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## **Design of a Low Cost, Highly Functional, Multi-fingered Hand Prosthesis**

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### **Abstract**

This paper presents the design, mechanical features, and proposed manufacturing of a functional self-adaptive, multi fingered prosthetic hand that will provide a less-expensive alternative to current high functionality prosthetic hands. Commercially available hand prostheses, though functional, have limitations such as weight, as result of vast numbers of parts, intricate mechanisms requiring constant maintenance as well as the extremely high cost to the user. In general, these types of prosthesis are virtually unattainable to those without medical insurance in developed countries and the general population in developing countries. The hand design discussed is based on an underactuated 15 degree-of-freedom, 1-degree-of-actuation configuration, fully capable of performing activities of daily living. Each finger is fully independent from each other and is designed to adapt to objects of any geometry while possessing the ability to pick up smaller objects through pinching, by means of a position adjustable thumb. The system provides safe and reliable grasping without the need for feed back sensors, multiple servos, or any type of data processing. The design is focused towards providing upper limb amputees with the option of a prosthetic hand that is cosmetically appealing, functionally comparable with other prosthesis of its type, while providing the benefits of decreased cost and weight by eliminating the need for complex electrical systems, micro-processors, and multiple servomotors while decreasing the number of parts and cost of manufacturing. This type of prosthesis can be especially beneficial to amputees from developing countries where the facilities that provide, create, and fit prosthesis have limited resources. The design of the prosthetic hand presented takes advantage of simple manufacturing techniques used in developing countries, hence reducing the dependency on imports from Western countries.

### **Keywords**

Hand Prosthesis, Underactuated, developing countries, thermoplastic, upper-limb amputees

## 1. Introduction

For the past decade or so, there has been an increased interest in the design of functionally and cosmetically anthropomorphic robotic end-effectors. The technology and expertise has crossed over into and benefited the area of prosthetic hand design [Dechev et al., 2001]. This type of technology is generally very expensive and inaccessible to those without insurance or monetary means in developed countries and almost completely inaccessible to most in developing countries. Therefore, prostheses for people with disabilities in developing countries need to be designed with requirements different from the ones for developed countries. Hence, the main requirements of such prostheses should include inexpensive production and maintenance. Ideally, the prosthesis itself should be designed in such a way that it could be manufactured and repaired without the need to import parts from other nations [Ullmann and Zoppi, 2004]. It is generally suggested that prostheses for developing countries have a relatively simple design, thus the prosthetic hand design presented is based on technology and engineering that dates back to the beginning of the 20th century. The key to making such prosthetic device accessible and affordable is manufacturing costs. The prosthesis has a relatively small number of key parts; many of them simple in nature and used repeatedly throughout the design.

## 2. Background Prosthetics

There are a wide variety of prosthetic devices available for upper-limb amputees ranging from those that are mostly cosmetic on one end, to those with functionality in mind on the other end. In general, most prostheses are designed with both extremes in mind [Leonard and Meier, 1998]. Though cosmetic prostheses offer a more natural look and feel, they sacrifice functionality and versatility while also being relatively expensive. Active prostheses can be divided into two general categories: body-powered prosthesis, and myo-electric prosthesis. Body-powered prostheses are powered and controlled by gross movements of the shoulder, upper arm, or chest and are captured by a harness system which is attached to a cable that is connected to a terminal device (hook or hand) [Leonard and Meier, 1998]. They tend to be of moderate cost and weight while being very durable at the sacrifice of aesthetics. Myo-electric prostheses use small electrical motors found in the terminal device (hand or hook), wrist, and elbow [Leonard and Meier, 1998]. Electrical activity transmitted from the residual limb to the surface electrodes on the prosthetic fitting control the different motors by means of a microprocessor unit. For the most part, these are pinched type devices consisting of a pair of rigid fingers in opposition to a rigid thumb which are limited to a single degree of freedom; that is an open or close. These types of prosthesis are sometimes covered by a hand like glove providing greater proximal function and increased cosmetic appeal (often at the expense of efficiency), but also tend to be much heavier and more expensive than any other types of prosthetic devices available.



