# DESIGN AND DEVELOPMENT OF COST EFFECTIVE EMG CONTROLLED PROSTHETIC HAND

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**Abstract -** This paper presents a design and development of cost effective EMG controlled single degree of freedom prosthetic hand. In countries like Pakistan where labor is inexpensive, most of the work in industries is done by labor and due to industrial accidents there are a large number of workers who get amputated each year. This demands a cost effective solution of prosthesis for amputated industrial workers as there buying power is weak. Importing these prosthetic devices costs a lot, which make them unaffordable and non-repairable. This paper discusses cost effective indigenous solution for EMG controlled single degree of freedom prosthetic hand which is comparable with state of the art products. Indigenous development of prosthetic hand will make it affordable. Hand can provide 114N gripping force, 1 sec opening/closing time, and mx opening of 120mm which are better than state of the art Ottobock and Steeper prosthetic hands. 320 grams weight of the hand is achieved by selecting optimal materials using stress simulation results. Simple and efficient design, fabricated locally ensures the cost effectiveness of the design. Hand is also installed on different patients using EMG control circuitry and they are using the hand in their daily routine.

**Keywords -** Degree of Freedom (DOF), EMG (electromyography), Full depth teeth, Gear, Module, Pressure angle, Pinion, Stub teeth, Speed, Torque

## I. INTRODUCTION

Amputation is one of the major problem around the globe. Every year there are people who get amputated due to trauma, disease or in war. In Pakistan most of the people who suffer amputation are from rural areas and are financially weak. These people live rest of their life in amputation or use body powered prosthetic hand rather than myoelectric hand as they cannot afford those devices. Body powered prosthetic hands uses harness that is fastened with the user's shoulder, which make the device difficult to remove and mount. Myoelectric prosthetic products available are imported from outside Pakistan which make them expensive and difficult to repair in case of fault. This problem demands the development of indigenous and cost effective prosthetic hand. Indigenous development of myoelectric prosthetic hand discussed in this paper ensures its cost effectiveness and with technical specifications better than state of the art products globally. This design reduces the cost of development of myoelectric prosthetic hand. Prosthetic hands available in market starts from 4500 USD and on the other hand our design costs only 500 USD which means that 89% of cost is reduced as compared to other products. This design will help amputees to use myelectric prosthetic hand at very affordable cost and perform their daily tasks independently.

150,000 to 200,000 people suffer from amputation every year which add up with existing 4 million; 30% of these amputees are upper limb amputees. 70% of amputations are caused by accidents or trauma are upper limbs amputees [1]. 1.7 million Amputations are stated in United States in 2007 [2].

Human hand is can perform complex task using its complex design. Due to amputation it becomes often impossible for people to perform even basic routine tasks. Prosthetic upper limb allow amputees to regain their lost work abilities.

The functions performed by upper limbs are more challenging to replace as compared to lower limbs. This is because of the primary function of lower limbs which includes only standing, walking, stair climbing etc. on the other hand upper limb has more complex tasks to perform. These tasks can only be achieved by precise motor action. Upper limb has high degree of freedom that allows it to move in the range of positions around the body [3].

There are various types of upper-Extremity prosthesis are being made to replace upper limb in case of amputee. These types are discussed in table 1 [4].

| | |
|---|---|
| Body Powered | Body powered prostheses uses harness that is fastened with the user's shoulder. Mechanical hook, hand is connected to that harness via cable. User has to stretch that wire open the hand |
| Myo-electric | Myoelectric prostheses is a battery operated device controlled by electromyographic (EMG) signals from active muscles. Signal are used to operate the motor that opens and closes the hand. |
| Hybrid | Hybrid prostheses allow user to operate both hand and elbow. It includes both electric and body-powered parts. |
| Terminal Device | This is the part of prostheses that often replace hand function of appearance. These devices provides primary functionality of gripping. |

| | |
|---|---|
| Socket | The socket is a device that holds the prostheses with the remaining limb. Socket is developed according to the user's amputation for ease of mounting. |

**Table 1. Types of Upper Limb Prostheses [4]**

## II. LITERATURE REVIEW

There are some available solutions of single DOF myoelectric prosthetic hand. These solutions are designed by well-known companies. Some of the products are discussed here:

The company Otto Bock [5] manufactures a variety of prostheses. Their products include single DOF as well as multiple DOF prosthetic hands. The products are used and recognized around the globe. One of the Otto Bock hand is shown in Figure 1 Otto Bock digital twin system electric hand. The hand is motor actuated and EMG signal controlled.



