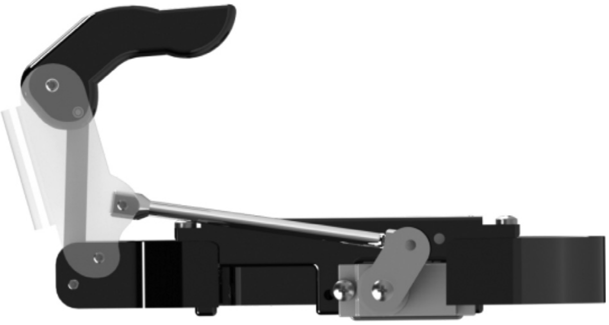


Fig. 3. Fingers actuation.

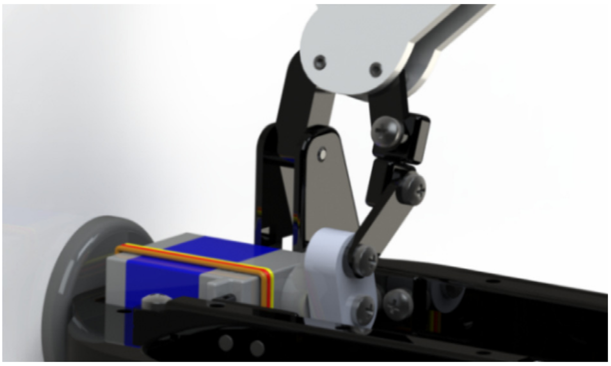


Fig. 4. Six-bar linkage of the thumb.

Fig. 5. Smart bionic open palm.

other fingers are in a closed position and the thumb is in contact with the side face of the middle finger, Fig. 6.

Key grip is in effect when; the amputee wants to handle thin objects like a credit card, a paper and a key. It provides precise control, and it enables him to complete multipart tasks like opening doors. In this pattern, he closes all fingers, while the thumb encounters the index side to hold the object, Fig. 7.

Precision grips have two configurations: closed and opened. In closed grip, the index touches the thumb meanwhile the other fingers are closed. This configuration provides a rapid, consistent method to pick up and to move tiny objects, including car keys, coins, and pens, Fig. 8. In open grip, the index finger grips against the thumb while the middle, ring and little fingers remain open. The configuration offers another useful way to pick up and manipulate small objects quickly and accurately, Fig. 9.

Hook grip provides a suitable solution for carrying heavy objects. With hook grip, the index, middle, ring and little fingers close to a hook shape while the thumb provides extra support to the index, Fig. 10.

Fig. 6. Smart bionic finger point.

Fig. 7. Smart bionic key grip.

Fig. 8. Smart bionic precision closed grip.

Fig. 9. Smart bionic precision open grip.

Fig. 10. Smart bionic hook grip.

The power grip is the best suitable way for hand shaking, throwing balls, using home utensils, or eating a piece of fruit. The power grip provides just the correct amount of grip force suitable for different situation, Fig. 11.

4. Dynamic analysis

Kinematic and kinetic analysis for linkage mechanisms used in bionic hand is investigated in this section. Fig. 12 shows the dimensions of the prosthetic hand. Kinematic analysis for the proposed linkage mechanism is performed as a function of input crank angle attached to servomotor and all dimensions as stated in Table 1. Skeleton diagram for the mechanism used for the four fingers is shown in Fig. 13. Using complex-polar technique, link angles are derived as functions of motor angles.

Fig. 11. Smart bionic power grip.

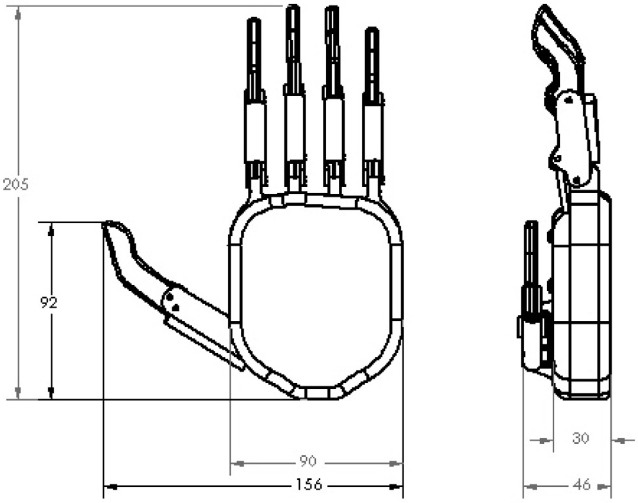


Fig. 12. Prosthetic hand dimensions.