**Figure 1 Body-Powered Prosthesis (left), Myo-electric hand with hand-like glove covering (right)**

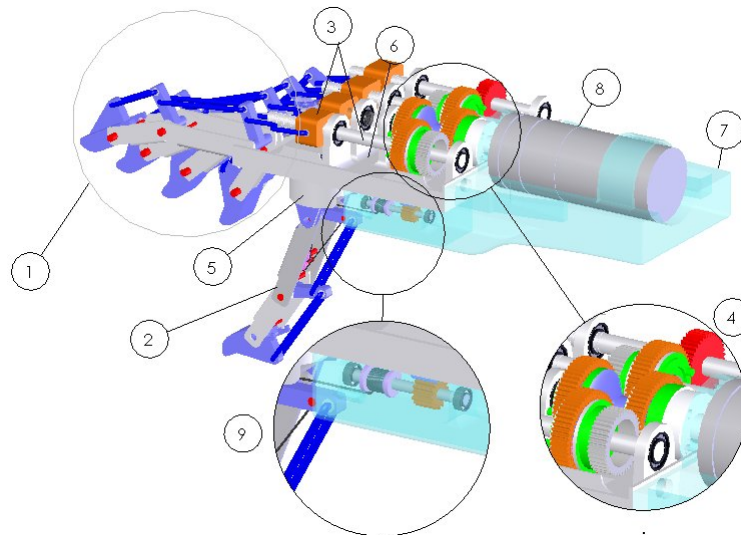
### 3. Design Parameters

The design parameters were chosen based on identified needs of prosthetic hand users and the desired features involving functional underactuated fingers and thumbs [Spires, 2000]. The following is a list of the seven main design parameters that were chosen for use in the design process:

1. Cost-effective and easy to manufacture
2. The prosthetic hand must be made up of five, three degree of freedom digits.
3. Fingers will be control by a single actuator
4. Fingers must passively conform to objects of different sizes and shapes
5. It must be engineered so as to allow each of the five hand digits to be actuated by a single input, while allowing each to operate independently with respect to the rest.
6. It must be able to perform gross grasping operations as well as pinch an object between the thumb and index finger, thumb and middle finger, or a combination of both.
7. Easy and inexpensive to maintain

### 4. Methodology

In order for the previously described parameters to be met, specially designed mechanisms were adapted and/or modified for the hand prostheses. A specifically arranged and designed differential system allowing for independent motion between all fingers using planetary gear systems was used. These planetary systems were connected to lead screws, which translated rotational motion to linear translation in order to actuate the specially designed 7-degree-of-freedom fingers. The thumb was actuated using a pulley system in response to the fact that its plane of motion is adjustable for different pinch configurations.



**Figure 2. (1) Multi-linked fingers, (2) Thumb, (3) Lead screw/nut, (4) Planetary Systems, (5) Thumb Pivot, (6) Palm plate, (7) Thumb/Wrist section, (8) Motor, (9) Pulley system**

Figure 2 in the previous page shows the main parts that comprise the prosthetic hand design and in the following sections each of these systems or mechanisms will be described in detail. Replicas of these parts can easily be made using hard plastic molds.

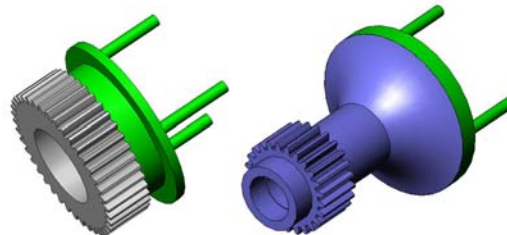
#### 4.1 Differential system

For all five fingers to work independently of each other, a differential mechanism based on the coupled, coaxial planetary gear system design for the end-effector robotic hand being developed by the University of Laval in Canada, to be used to in the Canada space arm, was designed [Laliberté et al., 2002].