**Figure 1. Otto Bock Digital Twin system electric hand [5]**

Steeper is another well-known company in the field of prostheses [6]. Myo Select is single DOF myo electric hand developed by steeper.

Some of the available solution of single DOF prosthetic hands are listed in article [7]. The article discusses Transcarpal Hand manufactured by Ottobock.

Table 2 shows a detailed comparison between technical specifications of available prosthetic hands and our design. The comparison clearly shows that our design is better than the existing products in terms of force, opening width and weight. 114N gripping force is designed in the gripper which is better than the listed sate of the art products. Opening width is achieved to be 120mm which is again better than other products. Cost effective development of the product is also one of the major achievement of the design. Prosthetic hands available in market starts from 4500 USD and on the other hand our design costs only 500 USD which means that 89% of cost is reduced as compared to other products.

| Specs | Digital Twin system electric hand | Select Myoelectric Hand | Transcarpal Hand | Our Design |
|---|---|---|---|---|
| Max Force | 90N | 40N - 80N | 90N | **114N** |
| Closing Time | 0.9 sec | 0.8sec – 1.5sec | 0.91sec | **1 sec** |
| Weight | 355g – 457g | 320g-520g | 308g | **320g** |
| Opening width | 100mm | 65mm-100 mm | - | **120 mm** |
| Cost | Starts from 4500 USD | | | **500 USD** |

**Table 2. Technical Specifications of available solutions of single DOF prosthetic Hands compared with proposed design**

## III. FLOWCHART

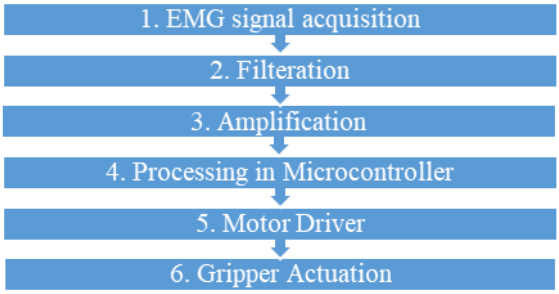



**Figure 2. Complete flow chart**

## IV. MECHANICAL DESIGNING

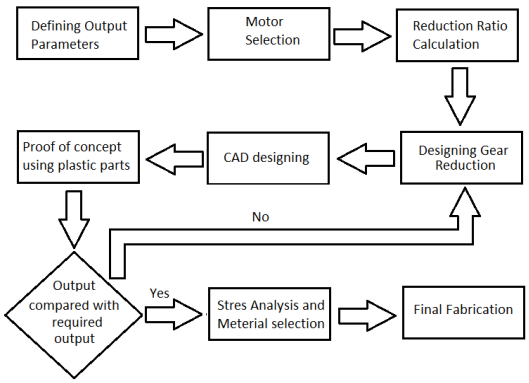



**Figure 3. Flow chart of mechanical design**

Mechanical design and fabrication is conducted according to the following steps:

1. First step was to define the output parameters which are required from the gripper.
2. Motor is than selected using its torque and speed.
3. Using the torque and speed of the motor gear train is calculated which should be capable of providing output parameters defined in first step.
4. Using the required value of gear train, gearbox

including complete hand is designed.
5. Using CAD software, CAD model of the hand is designed.
6. For the proof of concept plastic parts are used to manufacture the first prototype.
7. Using stress simulation results material of the gripper is selected.
8. Finally the gripper is fabricated and tested on patients.

***A. Output Parameters:***

For the sake of comparison with other state of the art hands, output parameters are selected higher than those hands. Output parameters selected for the design of prosthetic hand are $Force = 114N,\ Torque = 855\ Ncm,\ Closing\ time = 1sec,\ Speed = 13\ RPM$ , $Weight = 350\ g$ and $Opening\ Width = 100mm$.

***B. Motor Selection:***

Keysen RF-370CA-22170 motor is selected for the gripper [8]. Motor specifications are $Speed = 4600$ RPM and $Stall\ Torque = 1.34\ Ncm$ at 6VDC. Operating voltage range of motor is 4-10VDC. We will operate the motor at 8VDC at which motor's specifications are $Stall\ Torque = 1.79\ Ncm$ and $Speed = 6133\ RPM$.

