POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Mechanical design and kinematic analysis of a hand prosthesis from computerized tomography images

Tomografi görüntülerinden mekanik el protezi tasarımı ve kinematik analizi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Tasdemirci C. ve Ozkan A., "Mechanical design and kinematic analysis of a hand prosthesis from computerized tomography ımages", ***Politeknik Dergisi***, 25(3): 1091-1097, (2022).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.885995

Mechanical Design and Kinematic Analysis of a Hand Prosthesis from Computerized Tomography Images

Highlights

- *Mechanical prosthesis was design from Medical Images*
- *Kinematic and Movement analyses was done to optimize newly design*
- *The gripping ability of the newly designed finger prosthesis was analysed. Mechanical structure and movement abilities of the prosthesis were confirmed by experiments and measurements*

Graphical Abstract

In this study, finger prosthesis was designed from medical images and modelled based on hand skeleton structure.

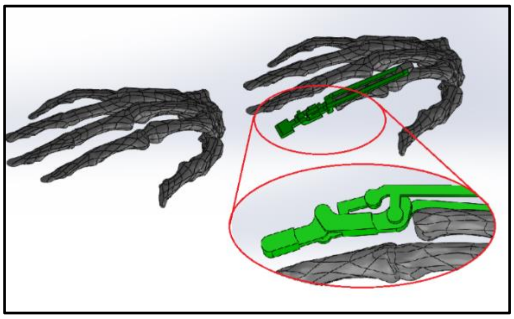

Figure. Hand model and assembled finger prosthesis design

Aim

The aim of this study was to design finger prosthesis which is perfect fit to user (personalised), easy to apply (does not required surgical operation), accessible (easy to manufacture) and sustainable.

Design & Methodology

At the beginning human hand was modelled from Computerized Tomography Images. Prosthesis was designed on the modelled hand structure and assembled by using CAD software. Movement of the designed prosthesis was analysed and the model was optimised according to movement capabilities of the prosthesis. By the kinematic analysis, movement of the designed prosthesis were determined and a new mathematic model was developed.

Originality

Finger prostheses are imitating functionality of the human fingers. However most of the finger prosthesis are only cosmetic and non-functional. On the other hand, most of the functional prostheses are not perfectly fit to user and are not designed personalised. Another big problem is, some prostheses need surgical operation to apply

Findings

Personalized, easy to manufactured, economic and accessible finger prosthesis was designed and manufactured.

Conclusion

Kinematic and dynamic analysis have done to provide design perfect fit to hand and different sized object increased grasp capability. By using obtained formulas, designing personalized prosthesis become easy and fast.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Mechanical Design and Kinematic Analysis of a Hand Prosthesis from Computerized Tomography Images

Araştırma Makalesi / Research Article

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(Geliş/Received : 24.02.2021 ; Kabul/Accepted : 06.04.2021 ; Erken Görünüm/Early View : 26.04.2021)

ABSTRACT

Advancement of technology brought along many prostheses design and developments. The main purpose of prostheses are to improve the life standard of people with limb loss. There are many types of prostheses that were developed in recent years. Prostheses can compensate many limb losses, upper body prostheses can be for not only finger losses but also full arm losses. Finger losses are the most common limb losses. Finger prostheses are imitating the functionality of human fingers. However most of the finger prostheses are only for cosmetic purposes and non-functional. On the other hand, the most of the functional prostheses are not perfectly fit to the users and are not designed personalised. Another big problem, some prostheses need a surgical operation to apply. The main purpose of this study is to design a finger prosthesis that is a perfect fit to user (personalised), easy to apply (does not required surgical operation), accessible (easy to manufacture) and sustainable. In this study, finger prosthesis was modelled based on human hand skeleton structure from computerized tomography (CT) images. Index finger distal and middle phalanges bones were removed from the hand model to simulate finger losses. Finger prosthesis was created on the modelled skeleton structure. Hand skeleton model and newly designed prosthesis were assembled by using CAD software. The designed prosthesis movement capability was examined, parts size and connections were optimised. Gripping ability of the designed prosthesis were analysed by kinematic analyses and a new mathematic model was developed. Created mathematic model can be use at other user's prosthesis, in this way analyses are not required for new designs, user parameters and measurements are enough to future designs manufacturs. Joint rotation rates were set to grip 40 mm diameter cylinder. The gripping ability of the newly designed finger prosthesis was analysed. Mechanical structure and movement abilities of the prosthesis were confirmed by experiments and measurements. Gripping tests are show that, designed and optimised prosthesis capable to grip perfectly 38-42 mm diameter cylinder. Smaller object also can be moved using prosthesis finger tips.

Keywords: Biomechanics, hand prostheses, kinematic analysis, personalized design.