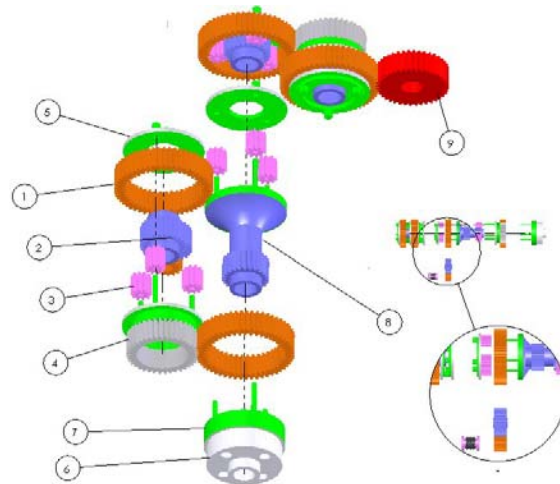
**Figure 3. University of Laval End-Effector using coupled planetary system**

In the case our prosthetic hand, a four coplanar-two coaxial planetary gear system was used. Adjacent coplanar systems were coupled together through the use of an adapted planet carrier gear mated with the adjacent ring gear. The coaxial planetary systems were coupled together using a specially designed sun gear to planet carrier piece.



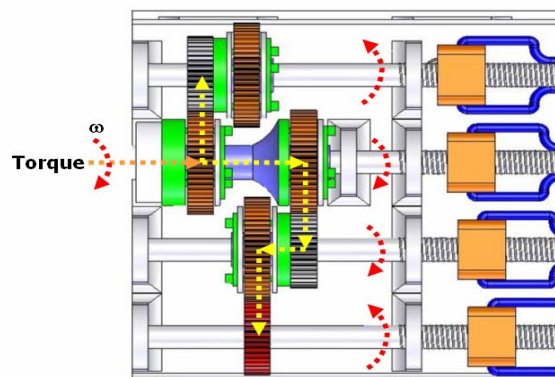
**Figure 4. (Left) Carrier gear (Right) Sun-to-carrier piece**

A single motor was used to produce the torque necessary to actuate the mechanism. This motor is connected to the index finger through the coplanar planetary systems and will stop rotating only as a result of all five fingers having reached their limiting positions. As figure 2 (side view) shows, the planetary systems on the index figure transmits motion to the thumb by means of two gears coupled to the index ring gear, and then through a shaft with a cabled pulley actuating the thumb. The only finger not directly attached to a planetary system is the fifth metacarpal (pinky finger), which is driven by a single gear coupled to the ring gear of the fourth metacarpal.



**Figure 5. Exploded view of planetary gear differential system**

Figure 5 shows the planetary systems driving each of the four fingers (index finger on the left and pinkie finger on the far right). The fully exploded planetary system on the left drives the index finger and marked from one to three are the ring, sun, and planet gears respectively. Items four and five are the planet carriers with piece four being the carrier gear with three shafts mating onto the female planet carrier (No. 5). In order to maintain the structural integrity of each planetary system, the planet carrier's inner and outer diameters were made small and larger respectively, with the sun gear anchoring the system to the respective finger's lead screw. Adjacent to the index planetary system are the two coaxial planetary systems, which are coupled through the sun-to-carrier piece (No. 8). Input from motor is received from the drive flange, which attaches to the shaft of the motor (No. 6) and is transmitted to the lower planetary system through a planet carrier, which is fixed to the drive phalanges by means of three screws. The figure shows how the sun-to-carrier piece transmits motion to the upper planetary system on the middle finger through the planet carrier, causing the sun gear, attached lead screw and ring gear to rotate in the opposite directions, independently. This is the case for all four planetary systems; input torque enters through the planet carrier and exit through the sun and ring gears independently. This will continue to happen while all fingers have not yet reached their limiting positions. Once this occurs, relative motion between gears will cease to occur and all fingers stop moving as a result of having fully conformed to the object being grasped or reaching a limiting positions. Figure 6 below shows how the motor's input torque is distributed through the system as well as the relationship between input (motor) and output (lead screw)  $\omega$ .