***C. Gears Reduction Calculation:***

Reduction Ratio [9]

$$Reduction\ Ratio = \frac{Output\ Torque}{Input\ Torque} \qquad (1)$$

$$= 477$$

End Speed [10]:

$$Speed = \frac{Motor\ Speed}{Reduction\ Ratio} \qquad (2)$$

$$= 13\ RPM$$

As depicted in equation 1 reduction ratio 477 will gives us the required output of torque and RPM. 477 gear reduction is implemented in 4 stages.

***D. Gears Design:***

Reduction ratio of 477 reduction is implemented using four stages reduction in the design. Design parameters for gears designing are $Pressure\ angle = \emptyset = 20$, $Reduction\ Ratio = m$, $Module = M = 0.5$. All parameters are discussed in table 3.

Minimum teeth of pinion (smaller gear) which can be used without interference [11]:

$$N_p = \frac{2k}{(1+2m)sin^2\emptyset}\left(m + \sqrt{m^2 + (1+2m)sin^2\emptyset}\right) \qquad (3)$$

$k$ in the equation 3 is for the tooth profile. Value of $k$ is 0.8 for stub teeth and 1 for full depth teeth. Smaller gears have stub teeth to make them interference free [11].

| Parameters | Stage 1 | Stage 2 | Stage 3 | Stage 4 |
|---|---|---|---|---|
| Reduction Ratio (m) | 3.66 | 2.77 | 5.88 | 8 |
| Module = M | 0.5 | 0.5 | 0.5 | 0.5 |
| Pressure angle ($\emptyset$) | 20° | 20° | 20° | 20° |
| Teeth profile (k) | 0.8 | 1 | 1 | 1 |
| Minimum pinion teeth to avoid interference | 12 | 13 | 16 | 17 |
| Pinion number of teeth ($N_p$) | 12 | 18 | 18 | 17 |
| Gear number of teeth ($N_G$) = m*$N_p$ | 44 | 50 | 106 | 136 |

**Table 3. Design calculations of 4 stage gear reduction**

Total reduction of the gearbox is the product of individual reduction ratio (first row of table 3) of individual stage. So, total reduction = 3.66x2.77x5.88x8= 477.

***E. CAD Model:***

CAD model of gripper in made following the specifications listed designed in table 3.



**Figure 4. Complete Assembly of the Hand**

Figure 4 shows the complete assembly of the hand. Gripper has 2 fingers and a thumb for gripping. Gearbox is designed in between front and back plate of the hand.

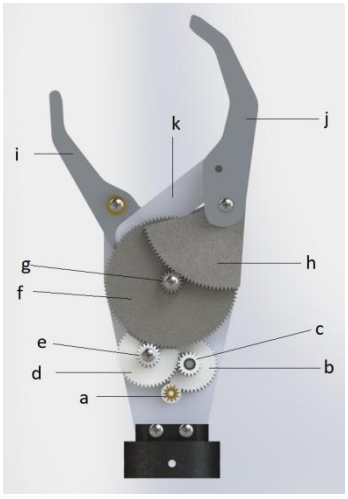



**Figure 5. Gearbox of the hand**

Figure 5 shows internal view of gearbox. Gear "a" is mounted on the motor and is meshing with gear "b", gear "b" is concentrically connected with gear "c", gear "c" is meshing with gear "d", gear "d" is concentrically connected with gear "e", gear "e" is transferring torque to gear "f", gear "f" is

concentrically connected with gear "g" and gear "g" is meshing with gear "h". Gear "h" is concentrically connected to finger "j" and rotate it. Finger "j" transfer the motion to thumb "i" via link "k".
Gear stages are shown in table 4.

| Stage | Pinion (smaller gear) | Gear (larger gear) |
|---|---|---|
| Stage 1 | a | b |
| Stage 2 | c | d |
| Stage 3 | e | f |
| Stage 4 | g | h |

**Table 4. Gear stages**

### *F. Stress analysis:*

Stress analysis on gears are done according to maximum stress acting on each gear. Stress on every gear is according to the force acting on its teeth. Two meshing gears will have same stress as the force at meshing point is same. Stress on each gears are explained in the table 5.

