

## Partial Hand Prosthesis: Design and Simulation

### Prótesis parcial de mano: Diseño y simulación

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#### Abstract

Nowadays, engineering has attempted to find a way to replace the loss of human limbs with unnatural devices that approximate their actual function. Current devices vary from hooks, mechanical prostheses, or simply cosmetic prostheses, where an important component when deciding which one to use is the cost of it, even above functionality. The aim of this article is the development of a mechanical prototype for partial hand prosthesis for patients who have suffered partial (middle and distal phalanges) or total (proximal, middle, and distal phalanges) finger mutilation. The results of this work show that the mechanism and the proposed design of the prosthesis are satisfactory to simulate the movement of a human finger, while the finite element analysis shows that the proposed design can adequately support the loads for extreme conditions.

**Partial hand prosthesis, Functional prosthesis, Six-bar mechanism, Simulation, Distal, Proximal**

#### Resumen

Actualmente la ingeniería ha intentado encontrar una solución de sustituir la pérdida de miembros humanos con dispositivos que aproximen su función real. Los dispositivos actuales varían desde ganchos, prótesis mecánicas, o simplemente prótesis cosméticas, donde un componente importante a la hora de decidir cuál utilizar es el costo de esta, incluso por encima de la funcionalidad. El objetivo de este artículo es el desarrollo de un prototipo mecánico de prótesis parcial de mano para pacientes que han sufrido una mutilación parcial (falanges medias y distales) o total (falanges proximales, medias y distales) de los dedos. Los resultados de este trabajo muestran que el mecanismo y el diseño propuesto de la prótesis son satisfactorios para simular el movimiento de un dedo humano, mientras que el análisis de elementos finitos muestra que el diseño propuesto puede soportar adecuadamente las cargas comunes.

**Prótesis parcial de mano, Prótesis funcional, Mecanismo de seis barras, Simulación, Distal, Proximal**

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## 1. Introduction

The hand is extremely important and therefore exposed to a range of injuries that can affect its function, resulting in disabilities that lead to serious problems in daily life (Binvignat et al. 2012). In Mexico, limb amputation is the fourth cause of disability, with most victims being people of working age between 20 and 45 years (Sandoval 2011). The replacement of some of the human limbs with devices has been performed for more than two thousand years (Perez Romero 2011) and is aimed at enabling affected individuals to incorporate into their daily lives. Therefore, prostheses play a key role as it means an increase in the quality of life of people who have suffered amputation.

Prostheses can be classified into two categories: passive and active. The first ones, also known as cosmetic prostheses, aim to reestablish the appearance although they lack mobility (Pérez Romero 2011). These prostheses are commonly manufactured with silicone or chlorinated polyvinyl chloride and offer advantages and disadvantages in terms of durability, realism, and price. Among the active prostheses are the mechanical prostheses (Loaiza and Arzola, 2011; Torres-SanMiguel, 2022), which are devices that are used to control closing or opening at any time, thus partially recovering the functionality of the hand.

Some reference examples of finger designs are those used in Stanford/JPL hands (Matthew and Kenneth, 1985), Utah MIT (Jacobsen et al. 1986), TUAT/Karlsruhe (Schulz and Pylatiuk, 2011), DLR (Butterfass et al. 1998), and those developed by NASA (Lovchik and Diftler, 1999) and those designs reported by Díaz Montes (Díaz Montes, 2013), Piña Quintero (Piña Quintero, 2010).

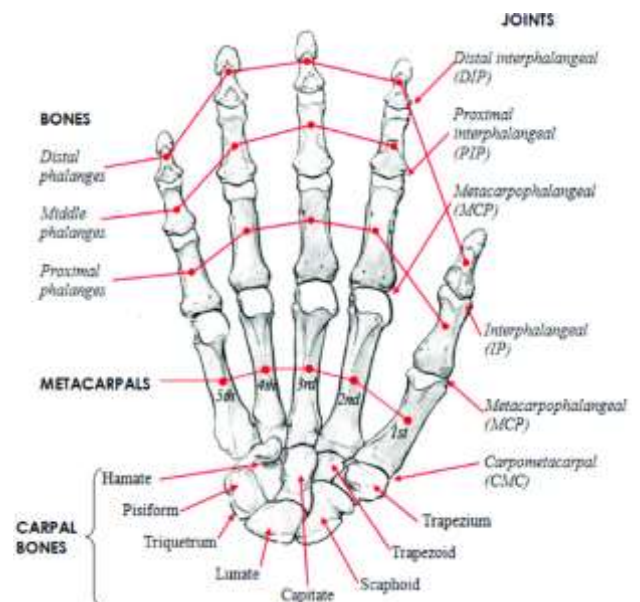
The recent invention that does not use electronic devices for its operation is called X-finger, which is specifically designed to address partial finger amputations. Each of these prostheses is individually manufactured to accommodate different amputation cases (Didrick D. 2005). This type of mechanical designs can present some disadvantages such as: limitations of movements caused by the restriction of the mobility of the proposed mechanisms, excessive weight due to the material with which they are manufactured.