**Figure 6. Torque flow through planetary systems and shafts**

Given that energy follows the path of least resistance, applying small amounts of friction to the shaft (lead screws) will allow for the manipulation of the order in which each finger will close with respect to the others. Technically, even the gears used could be made out of hard plastics or cast iron but that would make them less reliable more likely to fail in a shorter period of time.

## 4.2 Lead Screws

The sun gear is attached rigidly to self-locking lead screw shafts which converts rotary motion into linear motion to the screw mount (driving nut) connected to one of the four fingers by means of a driving link (the thumb is actuated using a pulley mechanism discussed at the end of the section). A self locking lead screw is one where the lead angle is less than five degrees and thus prevents back driving of the nut when external forces, such as the weight of the object being picked up, act on the fingers. This is very important since it prevents the need for the motor to continually apply torque to the fingers once the fingers have fully adapted to the object.

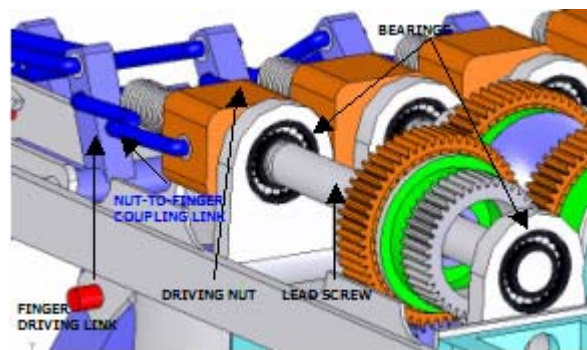
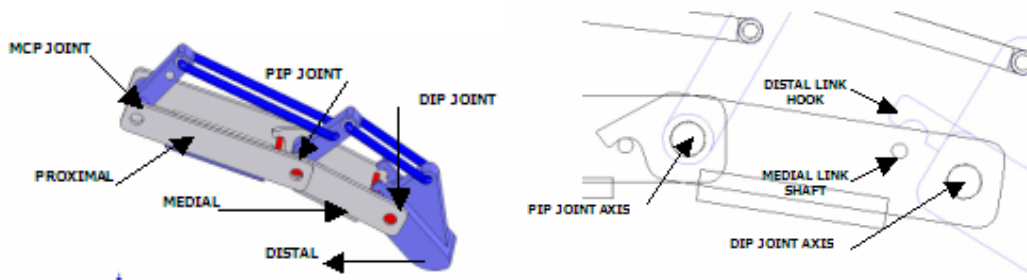


Figure 7. Lead screw setup

The figure above shows how lead screws are set up on each finger. The lead screw shaft is mounted on low friction ball bearings set on a specially designed mount on the palm. As input from the planet carrier causes the sun gear to move, the lead screw will rotate accordingly with the nut translating rotary motion into linear motion, causing the finger-driving link to begin rotating by means of the nut-to-finger coupling link. Each lead screw has a right or left-handed threading, depending on the corresponding direction rotation of the sun gear so as to allow each finger to flex in the proper direction. Based on simple conventions, the index and pinkie lead screws are left-handed while the middle and ring finger lead screw have a right handed threading (figure 6).