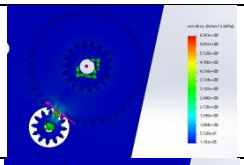
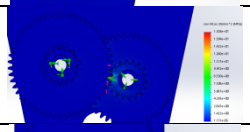
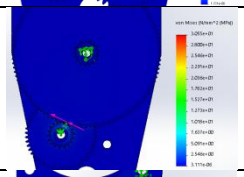
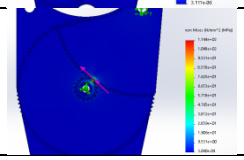
| Gears | Force at Pinion (N) | Stress Result | Maximum stress value (MPa) |
|---|---|---|---|
| a, b | 1.34 |  | 6.4 |
| c, d | 4.9 |  | 17 |
| e, f | 13.6 |  | 30.5 |
| g, h | 80 |  | 114 |

**Table 5. Stress Results on gears**

Stress analysis on other parts of hand is shown in table 6.

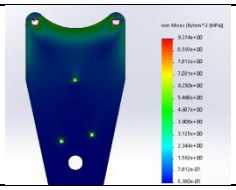
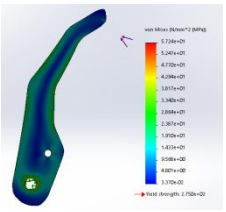
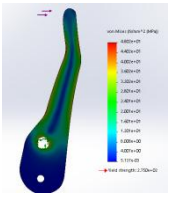
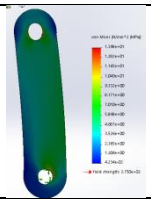
| Parts | Stress Result | Maximum Stress (MPa) |
|---|---|---|
| Front and Back Plate |  | 9.3 |
| Finger |  | 57 |
| Thumb |  | 48 |
| Link |  | 14 |

**Table 6. Stress on other parts of hand**

### *G. Material selection for infinite fatigue life of hand:*

In normal use hand will be under fatigue stress as it will open and close continuously. To make fatigue life of the gripper to be infinite fatigue strengths of the materials are studied. If the fatigue strength of the material is more than maximum stress on the part (table 5 and table 6) the part will have infinite life. Summary of material selection is shown in the table 7.

| Part | Maximum stress in MPa (table 5 and 6) | Material | Fatigue strength of material (MPa) |
|---|---|---|---|
| Gears (a) | 6.4 | Nylon | 50 [14] |
| Gears (b, c) | 17 | Nylon | 50 [14] |
| Gears (d, e) | 30.5 | Nylon | 150 [13] |
| Gears (f, g) | 114 | S275 Mild Steel | 150 [13] |
| Gear (h) | 114 | S275 Mild Steel | 150 [13] |
| Front and back plate | 9.3 | 3004 Aluminum | 103 [12] |
| Finger | 57 | 3004 Aluminum | 103 [12] |
| Thumb | 48 | 3004 Aluminum | 103 [12] |
| Link | 14 | 3004 Aluminum | 103 [12] |

**Table 7. Materials of all parts of hand**

### *H. Fabrication:*

Hand is finally fabricated according to the design and selected materials. Figure 6 shows the fabricated hand.



**Figure 6. Fabricated Hand**

## V. CONTROL DESIGN

EMG signal developed from muscle is used to control the prostheses. EMG signal is placed on muscle of amputees to control the prostheses. When the patient flexes the muscle, the amplitude of the signal is increased. Complete flowchart of the control is shown in figure 7.

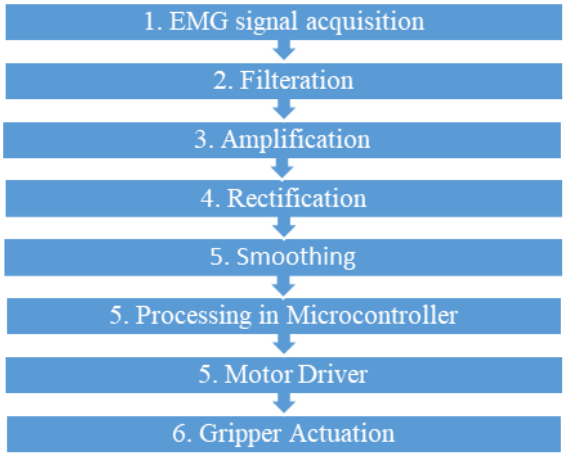



**Figure 7. Flow chart of control**

Control of prosthetic hand is implemented according to following steps:

1. First of all raw EMG signal is acquired using EMG sensor.
2. Raw signal coming from the sensor is then filtered to remove unwanted frequencies from the signal.
3. Signal is than amplified.
4. Signal is than rectified using precision rectifier to invert the negative peaks in the signal.
5. Signal is than smoothened to DC signal using smoothing filter.
6. The signal is then transferred to microcontroller.
7. Microcontroller operates gripper motor using motor driver.

