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DESIGN OF A BODY-POWERED FINGER PROSTHESIS FROM MEDICAL IMAGES AND KINEMATIC ANALYSIS

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Abstract

With the advancement of technology, many prosthesis were developed to improve the life standard of a person who lost one or more limb. One of the most common limb loss is finger lose. Many finger prosthesis were developed to imitate the functionality of natural human fingers. But most of them are not personalised (does not fit perfectly to the user) and/or not easy to apply. Some finger prosthesis needs surgical operation to apply. The aim of this study is to design and manufacture accessible and sustainable finger prosthesis that is easy to apply and personalised.

In this study, hand skeleton structure was modelled from computerized tomography images. Distal and middle phalanx bones were removed to show finger loss. Personalised finger prosthesis that fits perfectly to the user was designed on the hand skeleton structure. By using kinematic analysis, finger prosthesis movement capabilities are determined and general mathematic model was developed to be used in other patients. Before production, newly designed finger prosthesis movement was analysed and model was optimised with the result of the analysis.

Finally, the gripping ability of the prosthesis that was produced and its similarity to the natural finger mechanical structure were confirmed by experiments and measurements.

Key Words: Biomechanics, Finger Prostheses, Kinematic Analysis, Personalized Design

1. Introduction

According to the Healthcare Cost and Utilization Project data, finger losses make up 80% of the total upper limb amputation. In addition to physical ability limitation, finger loss also causes mental problems due to visual differences from others [1]. Many studies focus on regaining the physical ability [1-4] but overlook that prosthesis must fit perfectly to the user in order to accomplish regaining the physical ability.

Finger prosthesis can be classified under 3 main headings; non-functional fingers prosthesis (only aesthetics concern), external powered fingers prosthesis and body powered fingers prosthesis [3,4]. Body powered and external powered prosthesis are functional and can imitate natural finger movements. Most of the powered prostheses were designed to grasp an object with two or more fingers. Tendon-driven systems are usually used at finger prosthesis however these systems are not suitable for natural hand movement. Finger joints do not always start rotation at the same time. On the other hand, mechanic drive system provide smoother movement. Finger movement of the mechanic drive system is very similar to natural hand movements. For these reasons, mechanic system was used in this study.

Understanding hand anatomy is a significant requirement to make a functional finger prosthesis. Moving parts of the hand skeleton structure is phalanx bones. Distal phalanx (DP), middle phalanx (MP) and proximal phalanx (PP) lengths and anatomic structures are different from each other as seen in Figure 1.

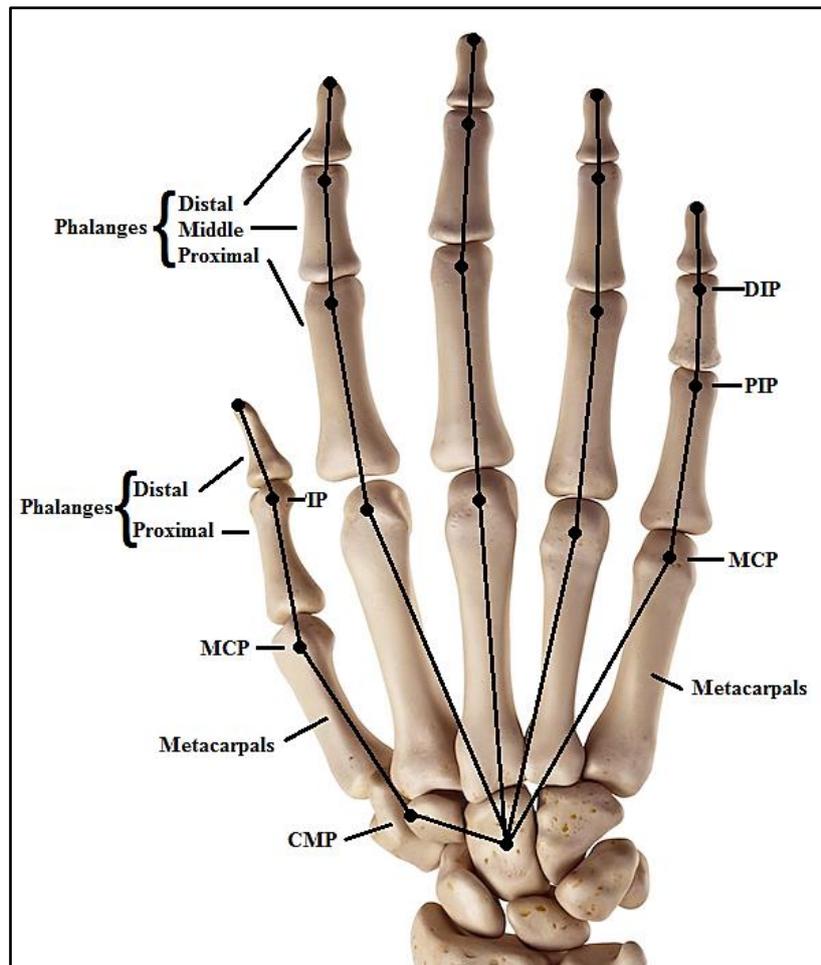


Fig 1 Human hand anatomy

In this study DP and MP bones are modelled from computerized tomography (CT) images. Finger prosthesis was designed based on kinematic analysis. Optimised finger prosthesis design was manufactured by using a 3D printer while gripping capabilities of manufactured finger prosthesis was tested by placing a hand.

2. Material and Method

This study aim to design personalised, easy to apply finger prosthesis. CT images (taken to corresponding author) were used in order to make design personalised. Distal and middle phalanx bones are removed at the solid modelling stage to simulate finger loss. It's not possible to get solid model directly from medical images. Therefore different image processing programs were used. Design stages of the finger prosthesis were shown in Figure 2.