Table 1
6-Bar linkage mechanism numerical parameters, [mm].

r_1	H	r_2	r_3	r_4
64	7	12	66	13
r_4'	r_5	r_6	H	r_4'
40	9	40	6	6

Let

$$\beta = \theta_4 - \theta_3$$

$$\beta = \cos^{-1}\left(\frac{r_3^2 + r_4^2 - (r_1 - r_2\cos\theta_2)^2 - (h - r_2\sin\theta_2)^2}{2r_3r_4}\right)\theta_4 - \theta_3 \qquad (1)$$

$$\theta_4 = \tan^{-1}\left(\frac{r_1 - r_2\cos\theta_2}{h - r_2\sin\theta_2}\right) - \tan^{-1}\left(\frac{r_3\cos\beta - r_4}{r_3\sin\beta}\right) \qquad (2)$$

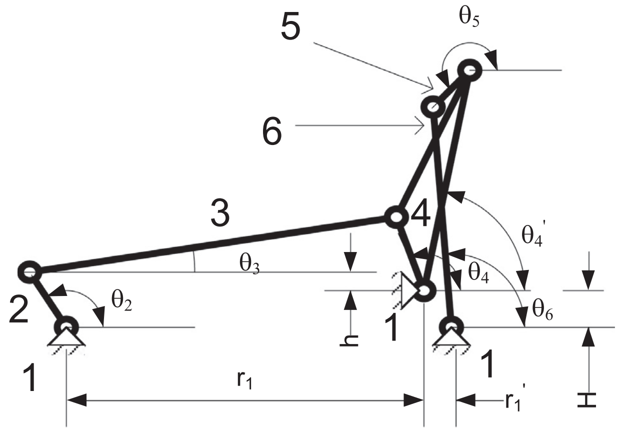


Fig. 13. Skeleton diagram for the six bar linkage mechanism.

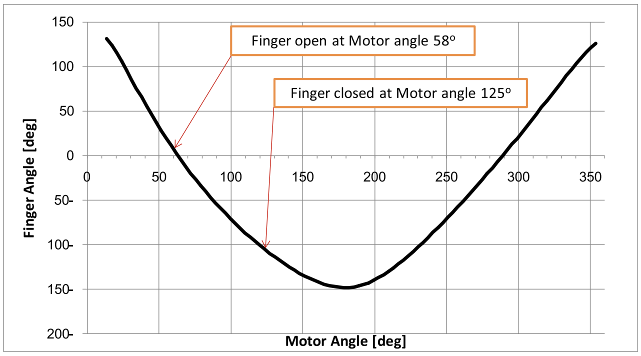


Fig. 14. Finger orientation.

Hence the angle θ'_4 is then calculated as the vertix angle of the ternary link no. (4) is known. Let

$$\varphi = \cos^{-1}\left(\frac{r_5^2 + r_6^2 - (r'_1 - r'_4\cos\theta'_4)^2 - (H - r'_4\sin\theta'_4)^2}{2r_5r_6}\right) \tag{3}$$

Then

$$\theta_6 = \tan^{-1}\left(\frac{r'_1 - r'_4\cos\theta'_4}{H - r'_4\sin\theta'_4}\right) - \tan^{-1}\left(\frac{r_5\cos\varphi - r_6}{r_5\sin\varphi}\right) \tag{4}$$

Finally, finger angle is then defined as:

$$\theta_5 = \theta_6 - \varphi \tag{5}$$

As limited range of angle is applied to fingers, motors are constrained to rotate from angle 58° to 125°. The resulting finger orientation is shown in Fig. 14.

The dynamic analysis of the linkage mechanisms used herein is accomplished through the use of Matlab Simulink to determine the necessary torque to drive the motor and to measure the output force and the load that each finger can handle in the different position in each grip pattern.