Signal output at all stages are shown in figure 8.

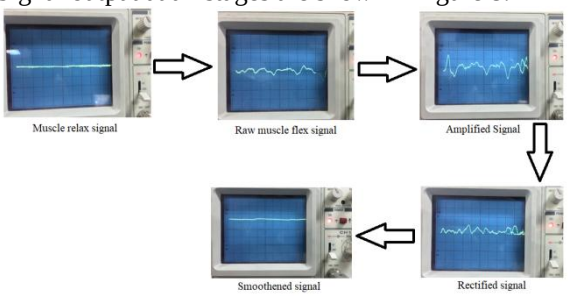



**Figure 8. EMG signal processing output after each step**

## VI. RESULTS

Results of our designed prosthetic hand is compared with the specifications of Otto Bock and Steeper hands. Table 8 shows the comparison of this design parameters.

| Specs | Digital Twin system electric hand | Select Myoelectric Hand | Transcarpal Hand | Our Design |
|---|---|---|---|---|
| Max Force | 90N | 40N - 80N | 90N | **114N** |
| Closing Time | 0.9 sec | 0.8sec – 1.5sec | 0.91sec | **1sec** |
| Weight | 355g – 457g | 320g-520g | 308g | **320g** |
| Opening width | 100mm | 65mm-100mm | - | **120 mm** |
| Cost | Starts from 4500 USD | | | **500 USD** |

**Table 8. Comparison of the proposed design with some available solutions**

Table 8 clearly shows comparison between our proposed design and some of the available state of the art hands. Opening width of the proposed design is 120mm which is more than the other state of the art hands in the table. Weight is reduced to 320g which is again a big achievement. Light hand will allow user to use the hand efficiently. Closing time of proposed design is 1sec. 114N force is achieved in the design which is better than state of the art products listed in table 8. Simple and efficient design along with indigenous manufacturing ensures the cost effectiveness for amputees in developing countries like Pakistan where people have low buying power. As reflected in table 8, cost of prosthetic hand is reduced by 89% as compared to similar products available in market. This will help amputees to use the prosthetic hand in their daily life at very affordable cost.

## VII. PATIENT TESTING

To test the prosthetic hand in real world scenario, complete prosthetic socket along with the control circuitry is developed for amputees. It can be seen in the pictures 9, 10 and 11 that amputees using prosthetic hand are doing their routine task like drinking, writing and picking. Real world testing also shows the robustness and durability of the hand.



**Figure 9. Patient 1 is drinking water using prosthetic hand**



**Figure 10. Patient 2 is writing using prosthetic hand**

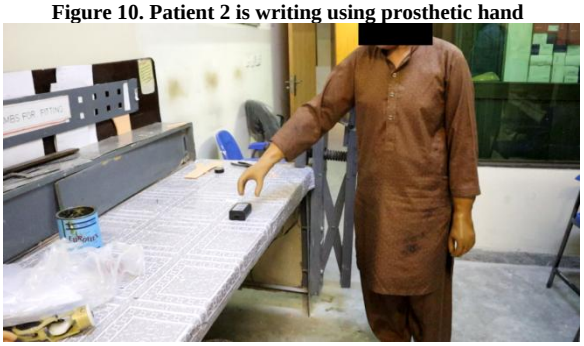


**Figure 11. Patient 2 is picking object using prosthetic hand**

## VIII. CONCLUSIONS

The paper successfully proposed cost effective solution of upper limb prosthesis. Simple and efficient design of the hand ensured the weight to be 320g which is less than the state of the art prosthetic hands like Ottobock and Steeper. Light weight helps the user to use the hand more efficiently. Opening of 120mm which is 20% more than Otto Bock hand. Wide opening of hand will allow the user to pick larger objects. Complete opening time of 1 sec and firm grip of 114N force is achieved in this the proposed design which is again better than the available products in market. The hand has infinite fatigue life that make it durable. Patient testing is also done to check the stability of the hand. Patients are using the hand in improving their life and performing daily tasks such as eating, drinking and picking objects etc. Patients as well as doctors, prosthetists and other people related to this field recognized this work and gave positive feedback. By using indigenous manufacturing, cost of the hand is reduced which is one of the major achievement of the work and it will help amputees to use the device at very affordable cost. Existing similar prosthetic devices starts from 4500 USD and our design costs only 500 USD for amputees with better performance.

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