In addition, it cannot be considered to make grips where too much force is printed and the main disadvantage is caused by its high cost, which makes them not accessible to all people of working age.

Therefore, the aim of this investigation is to design and analyze a mechanical prototype of a partial hand prosthesis for patients who have suffered mutilation of one or more fingers of the hand either partial (middle and distal phalanges) or total (proximal, middle, and distal phalanges).

## 2. Human hand anatomy

Anatomical knowledge of the human hand is a fundamental step in the design of prostheses, since it is important to know all the possible movements that it can perform. The skeleton of the human hand can be divided into three regions: i) the carpal region (wrist), ii) the metacarpal region and iii) the phalangeal region (fingers), the last of which can be further subdivided into proximal middle and distal phalanges (see Figure 1). Table 1 shows the dimensions of the phalanges of fingers and Table 2 the range of movements. Thus, it can be stated that the human hand is a complex structure with 22 degrees of freedom that allow multiple configurations of grasping and manipulation. Each finger, except for the thumb, has two hinge joints and a joint at the base with two degrees of freedom, where one of its rotation axes is parallel to the rotation axes of the joints and the second is perpendicular to it and normal to the palm (Gutiérrez T. 2010).



**Figure 1** Human hand anatomy (Nanayakkara et al., 2017)

Phalange type	Finger length (mm)			
	Index	Middle	Ring	little
Proximal	32.50±0.5	37.50±0.5	35.50±0.5	27.5±0.5
Middle	28.50±0.5	30.00±0.5	29.20±0.5	20.00±0.5
Distal	21.50±0.5	21.50±0.5	21.50±0.5	13.00±0.5

**Table 1** Index, middle, ring, and minimum finger dimensions (Gutiérrez, 2010).

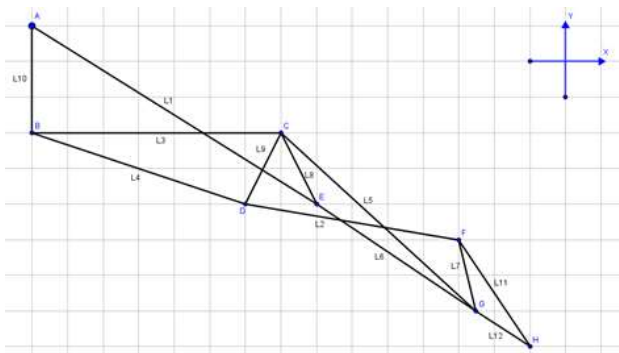
		Fingers range of motion of flexion/extension			
		Index	Middle	Ring	little
Distal	inter-phalangeal	72°/8°	71°/8°	63°/8°	65°/8°
Proximal	Inter-phalangeal	102°/7°	105°/7°	108°/6°	106°/9°
Metacarpophalangeal		86°/22°	91°/18°	99°/23°	105°/19°

**Table 2** Finger range of motion (Gutiérrez, 2010)

### 3. Mechanism synthesis

The synthesis of mechanisms consists of finding a solution to the problems of trajectory generation, operation, and movement (Erdman and Sandor, 2007).

The proposed mechanism consists of six linkages joined together, which form two four-bar mechanisms, the first one is located at the base of the finger that provides movement to the middle phalange, which in turn, activates the other mechanism to move the distal phalange. Thus, the activation is performed by the  $L_1$  and  $L_3$  link which are connected to the middle phalange producing flexion in the distal phalange, as shown in Figure 2.