Proper motor selection is an important aspect of this design because the same type of motor could power all 5 degrees of freedom. To determine the required torque of the motor a Simulink model is designed of the index finger in the hook position to measure the torque of the motor required to hold a mass of 1 kg or higher.

The Simulink model consists of six bars each one represent a linkage of the index finger with its dimension, mass, mass moment of inertia, seven rotational joints representing the pivot point that connect the linkage together, and a sensor connected to the first joint to measure the required torque to hold the mass are shown in Fig. 15.

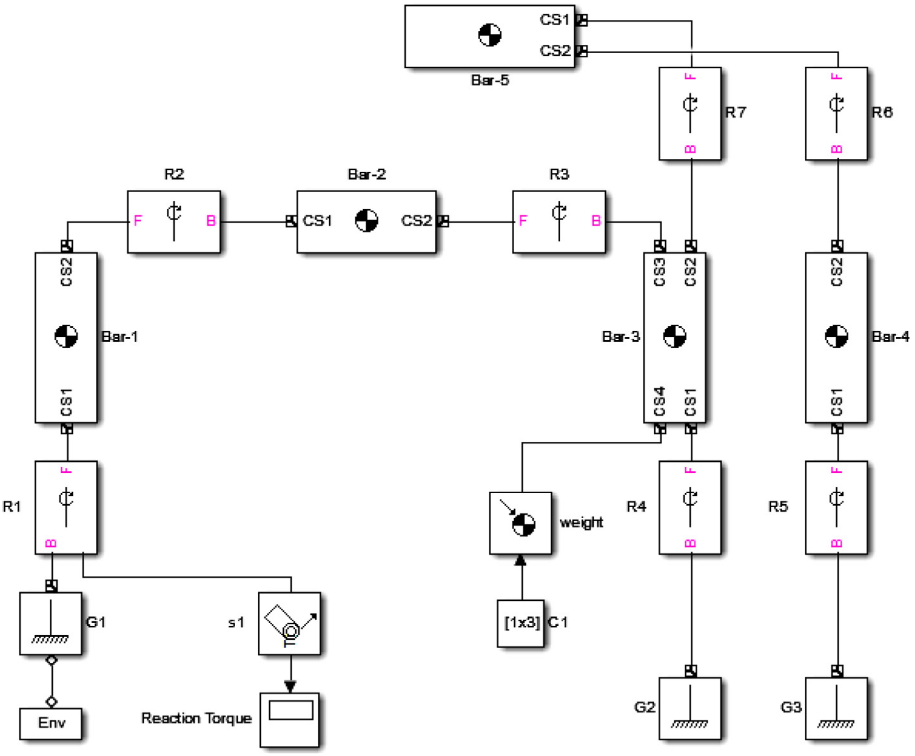


Fig. 15. Simulink model for index finger analysis.

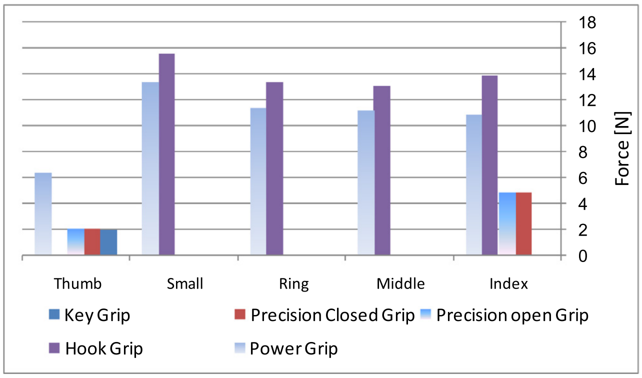


Fig. 16. Output force for each finger in different grip pattern.

The output signal of the sensor represents the required torque of the motor, which is at least 0.25 N-m to make the hand capable of holding and carrying daily objects.

Once the driving motor is selected, the next thing to do is to calculate the output force of each finger in the different grip pattern and the weight that the hand can carry in the hook position. To calculate the hand output a Simulink model is designed with the dimension and position of every finger in the different grip pattern. Calculated output forces are then shown in Fig. 16.