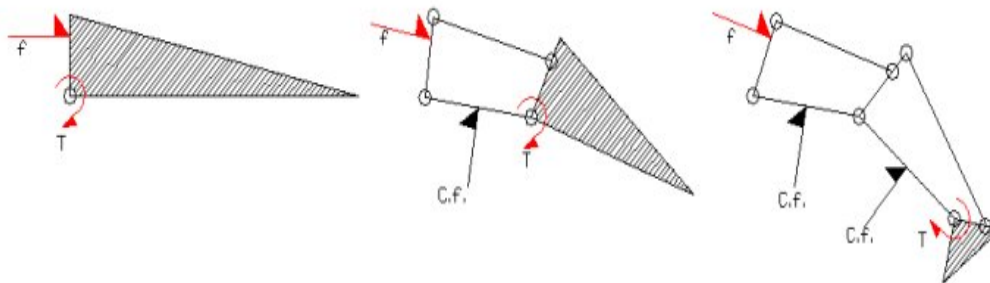
## 4.3 Finger Design

The hand's ability to adapt to different shapes and objects required fingers with the capacity to be self-adaptable without the need for external power or control. This necessity was met by using a seven-bar mechanism for each finger. In order for the fingers to function in similar fashion to that of human finger, it was designed using three different sections (distal, medial, and proximal). The axis of rotation for the proximal link will be referred to as the metacarpal-phalangeal joint (MCP), the axis of rotation of the medial link is referred to as the proximal inter-phalangeal joint (PIP), and the axis of rotation of the distal link will be referred to as the distal inter-phalangeal (DIP). Figure 9 highlights the different features of the fingers.



**Figure 8. General Finger design (left), See-through view of a finger between the medial and distal axis of rotation (right)**

The proximal and medial sections are composed of four-bar mechanisms couple to each other at the PIP joint, while the distal section of the finger is represented by using a tertiary link at the end of the medial four bar mechanism. The figure below shows how the finger behaves as each section comes in contacts (and stops).



**Figure 9. Finger Configurations: (a) No external force, (b) proximal link external force, (c) Proximal & Medial external forces**

Initially, the finger behaves as one single tertiary link actuated at the MCP joint of the proximal link. The ability of each link to maintain its position relative to the others while no external forces are applied is achieved through the application of an opposing torque at the joints, in this case achieved through the introduction of small frictional forces, at the axis of rotation of the medial and distal links. To achieve this, the fit between each link was designed to be flush so as to create just enough fictional forces at these points. In the case where more friction was needed, C-rings were placed at the connecting shaft's bolt head. As each link comes into contact with the object, it shifts from behaving as a simple tertiary link, to a four-bar mechanism (composed of three binary and one tertiary link), and finally to a seven-bar mechanism.

In order to prevent hyperextension at any of the joints when they hand is opening, it was necessary to place mechanical limiters composed of a shaft on one link and a hook on the adjacent link. As figure 9 shows, as the hand extends open the links rotate counterclockwise. Hyperextension is prevented by the use of hook-like sections at the ends of the distal and medial sections, which lock into the corresponding pin shaft when maximum extension is achieved. In the case of the PIP joint, the limiting angle is 20 degrees, were at the distal it is 0 degrees. The dimensions and proportions used in the design were obtained from average population data. The nominal values for the palm, hand, finger lengths as well as the handbreadth were used and the standard deviation added on to this value. The reason for adding the standard deviation to the nominal value was very basic. Due to the use of planetary systems, it was necessary to make the hand as large as possible while still stay within portion of what is considered a human hand so that the planetary gears would comply with design specifications and needs. Fingers link lengths were calculated using the “Golden Section” rule, as shown by the calculations in figure 10.

Finger Phalange Lengths:

Distal Phalange Length= $x$  Golden Proportion= $1.61803$

$$x + x \cdot 1.61803 + x \cdot 1.61803^2 = 3.62 \text{ solve , } x \rightarrow .69136071135841084266$$