**Figure 2** Six-bar mechanisms generating the mobility of the prosthesis prototype

To verify the mechanism's mobility and functionality, a position analysis is performed between the proposed linkages and types of joints.

The position of the prototype was obtained based on a kinematic analysis using the vectorial loops method, since there are two four-bar mechanisms generated from the 6-bar mechanism from Figure 2. The analysis shows a generalized method, since the mechanism is repeated in each of the fingers, changing only the dimensions of the linkages according to the dimensions of the fingers to which a prosthesis is to be made.

Equation (1) describes the position of the vector loop 1, shown in figure 3.

$$\vec{L}_{10} + \vec{L}_3 - \vec{L}_8 - \vec{L}_1 = \vec{0} \quad (1)$$

Dividing the vector loop 1 into its Cartesian components we obtain the following equation system for position:

$$L_1 \cos \phi_1 = L_{10} \cos \phi_{10} + L_3 \cos \phi_3 - L_8 \cos \phi_8 \quad (2)$$

$$L_1 \sin \phi_1 = L_{10} \sin \phi_{10} + L_3 \sin \phi_3 - L_8 \sin \phi_8 \quad (3)$$

Solving for  $\phi_8$  we have:

$$(A^2 - B^2) \tan^2 \phi_8 + 2BC \tan \phi_8 + (A^2 - C^2) = 0 \quad (4)$$

where:

$$A = L_1^2 - L_8^2 - L_3^2 - L_{10}^2 \quad (5)$$

$$B = 2L_{10}L_8 \sin \phi_{10} \quad (6)$$

$$C = 2L_3L_8 \cos \phi_3 \quad (7)$$

On the other hand, Equation (8) describes the position of the vector loop 2, shown in figure 4.

$$\vec{L}_2 + \vec{L}_7 - \vec{L}_5 - \vec{L}_9 = \vec{0} \quad (8)$$

Calculating the components of each vector, and substituting in the vector loop 2 we have the following system of position equations:

$$L_2 \cos \phi_2 = L_5 \cos \phi_5 + L_9 \cos \phi_9 - L_7 \cos \phi_7 \quad (9)$$

$$L_2 \sin \phi_2 = L_5 \sin \phi_5 + L_9 \sin \phi_9 - L_7 \sin \phi_7 \quad (10)$$

Solving for  $\phi_7$  we have:

$$(A^2 - C^2) \tan^2 \phi_7 - 2BC \tan \phi_7 + (A^2 - B^2) = 0 \quad (11)$$

Where:

$$A = L_2^2 - L_5^2 - L_9^2 - L_7^2 - 2L_5L_9 \cos \phi_9 \cos \phi_5 - 2L_5L_9 \sin \phi_5 \sin \phi_9 \quad (12)$$

$$B = -2L_7L_5 \cos \phi_5 - 2L_7L_9 \cos \phi_9 \quad (13)$$

$$C = -2L_7L_9 \sin \phi_9 - 2L_7L_5 \sin \phi_5 \quad (14)$$

Equation (11) describes the motion of the second vector loop for the four-bar mechanism that is formed between point C, D, F and G (Figure 4) which provides the motions of the prosthesis prototype.

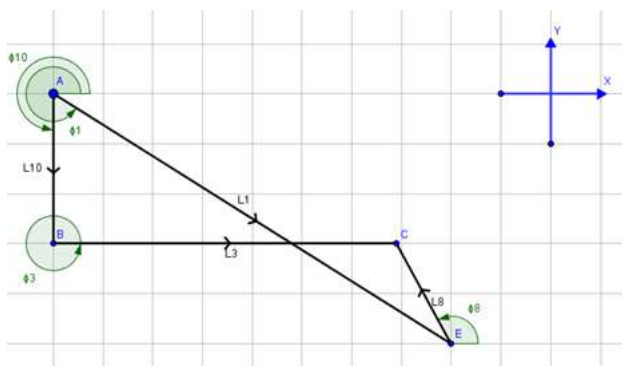


Figure 3 Analysis of the first four-bar mechanism

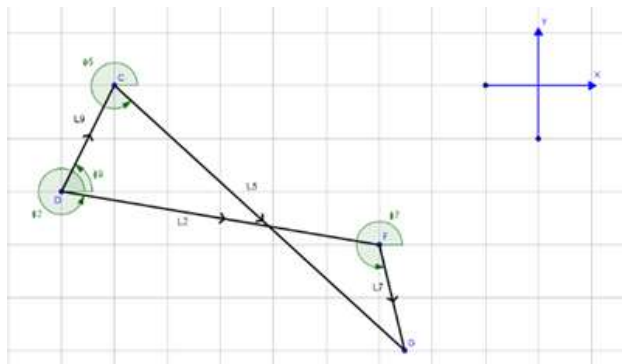


Figure 4 Analysis of the second four-bar mechanism.