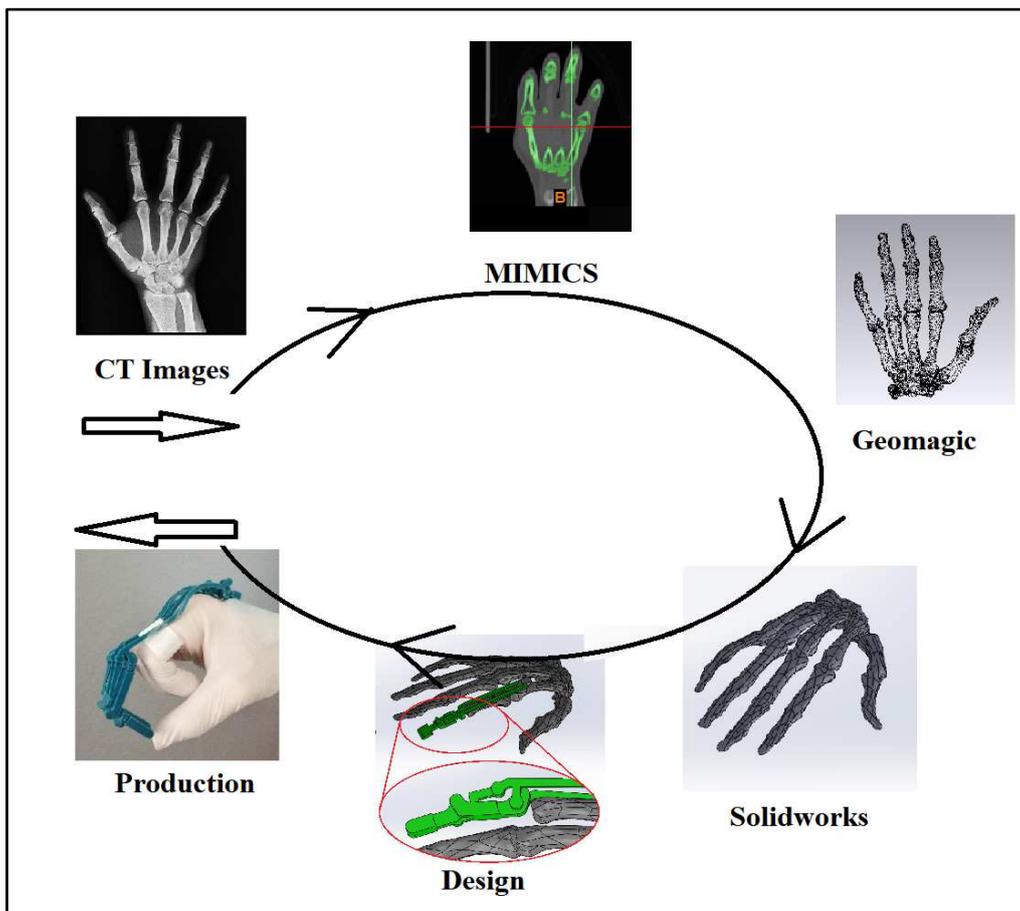


Fig 2 Design stages of the finger prosthesis

Advantage of using mechanic drive system is that all joints rotate at the same time but with different ratios. In this design, movement of the MCP joint, make the PIP and DIP joints move simultaneously. Patient's proximal phalanx connect to finger prosthesis linking bar and the finger prosthesis moved using proximal phalanx.

Image processing stage is required to personalise the prosthesis design. Prosthesis finger parts measurements were determined according to bone models. Therefore, bone models must be accurate to successfully measure prosthesis finger parts. Results of kinematic analysis were used to determine joint rotation rates. After the determination of joint rotation rates, finger prosthesis design was completed and assembled to bone models. Movement analysis of assembled hand model was done and finger prosthesis was optimised for better grasp and perfect fixation.

2.1 Image processing

MIMICS program was used to create a hand model. 226 – 2136 HU threshold was set in order to get bone model from CT images. Small bones on the finger joints were erased and smooth mask operation was utilized for model surface segmentation. Creating accurate model is the most important stage of image processing. If there are sharp points, spikes or cracks, getting surface model at the further stages would be very difficult and some details might be lost. Created hand model, shown in Figure 3, is exported as a point cloud (.txt format).

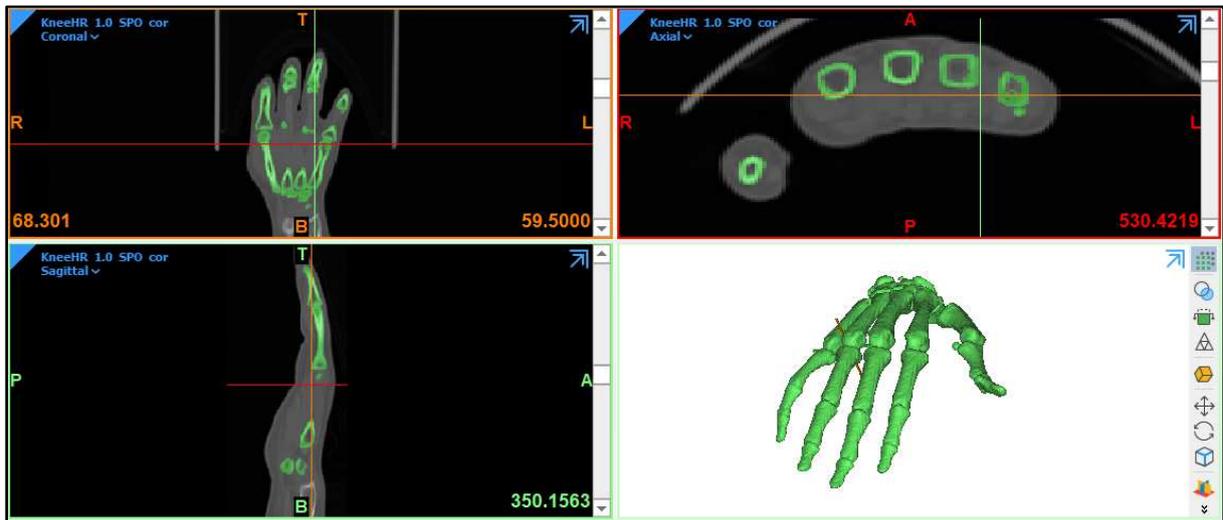


Fig 3 Created hand model at MIMICS

Point cloud data is opened in Geomagic software to create the surface model. Editing or smoothing cannot be done after 3D Surface model created. Therefore spikes, holes, and cracks etc. must be fixed carefully prior to creation of 3D Surface model. From point cloud, surface model is created and transferred to 3D solid model. Point cloud, surface model and 3D solid model are shown in Figure 4.

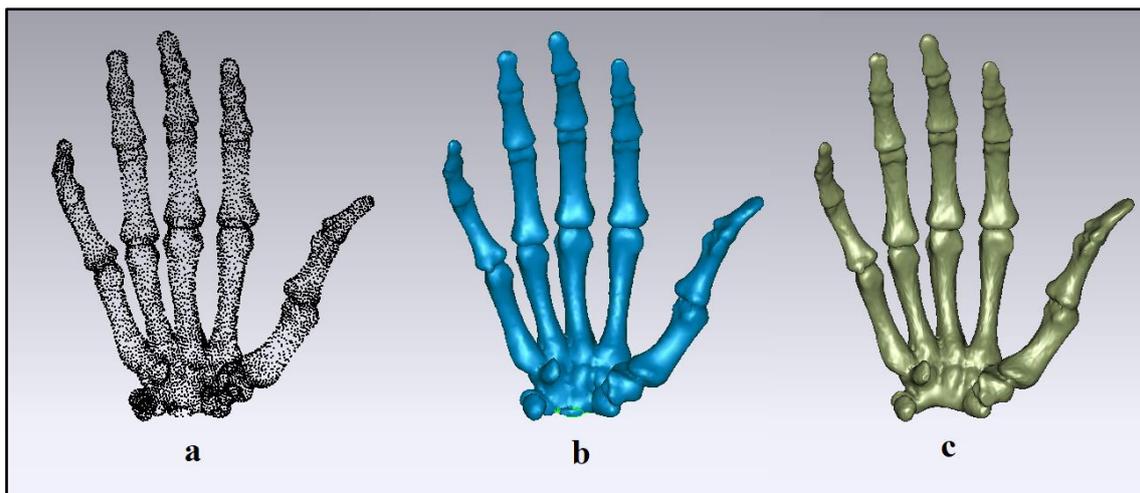


Fig 4 Creating surface model at Geomagic (a. Point cloud, b. surface model, c. 3D solid model).

2.2 Prosthesis design

3D solid model transferred to SolidWork program for prosthesis design. In order to simulate finger loses, index finger (distal and middle phalanxes bones) was removed from hand model. CT images of the author, who does not

have any finger loss, were used for this study. Therefore, finger parts were removed to simulate target group of this study. Reason of removing finger parts, CT images were used for this study belong to corresponding author who don't have any finger losses. To simulate target group this revision has done.

The patient is assumed to has index finger loss. For this reason, ring finger measurements were used for index finger prosthesis design. After the completion of design, movement capabilities were analyzed at the assembly section of the SolidWorks program. Finger prosthesis design and assembly with hand model can be seen in Figure 5.