Distal =.69

$$.69 \cdot 1.61803 = 1.116$$

Medial =1.12

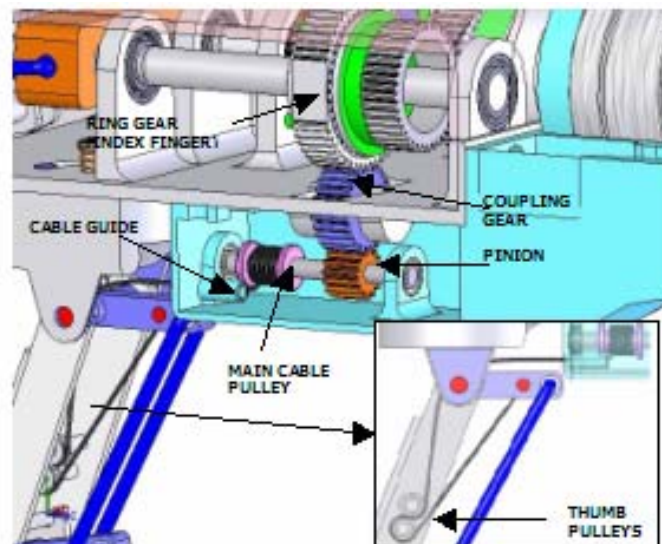
$$1.12 \cdot 1.61803 = 1.812$$

Proximal =1.8

**Figure 10. Calculation of finger link lengths**

#### 4.4 Thumb design

The actuation of the thumb is of greater complexity than that of the fingers due to the design parameters, though both are exactly the same in portion and general link design. First, the MCP joint is required to have two degrees-of-freedom as opposed to the fingers that only have one degree-of-freedom MCP joints. This feature stems from the design parameter requiring a variety of pinching configurations between the index, middle finger, and the thumb. Second, because the thumb has multiple degrees of freedom, actuation by means of a lead screw was not feasible. It was then decided that a cable and pulley system was the best suited mechanism to use since it would allow the thumb to rotate into several pinch positions while maintaining the capability to actuate. The pulley system was designed to actuate the thumb utilizing input torque from the ring gear of the index finger's planetary systems on the top half of the palm.

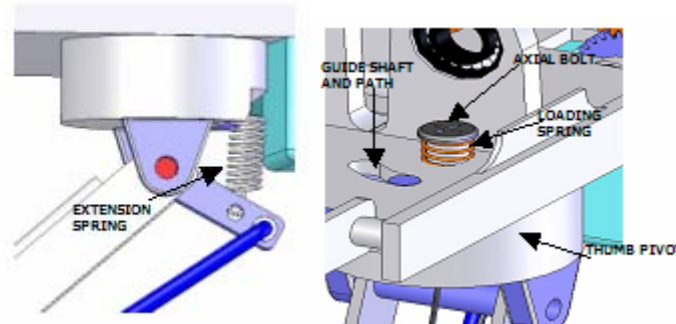


**Figure 11. Pulley/Cabling system setup for thumb actuation**

Figure 11 shows how a gear mounted at the base of the plot is used to couple the ring gear of the index finger planetary system with a pinion gear below the palm. The pinion gear is rigidly attached to a shaft at its axis of rotation, which is also connected at the other end to the main cable pulley. From the drive pulley, a line is fed through a cable, which runs from the pulley inside the palm up to the thumb pulleys. The line then runs through two small pulleys placed in the middle of the proximal figure by means of a small shaft fixed to each side of the links and attached to the driving link in the proximal four-bar mechanism. This allows the thumb to rotate about the MCP joint and close on an object in a similar



fashion as the other fingers. In order for the thumb to retract when the hand opens, a tension spring was attached between the thumb's driving link and to the thumb's pivot joint as seen in the figure below.