#### 4. Stress analysis

Once the mobility of the mechanism and the trajectories were determined, a stress and deformation analysis of the proposed mechanism was performed by means of finite elements (FEM), this allows proposing a suitable material for the subsequent manufacture of the prototype considering the weight and the redesign of the critical areas where stress concentrations are present. For this purpose, some critical movements of the prototype are considered, where the application of force on the phalanges is required.

#### 5. Results

The analysis and synthesis of the proposed mechanism provides the necessary elements to determine the desired trajectories of the mechanism simulating the hand opening and closing. From this analysis and with the typical dimensions of the fingers, the prototype shown in Figure 5 was obtained. The trajectories followed by the distal phalange of the mechanisms of each finger of the hand are shown in Figure 6, where a similarity to the movement of the hand can be appreciated.

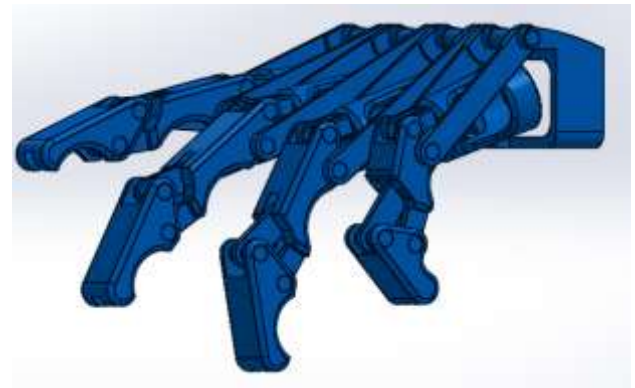
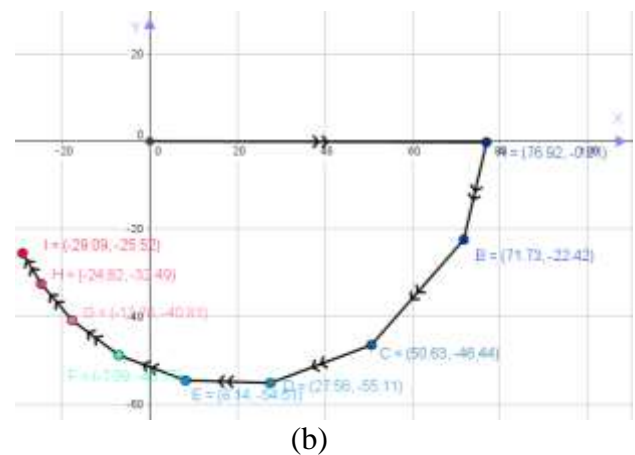
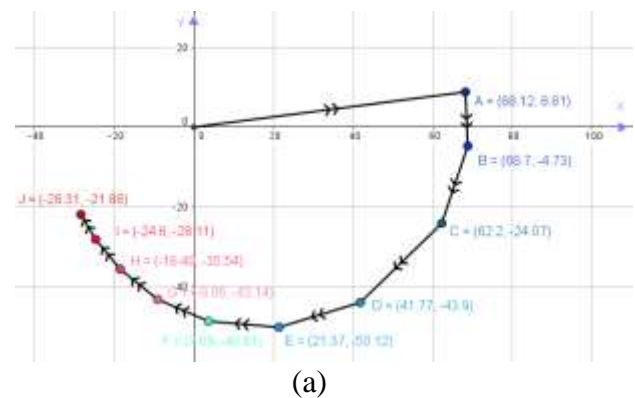
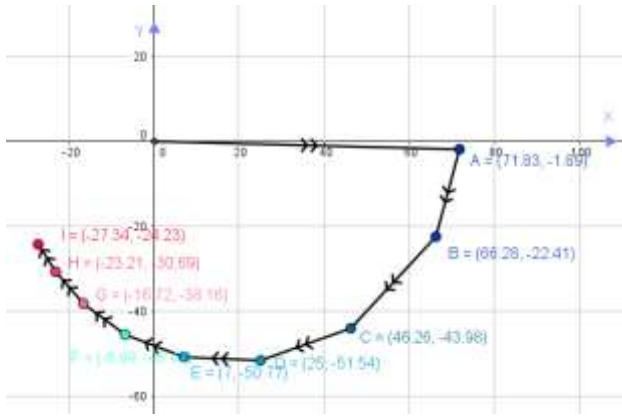
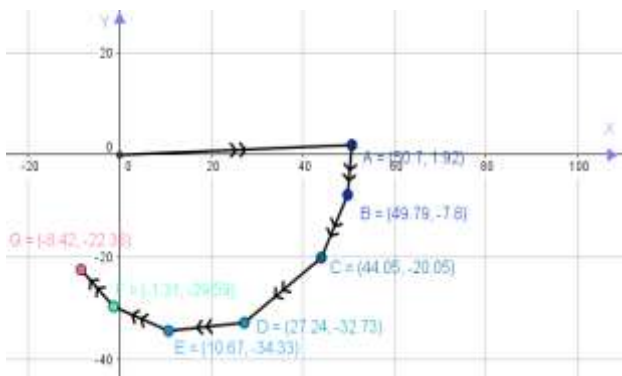