5. Sensory feedback systems

One of the most important components of the bionic hand design is the grip force sensing. Having the ability to measure the applied force on each finger, and then be able to react to that force, leads to better user experience, making the user capable of grasping a fragile object without breaking them, and allowing the microcontroller to stop the motors before stalling them and eventually burns out.

The simplest and easiest way to obtain a force measurement, without adding mechanical sensor, is to measure the motor current. It is directly proportional to the applied load. As finger force increases, the current draw increases. For controlling the five servomotors, the micro controller read all the analog inputs coming from acs712 current sensors. It then compares these readings with stored value for each motor for each grip pattern. If some obstacle stops the finger, motor current increases. Consequently, microcontroller change motor angle backward until current reaches its normal values.

However, the current sensors have some drawbacks, as they require some tuning and adjustment to become useful. They, also, shortly draw a large amount of current when the motor start to move even if the finger is still under no load condition. Moreover, the motor has to be gear down to provide enough torque; this will lead to inaccurate measures for the small loads.

In order to make the prosthesis as much as possible like a real human hand, the smart bionic is equipped with temperature feedback system. This enables the user to feel the temperature of what she holds with her bionic hand. Amlx90614 infrared thermometer is then used for its capability of measuring temperature from a portion of the thermal radiation emitted by the object being measured without the need of physical contact with the object. These measurements are then converted to the user via a thermoelectric cooler known as *Peltier*. It consists of two ceramic plates with a series of P and N type semiconductor material between them. The module conveys heat from one side to the other, with consumption of electrical energy, relaying on the direction of the current.

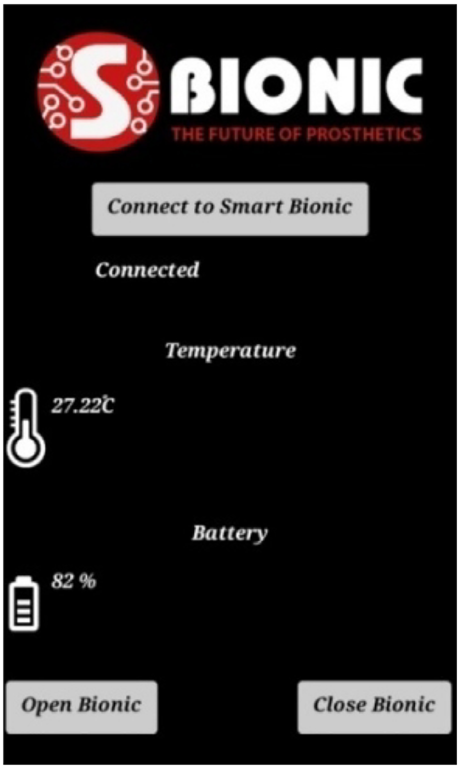
Furthermore, a vibrator motor is integrated into the prosthesis itself that will vibrate whenever the fingers are moving or when the user changes the grip pattern, to make the user able to know that the signal coming from her muscles when flexing them is read and analyzed by the microcontroller. Tactile sensory feedback is an essential element of life.

Another way for the user to interface with the smart bionic to open, close and change the grip pattern of the hand is by a Bluetooth program on an android device connected with the hand by Hc-05 Bluetooth module, Fig. 17. It uses serial communication to communicate with the microcontroller and the Android program. Moreover, it makes the user able to get a live feedback from her smart bionic throw her mobile phone or tablet like the temperature of what she touches as well as the battery percentage. To design the Android program, the *MIT App Inventor 2* is used to develop the layout and the user interfaces as well as the program blocks.

For the user inputs, the myoelectric sensors are one of the most commonly used control methods for bionic hands. The smart bionic uses two myoelectric sensors for closing, opening and changing the grip pattern of the hand. These sensors measure the bioelectric potentials related to muscle activity compose the EMG. To connect the muscle sensors with to forearm of the user six electrodes are used, three for each muscle.

The smart bionic hand requires an on board microcontroller capable of handling all movements of the hand in addition to all the sensors inputs and user feedback. Large amount of processing power, with considering the extreme space limitations, many analogs inputs and general digital I/O are necessary. Each degree of freedom requires one digital channel as an output to generate the PWM signal for the servomotor, and one ADC analog input to read the value of the feedback sensor for measuring the force of that degree of freedom. Additionally, it is necessary to have more analog input to measure the temperature of the holding object and for controlling the user feedback system.