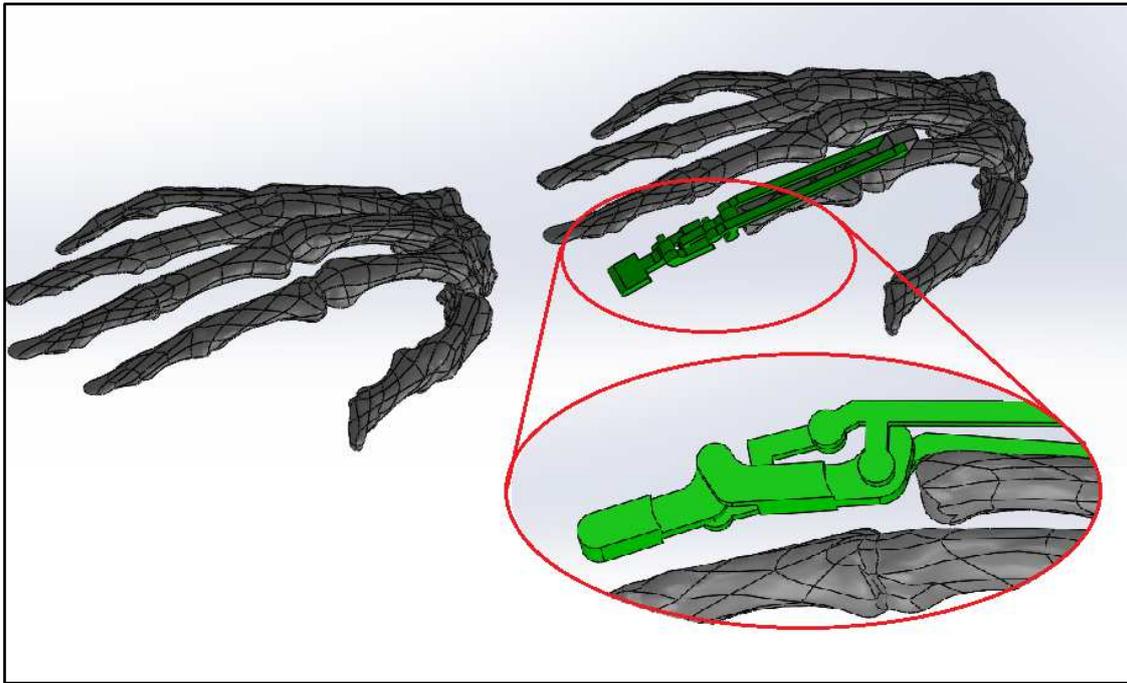


Fig 5 hand model and assembled finger prosthesis design

3. Kinematic Analysis

The designed prosthesis model provides a mechanical system that can be used in place of the lost limb for people who have finger loss. Applying newly designed prosthesis is painless and easy, do not required surgical operation.

Designed prosthesis have 4 moving connections and 3 main joints. 2 fingers were modelled at this study (index and middle finger). Up to 4 independent finger can be designed if needed.

The system was designed as 4 bar mechanism. This mechanism can be used as basic and cross (X) 4 bar. While X bar system is transferring reverse rotation to joints, basic system provides same direction rotation.

X bar mechanism was used between MCP - PIP and basic bar mechanism was used between PIP - DIP joints. Figure 6 shows X and basic bar mechanism at designed prosthesis.

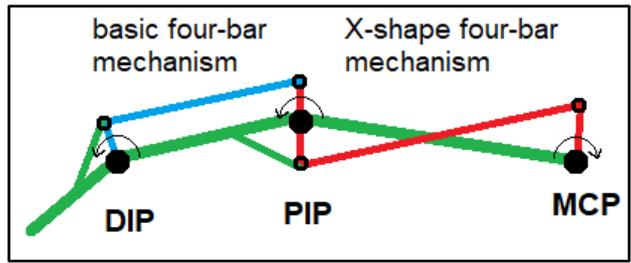


Fig 6 Cross (x) and basic bar mechanism

Kinematics and dynamic analysis must be solved together. But with the help of kinematic analysis result, it will not be necessary to repeat the same analysis every time. Determining joint rotation rates will be quite easy using these results. The link structure of the 3-pieced prosthetic finger which is shown in Figure 7 was placed to x - y coordinate system.

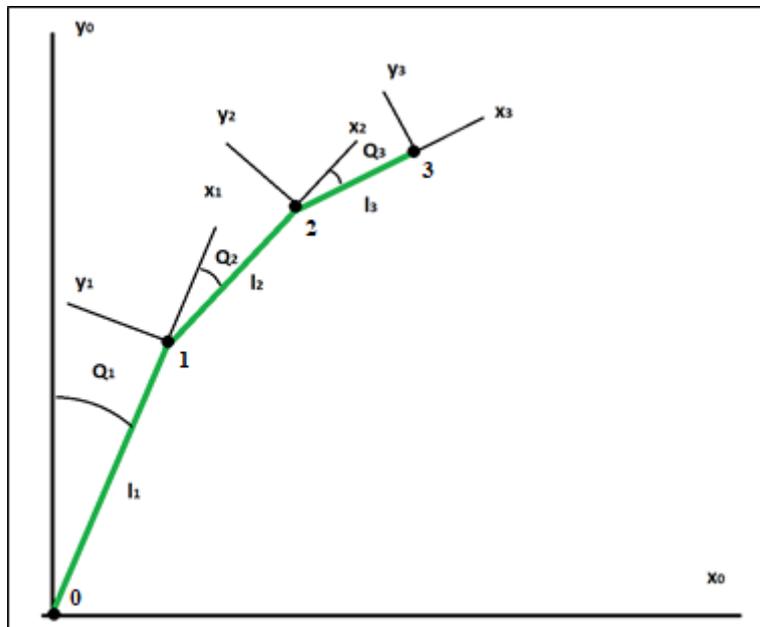


Fig 7 The link structure of the 3-pieced prosthetic finger

Denavit-Hartenberg parameters is a naming technique for expressing the position and orientation of each part of a multi-part robot compared to the previous link. While normally 6 parameters are needed to express the position and orientation of an object in space, the transfer matrices can be easily calculated using 4 parameters. These four parameters are part length (ai), part twist (ai), joint offset (di) and joint angle (θi) [8-10]. Denavit-Hartenberg parameters are shown in Table 1 for each moving part of the prosthetic finger. Links were assumed rigid hence the link part twist was ignored.