Figure 5 Prosthesis prototype for four fingers of the hand.





(c)



(d)

Figure 6 Prostheses movement path for (a) index finger, (b) middle finger, (c) ring finger, (d) little finger

The results from the finite element analysis of the total deformation generated in the distal phalange is shown in Figure 7, having a maximum displacement of 1.15 mm. On the other hand, Figure 8 indicates the maximum Von Mises stress, produced in the bars supporting the prototype. The maximum value calculated was 156 MPa and was presented in the geometry changes of the same bars where the stress concentrators are located.

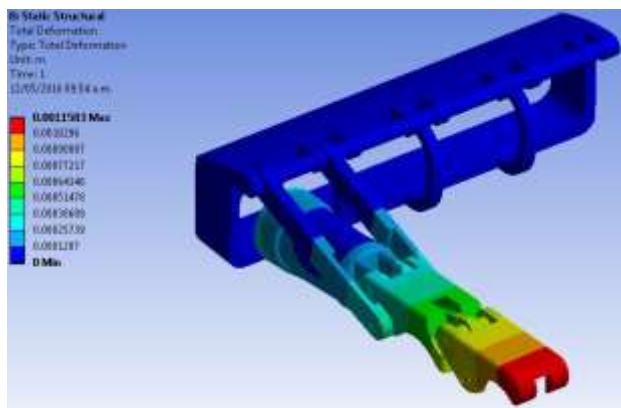


Figure 7 Deformation distribution of the prototype

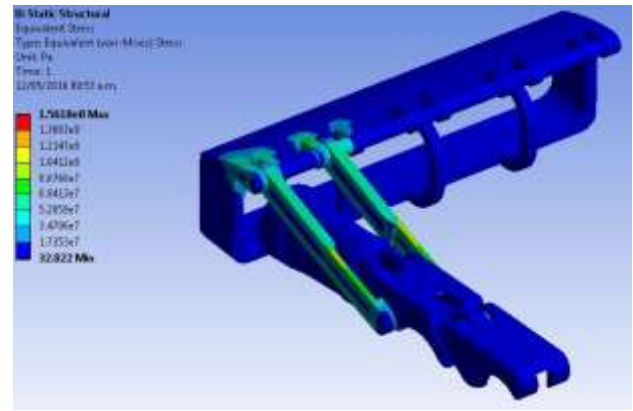


Figure 8 Von Mises Stress analysis

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Conclusions

The proposed six-bar mechanism fulfills the opening and closing conditions of mobility performed by the fingers of the hand, in addition, we ensure with the position equations that there will be no interference between the movements of the bars and their types of joints.

The stress analysis on the design of the mechanism showed that the design of the proposed prototype adequately withstands the stresses, obtaining a minimum-security factor of 1.8. This provides assurance that the design for the phalanges is adequate to support extreme loading conditions.

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