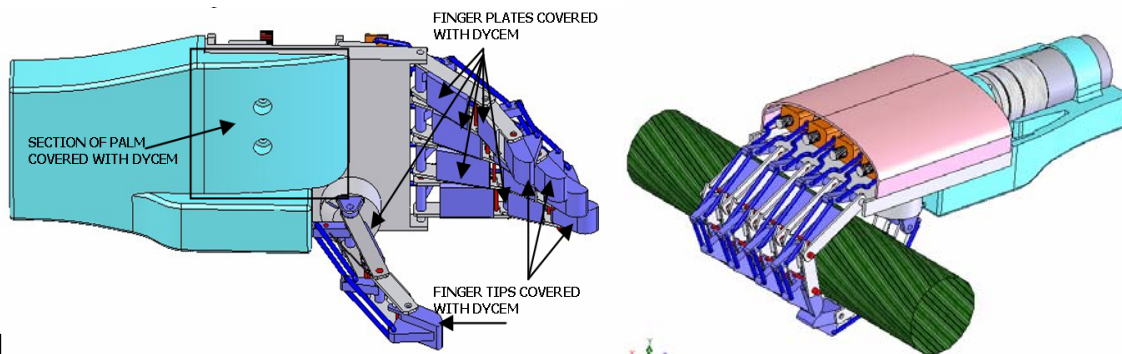


**Figure 12. Thumb extension spring system (left), Thumb Pivoting Mechanism (right)**

Changing pinching configurations is a simple process and is done manually by the user. The thumb MCP pivot joint is held in place by means of a spring-loaded axial screw, which attaches to the hand's palm. Spring loading the screw against the palm causes the pivot to be held in place by means of an upward force and friction. Changing a position simply implies rotating the thumb pivot with a certain amount of force. A guide shaft runs through a path on the palm, which limits the range of motion to 35 degrees.

#### 4.5 Increasing grasping/ pinching capabilities

Given the limited contact area between fingers and small object in pinching configurations, it is often difficult to secure the object in place when lifting or moving without having to increase the surface contact area or force. In order to minimize this effect all of the finger links would ideally be covered at the bottom end plates with a special material called Dycem®. Dycem® is a specially design polymer material with an extremely high coefficient of friction several times larger than that of the human skin which is relatively inexpensive but would have to be imported. Other alternatives such as covering the contact point with a soft robbers were also be a possibility where this material not available.



**Figure 13. Contact surfaces covered with high friction polymer or rubber (left); Hand in grasping model (right)**

### 5. Manufacturing and Cost

The final design has a total of 93 components (not including fasteners) derived from 28 key parts. A key part is defined as one which has a single or more duplicates (i.e. planet gears and finger segments). All finger and thumb components are the same with the exception of the proximal section of the thumb. Most key components of the different planetary gear systems are identical and the gear specifications chosen are standard, making manufacturing of the gears more cost effective. In general, the fact that there are relatively few parts in comparison to commercial electric-driven hand prosthetics inherently lowers the

cost of production. Furthermore, the relative simplicity of the parts designed, along with the use of stock items such as the lead screws, nuts, and ball bearings will reduce production cost even more. Considering that the cost of a myo-electric hands ranges from \$14,000 to \$70,000 [Davies et al., 1970], the savings passed on to the end user could be significant. The benefits would be even more significant in developing countries where myo-electric prostheses are not common. While gears and lead screws will be made out of steel or aluminum to increase its useful life, a simple production line can be set-up to create the remainder parts out of plastic. This will provide a locally controlled, easily adaptable, and cost effective means of production.

Currently, a prototype is being created with 90% of the parts produced with a stereo lithography apparatus (SLA). The total cost of manufacturing the prototype is estimated at around \$1,100, including the motor, lead screws, ball bearings, and fasteners, all of which are stock items and relatively inexpensive. The final cost of manufacturing can be decreased by using more cost effective manufacturing processes.

## 6. Discussion

Ultimately, this design will provide a cheaper, less complex, lighter, and more easily manufacturable hand prosthetic device. Its functionality and anthropomorphic design will make it more acceptable to amputees who have a hard time adapting to prosthetic devices use. Moreover, the fact that all five fingers, planetary gears systems, and lead screws/nuts are identical; this means manufacturing costs would be substantially lower than that of myo-electric prosthetics, which contain expensive servo's and electronics. This would make functional prosthetic devices accessible to people with limited resources not only in the U.S. but also developing countries, where resources are extremely limited to those most commonly afflicted with these types of injuries.

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