Table 1 Hartenberg parameters

connection	ai	di	θi
1	l_1	0	θ_1
2	l_2	0	θ_2
3	l_3	0	θ_3

By determining the parameters, transfer matrices can be obtained. Transfer matrices enable each part of the prosthetic finger to be expressed relative to the centre of the previous coordinate system. The transfer matrices (A_i^{i-1}) used to associate the coordinate system (ith) with the preceding coordinate system. Each of the transfer matrices determined as $i-1$ at equations. Transfer matrices for coordinate systems shown in equations 1,2 and 3.

$$A_1^0 = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & l_1 \cos \theta_1 \\ \sin \theta_1 & \cos \theta_1 & 0 & l_1 \sin \theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$A_2^1 = \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & l_2 \cos \theta_2 \\ \sin \theta_2 & \cos \theta_2 & 0 & l_2 \sin \theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$A_3^2 = \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & l_2 \cos \theta_3 \\ \sin \theta_3 & \cos \theta_3 & 0 & l_2 \sin \theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

By expressing the position and orientation of each part relative to the previous part, the transfer matrices are multiplied with each other and the end point of the prosthetic finger can be expressed relative to the centre of the system's coordinates. The transfer matrices expressed in equation 4 with the name T_i^0 are used to convert the coordinates defined in the ith coordinates into the coordinates defined in the system's root coordinates [12]. Equation 5 and 6 show to obtaining transfer matrix for root coordinates.

$$T_3^0 = A_1^0 A_2^1 A_3^2 \quad (4)$$

$$T_2^0 = A_1^0 A_2^1 = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) & 0 & l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) & 0 & l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$T_3^0 = \begin{bmatrix} \cos(\theta_1 + \theta_2 + \theta_3) & -\sin(\theta_1 + \theta_2 + \theta_3) & 0 & l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \\ \sin(\theta_1 + \theta_2 + \theta_3) & \cos(\theta_1 + \theta_2 + \theta_3) & 0 & l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(6)

In order to the designed prosthesis to replace the fingers and give a realistic sense of use, it must also follow the path followed by human fingers during grip. With dynamic analysis joint rotation rates must be determined. In this section, grip capabilities of the human hand and designed finger prosthesis were compared. Figure 8 shows the path of the human finger follow while gripping a ball.

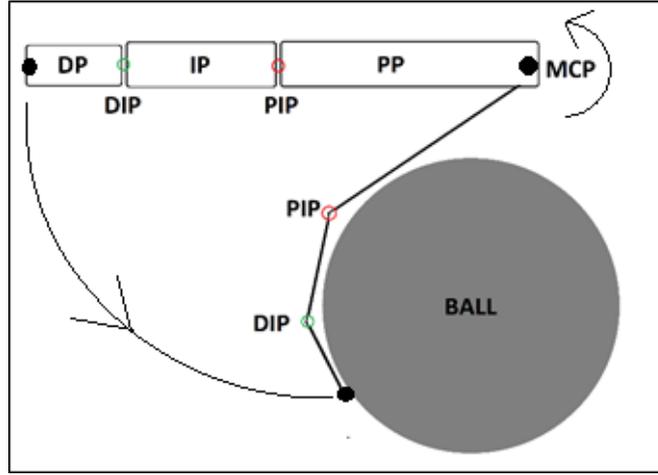


Fig 8 Human finger gripping path

When the grip movement is examined, using the kinematic analysis results the displacement of the fingertip in the x and y coordinates can be expressed with the equation 7 and 8.

$$x = l_{PP} \cos \theta_{MCP} + l_{IP} \cos(\theta_{MCP} + \theta_{PIP}) + l_{DP} \cos(\theta_{MCP} + \theta_{PIP} + \theta_{DIP}) \quad (7)$$

$$y = l_{PP} \sin \theta_{MCP} + l_{IP} \sin(\theta_{MCP} + \theta_{PIP}) + l_{DP} \sin(\theta_{MCP} + \theta_{PIP} + \theta_{DIP}) \quad (8)$$

Parameters l_{PP} , l_{IP} ve l_{DP} are phalanx lengths, θ_{MCP} , θ_{PIP} ve θ_{DIP} are joint angles. Phalanx lengths determine from bone models (from ring finger), joint angles will be determine at this stage. The route of the joint follows depends on gripping object diameter. At this point, object diameter also must be certain. Before the final decision of the joint rotation rate, for different gripping object diameters joint rotations must be analysed.

4. Result

Joint rotation is change according to gripping object size. Figure 9 shows different rotation angles for different gripping object diameter.

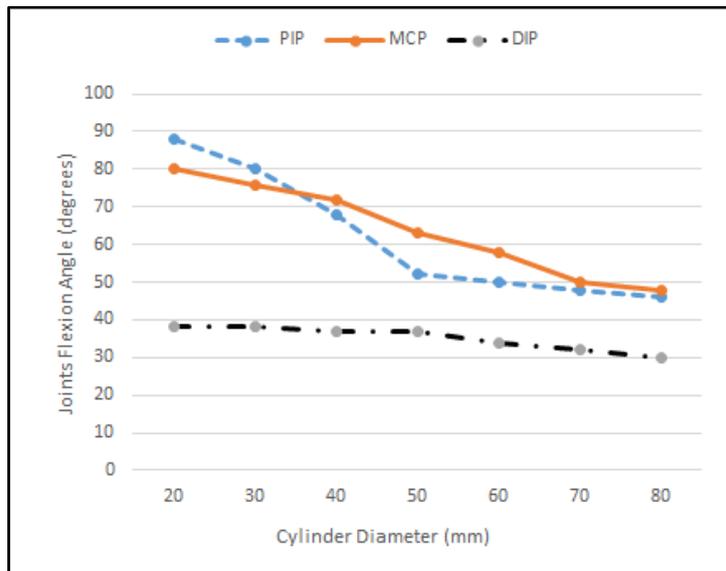


Fig 9 Different rotation angles for different gripping object

After kinematic and dynamic analyses were made, finger prosthesis design was optimized. Parts of the designed finger prosthesis were manufactured by using 3D printer as shown in Figure 10



Fig 10 Designed finger prosthesis parts.

1% tolerance used in dimension of the connections. Poly lactic acid (PLA) material was used for manufacture. Joint rotation rates were set to grip 40 mm diameter cylinder. The ratio between MIP to PIP and DIP joints are determined 0,94 - 0,51 respectively for one unit of MIP rotation. Manufactured finger prosthesis were given in Figure 11

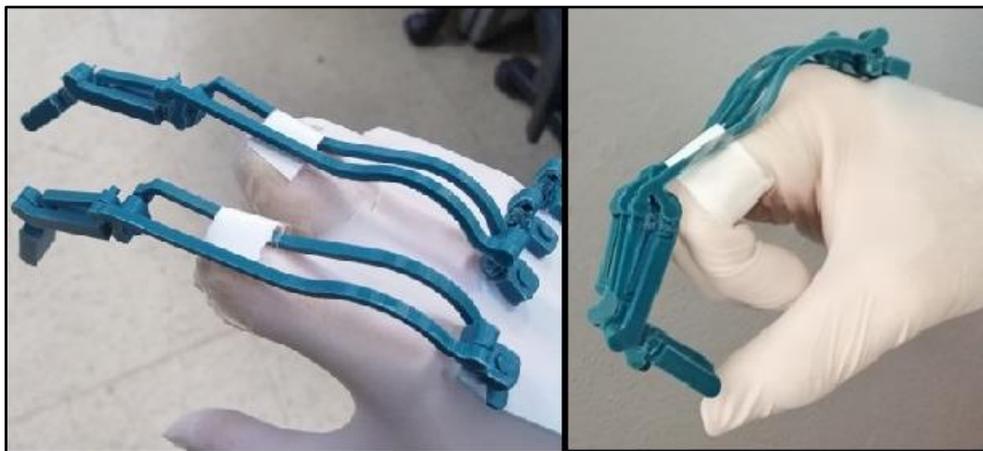


Fig 11 Manufactured finger prosthesis.

5. Discussion

In this study, a prosthetic model, which is mechanically operated (controlled by muscles), has been developed to minimize disadvantages of the limb loss (finger loss). By using a 3D printer and making a personal design from participant's anthropometric measurements; economic, easy to manufacture, and sustainable prosthesis can be produced. Another positive feature of this design, this prosthesis is not required surgical operation

The analyses in this study were carried out to fully grasp cylindrical objects with a minimum diameter of 20mm, it was assumed that smaller diameter objects could be grasped with fingertips. The prosthesis was designed to allow easy assembly and replacement of the fingers. It is possible to change prosthesis fingers parts and joint ratios

thus finger parts can be designed and manufactured for gripping different sized objects. This adaptable design increase the life quality of the patient.