Moreover, the controller requires having serial input through USB or similar standard to make sure it is able to communicate with prospective third party devices or as a research platform



Connected

Temperature

27.22C

Battery

82 %

Fig.17. Android program for the smart bionic.

linked to a computer. Two Arduino Nano are perfect for this application of limited space. It is hard to find another controller with the same amount of analog inputs close to this size or cost.

For holding the Arduino boards and the sensors, two printed circuit board (PCB) are then designed to mechanically support and electrically connect electronic components. Lines connecting the components together, the trace width must be taken into account as the current reaches 8 A whenever all motors and sensors are active. When dealing with high current in small boards the traces width have to be calculated to be able to withstand the high current according to the IPC standard, and electromagnetic shielding is necessary. Fig. 18 summarize sensing and control algorithm.

6. Experimental results

All systems are integrated to give the final prosthetic hand without the cover; Fig. 19. Various tests were conducted to measure its performance in different grip pattern. Hook grip, for instance, is tested to carry 6.5 kg dead weight and the hand worked well.

The current sensors are a successful proof of concept for measuring the force in each finger. They are able to detect the current change in each motor when they come in contact with fragile objects like a disposable plastic cup, Fig. 20. The microcontroller instantly starts reducing the angle of the servo motors before breaking or crushing the object being carried unless the user overrides the sensors by flexing her muscle again for closing the hand to output more force in the fingers to firmly hold the object. Table 2 gives the difference in motor's angles due to current feedback system.

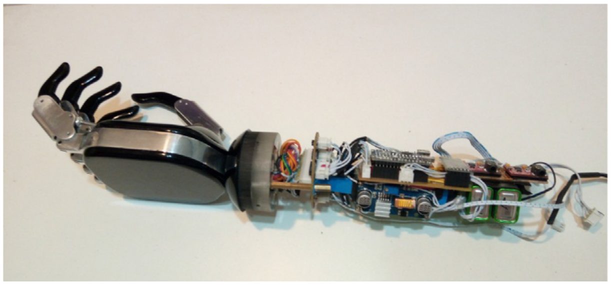
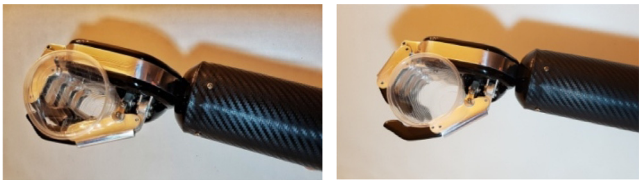


Fig. 19. Assembled prosthetic hand.



a) Power grip without current feedback

b) Power grip with the current feedback

Fig. 20. Power Grip.

Table 3 shows a comparison between the proposed prosthetic hand and leading brands. The proposed design has faster response as time required for completing both power and key grips is