Many studies have been done on hand prosthesis design. In these studies, general hand measurements were used, personalized design methods were ignored. This may cause these studies to be inaccurate. Compatibility of the prosthetic and hand is very important both in scientific studies and in daily use. In this study, the factors that cause inaccurate results have been eliminated by making a personal design. As a result of the analysis and the formulas produced, the production of perfectly compatible prostheses has been easy and accessible [11-18].

In future studies, prosthesis models that include all fingers can be designed. The Disadvantage of this study, the proximal phalanx is needed for the movement of the prosthesis. It is not suitable for those who suffer from complete finger loss. To eliminate this disadvantage different prosthesis designs can be made.

The design is envisaged to be used on human subjects with limb loss, but difficulties have been encountered in finding the participants. For the development of the model, the sense of touch can also be taken as feedback with the pressure sensors placed on the fingertips.

6. Conclusion

In this study, personalized, easy to manufactured, economic and accessible finger prosthesis was carried out. In this context finger prosthesis modelled from CT images and model manufactured from 3D printer. Kinematic and dynamic analysis have done to provide design perfect fit to hand and different sized object increased grasp capability.

Declarations

Author contributions All the authors have equally contributed.

Funding None.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Research involving human and/or animals rights Hand photos and CT images are belong to corresponding author (Cagatay TASDEMIRCI), has consent.

Informed consent Not applicable

7. Referances

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Figures

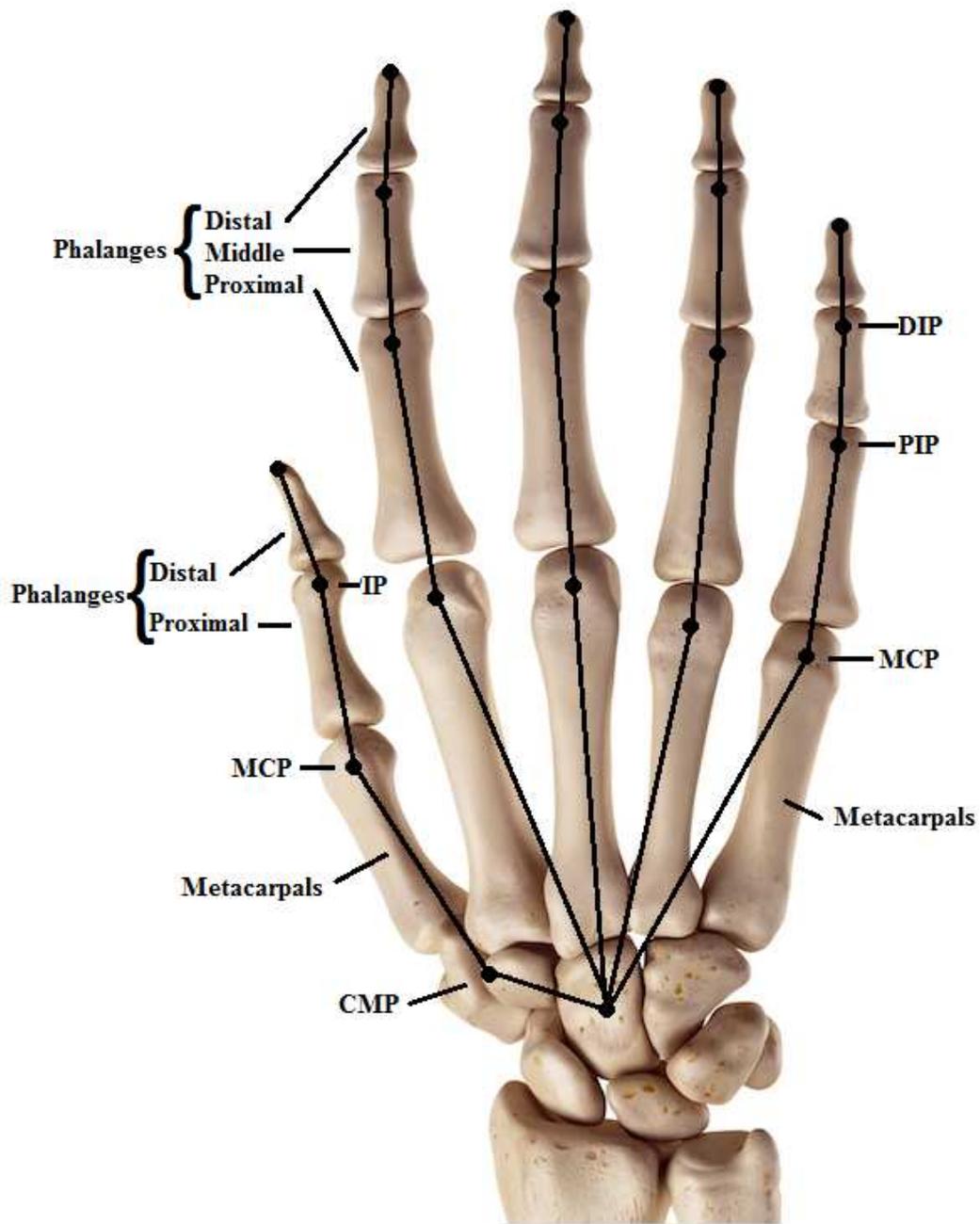


Figure 1

Human hand anatomy

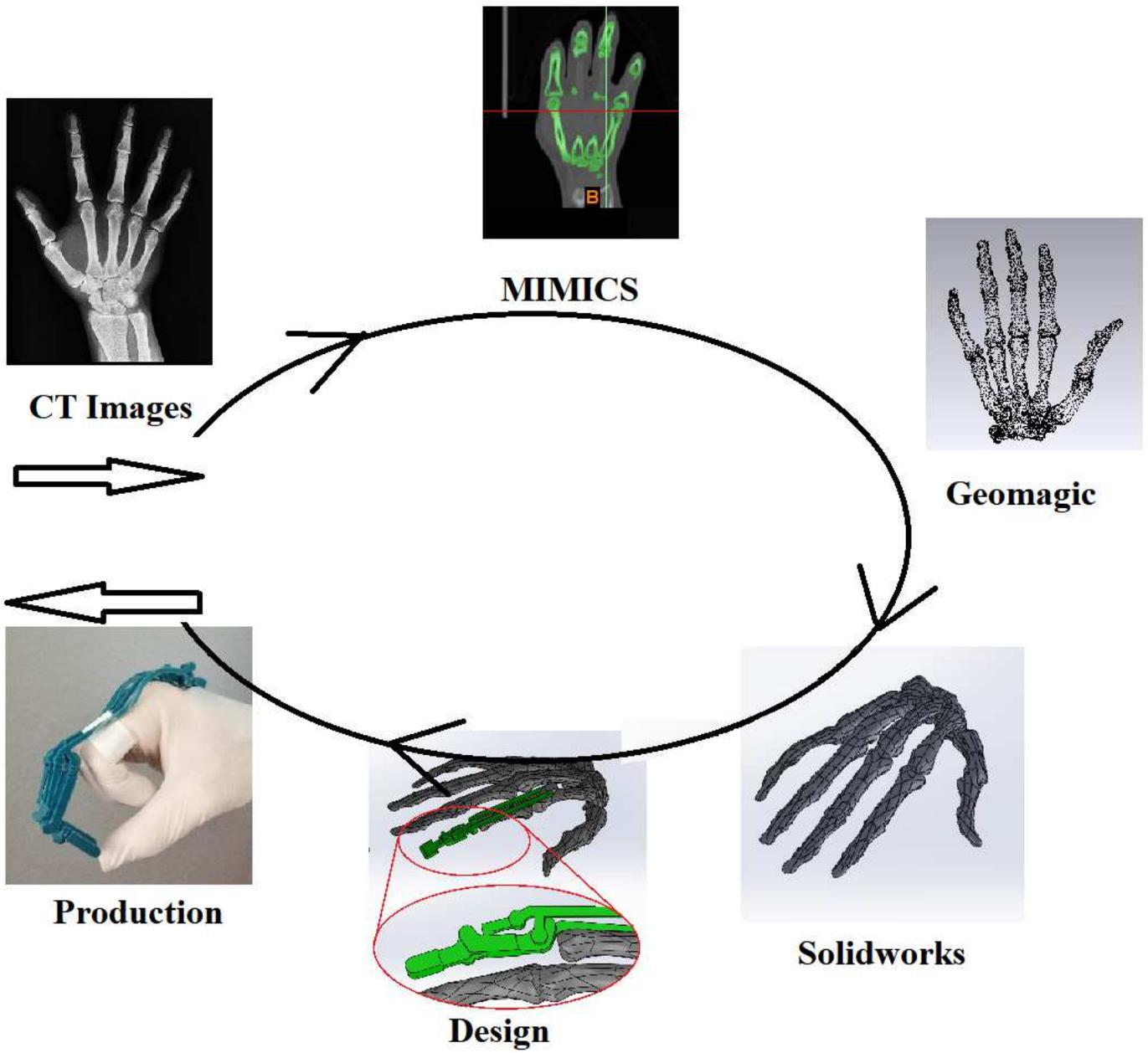


Figure 2