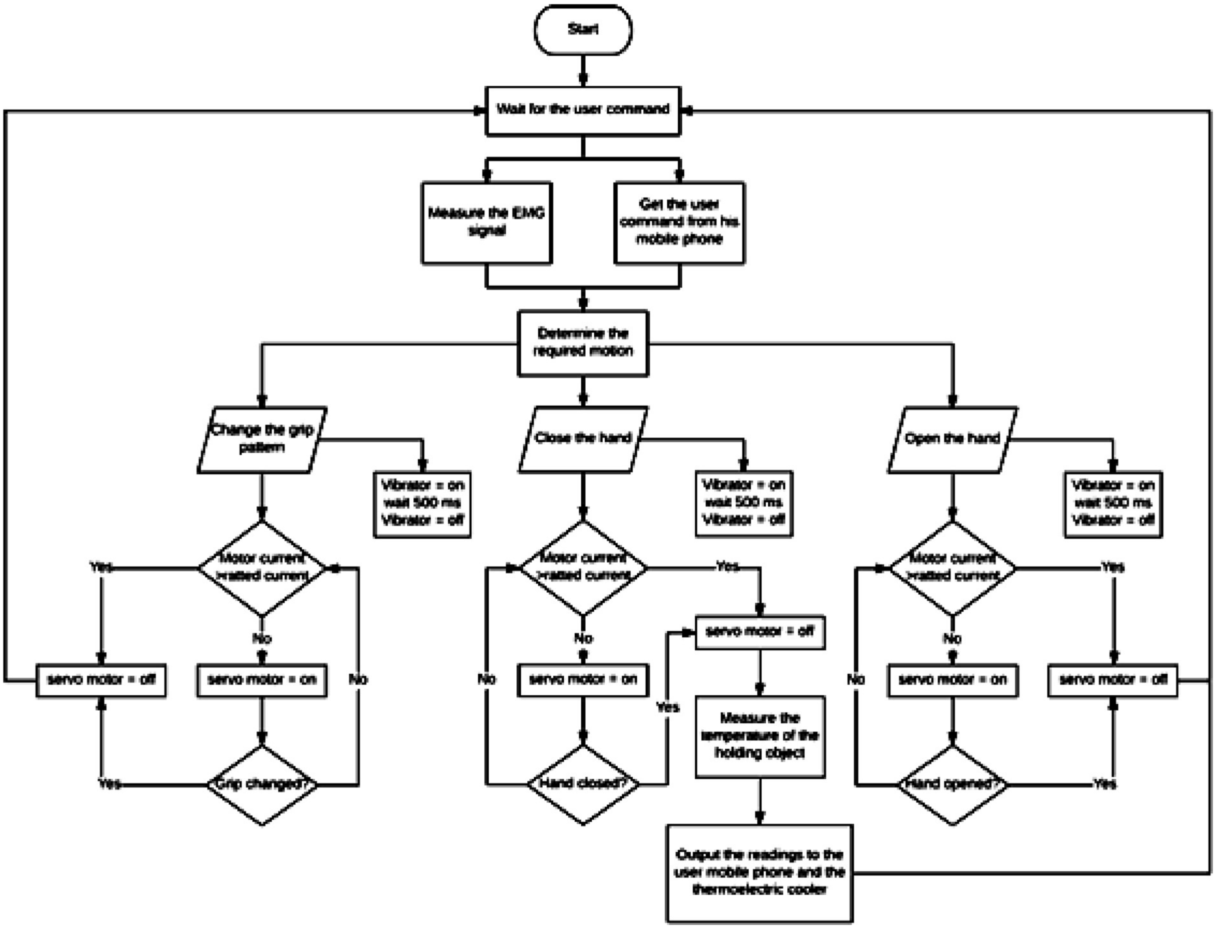


Fig. 18. Sensing and control flowchart Fig. 19 Assembled prosthetic hand.

Table 2
Comparison between motor's angles without and with current feedback system.

Motor	Angles without current feedback (deg)	Angles with current feedback (deg)
Index	10	18
Middle	7	12
Ring	9	15
Pinky	7	10
Thumb	21	33

Table 3
Comparison between proposed prosthetic hand and some leading brands.

	Proposed design	Bebionic b3	I-limb quantum
Time to open or close – Power grip	0.2 sec	1.0 sec	0.8 sec
Time to open or close – Hook grip	0.2 sec	–	–
Time to open or close – Precision closed grip	0.15 sec	–	–
Time to open or close – Precision open grip	0.15 sec	–	–
Time to open or close – Key Grip	0.1 sec	1.0 sec	–
Maximum power grip force	53.27 N	140.1 N	–
Maximum key grip force	6.88 N	26.5 N	–
Maximum static load – Hook grip	6 kg	45 kg	90 kg

reduced to 20% and 10%. However, it has less griping force capabilities (http://bebionic.com; http://touchbionics.com).

7. Conclusions

The proposed prosthetic hand with proprioceptive feedback system showed its ability to be used as an efficient hand for amputee. Different grip pattern are analyzed and programmed to microcontroller with an effective muscles EMG or android application. User of the proposed bionic hand has the ability to manipulate different objects ranging from a sheet of paper to a heavy bag. User has no need to continuously make a visual tracking for finger motions as current sensors are continuously measure motor current consumptions and change motors commands if necessary. User also has no risk of moving hot sustenance to her mouth, as the hand is equipped with temperature sensors that feel the heat radiated for any hot nearby object. Finally, the proposed bionic hand has a human hand shape and size to a far extend.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksues.2019.05.002.

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