Design stages of the finger prosthesis

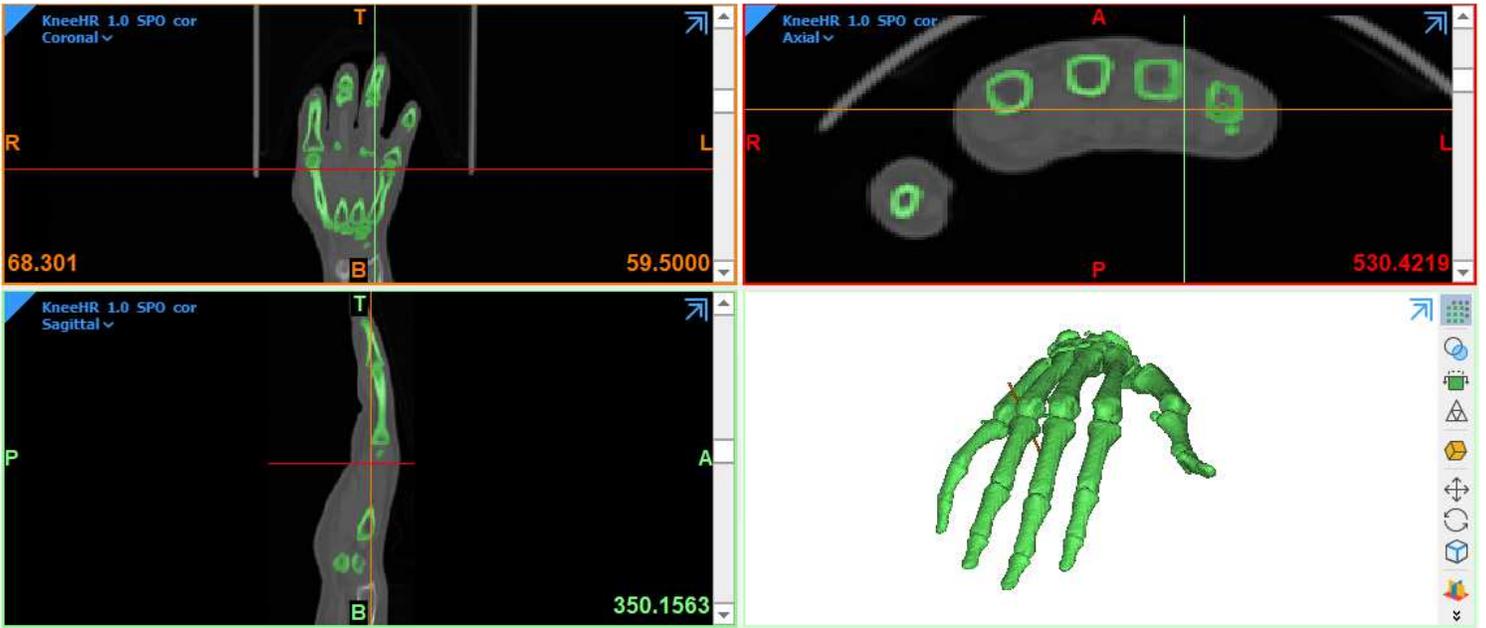


Figure 3

Created hand model at MIMICS

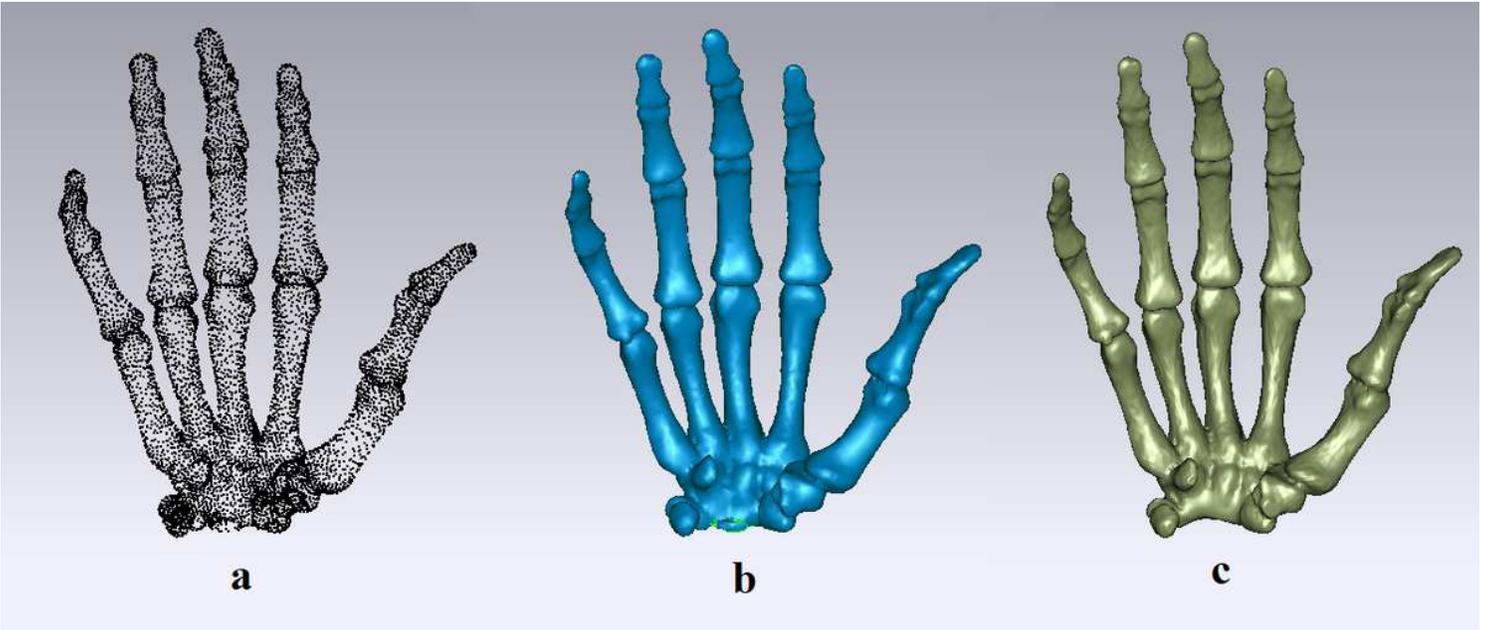


Figure 4

Creating surface model at Geomagic (a. Point cloud, b. surface model, c. 3D solid model).

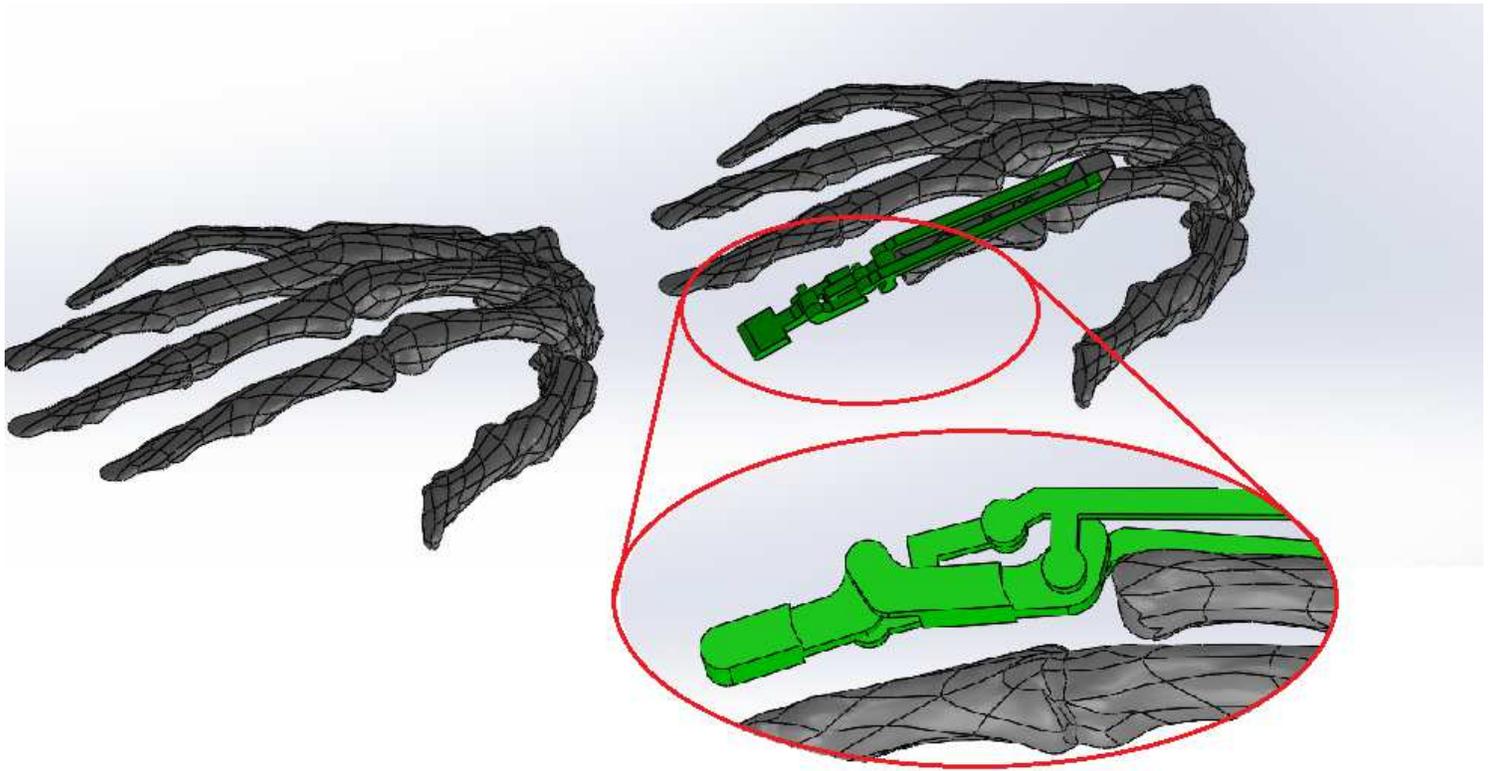


Figure 5

hand model and assembled finger prosthesis design

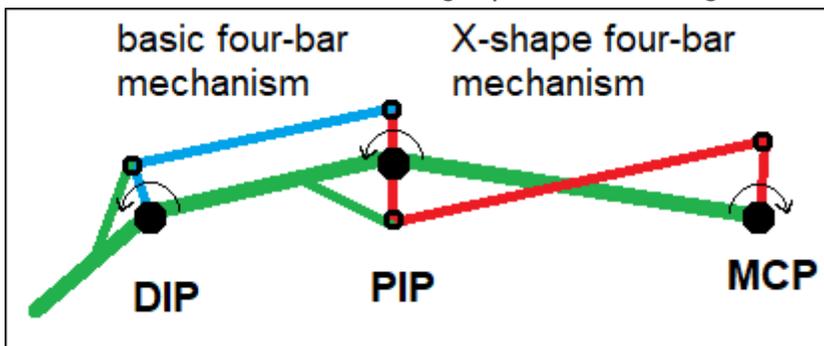


Figure 6

Cross (x) and basic bar mechanism

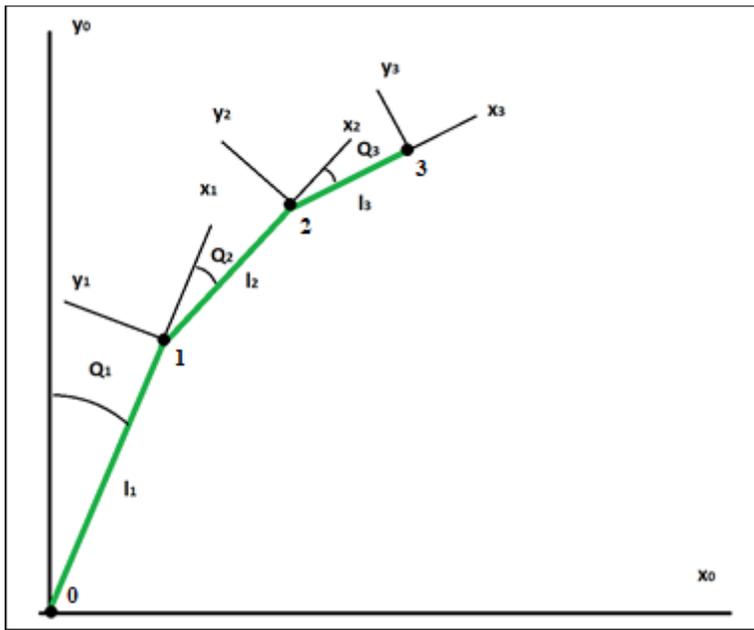


Figure 7

The link structure of the 3-pieced prosthetic finger

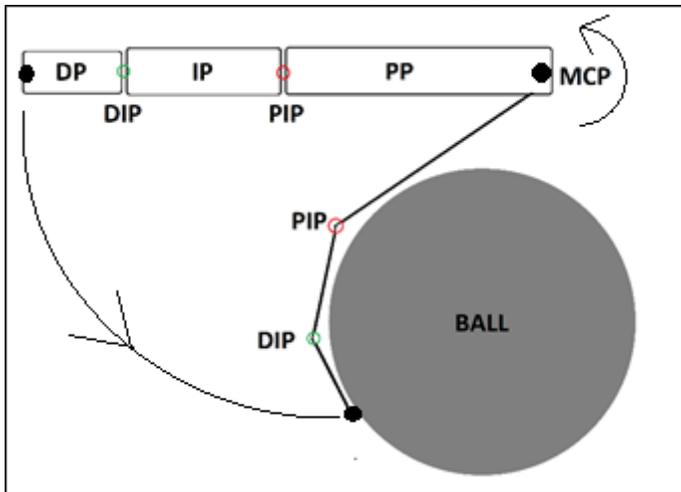


Figure 8

Human finger gripping path

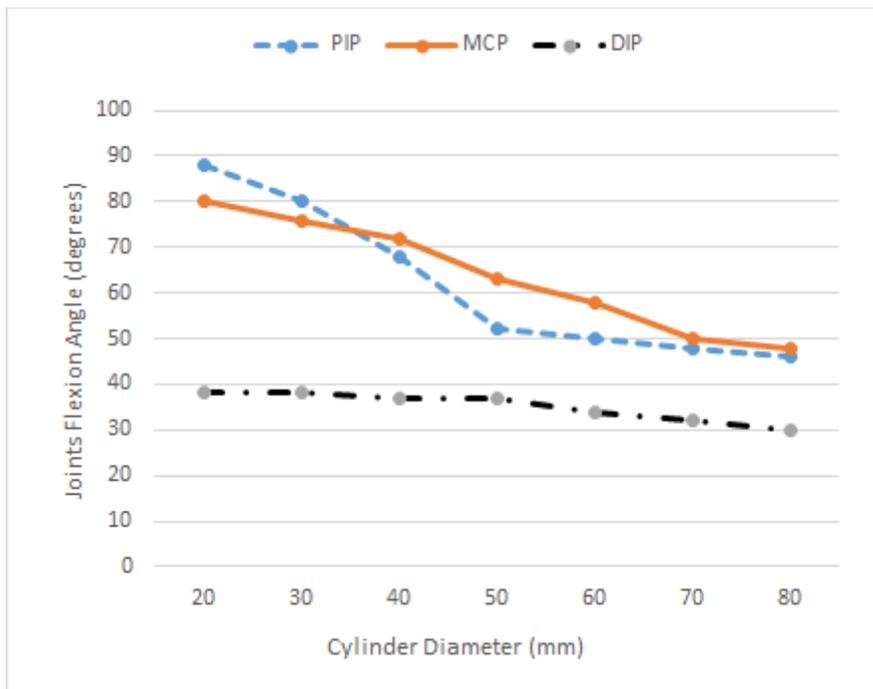


Figure 9

Different rotation angles for different gripping object

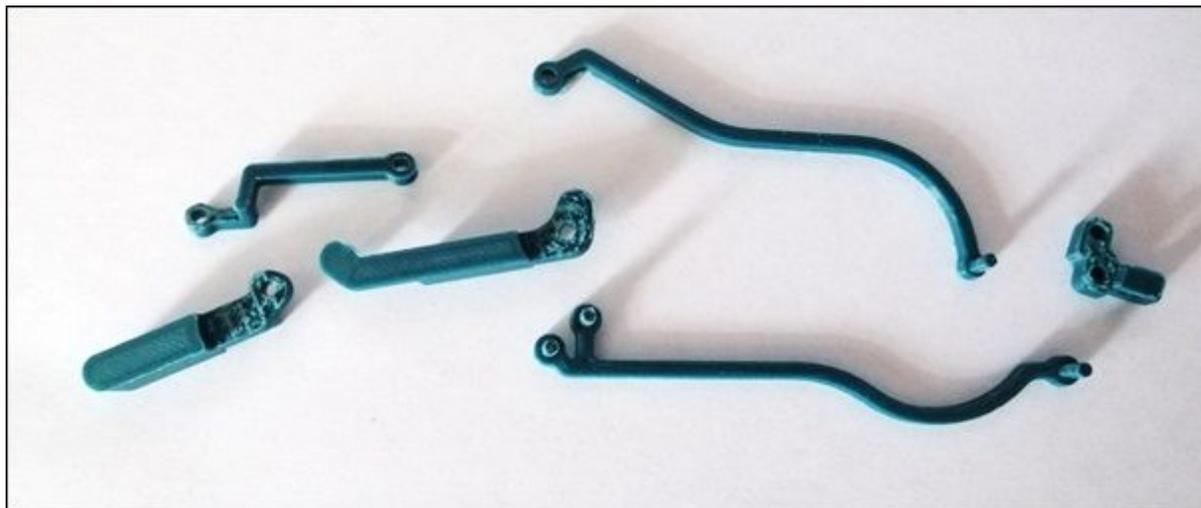


Figure 10

Designed finger prosthesis parts.

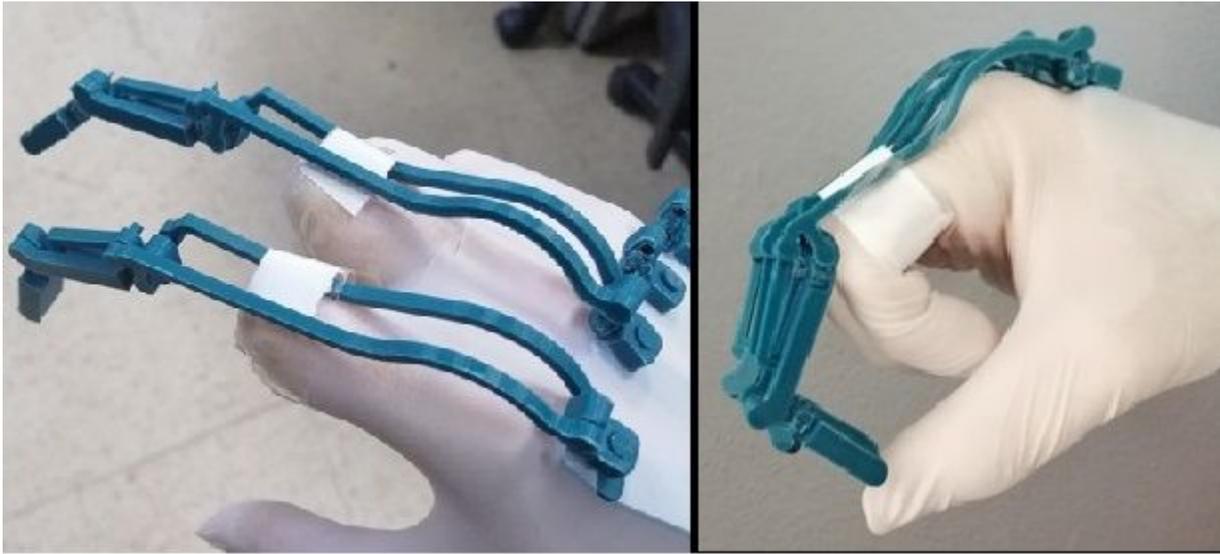


Figure 11

Manufactured finger prosthesis.