Tomografi Görüntülerinden Mekanik El Protezi Tasarımı ve Kinematik Analizi

ÖZ

Teknolojinin gelişmesi birçok protez tasarımını ve geliştirmesini beraberinde getirdi. Protezlerin temel amacı uzuv kaybı olan bir kişinin yaşam standardını yükseltmektir. Geliştirilmiş birçok protez türü vardır. Protezler birçok uzuv kaybını telafi edebilir, üst vücut protezleri sadece parmak kayıpları değil tam kol kayıpları için de olabilir. Bilindiği gibi parmak kayıpları en sık görülen uzuv kayıplarıdır. Parmak protezlerinin temel amacı insan parmaklarının işlevselliğini taklit etmektir. Ancak parmak protezlerinin çoğu sadece kozmetiktir ve işlevsel değildir. Öte yandan, fonksiyonel protezlerin çoğu kullanıcıya tam olarak uymaz ve kişiye özel tasarlanmamıştır. Bir diğer büyük sorun ise bazı protezlerin uygulanması için cerrahi operasyona ihtiyaç duymasıdır. Bu çalışmanın temel amacı, kullanıcıya mükemmel uyan (kişiselleştirilmiş), uygulaması kolay (cerrahi işlem gerektirmeyen), erişilebilir (üretimi kolay) ve sürdürülebilir parmak protezleri tasarlamaktır. Bu çalışmada bilgisayarlı tomografi görüntülerinden parmak protezi tasarlanmıştır. Protez, insan eli iskelet yapısına göre modellenmiştir. Parmak kayıplarını simüle etmek için distal ve orta falanks kemikleri modelden çıkarıldı. Modellenen iskelet yapısı üzerine parmak protezleri oluşturuldu. El iskelet modeli ve yeni tasarlanan protez, CAD yazılımı kullanılarak monte edildi. Tasarlanan protez hareket analizleri tamamlandı ve model optimize edildi. Kinematik analiz ile tasarlanan protezin hareket kabiliyetleri belirlenmiş ve yeni bir matematiksel model geliştirilmiştir. Oluşturulan matematiksel model diğer kullanıcının protezinde kullanılabilir, bu şekilde kişiselleştirilmiş protez üretimi için yeni tasarım modellemesi gerekmez, kullanıcı parametreleri ve ölçümler gelecekteki modeller için yeterlidir. Yeni tasarlanan parmak protezinin kavrama kabiliyeti incelendi. Protezin mekanik yapısı ve hareket kabiliyetleri deneyler ve ölçümlerle doğrulandı.

Anahtar Kelimeler: Biyomekanik, el protezi, kinematik analiz, kişisel tasarım.

1. INTRODUCTION

According to the Healthcare Cost and Utilization

Project data, finger losses make up 80% of the total upper limb amputation. Finger loses cause many difficulties in business and social life of the human because they do not fully perform their physical activities. 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.

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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. Body powered and external powered prostheses 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 [3]. 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 mechanical drive system is very similar to natural hand movements [4]. 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.

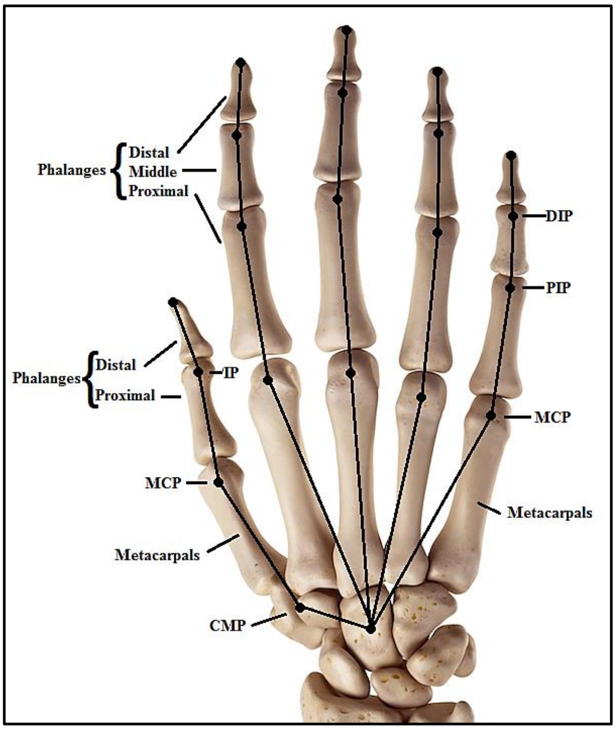

Figure 1. Human hand anatomy

Joint names come from the following bone names. DIP mean "distal interphalangeal joint", those are between the second (intermediate) and third (distal) phalanges. In addition middle phalanges also named intermediate phalanges. MCP shows the metacarpophalangeal joint which is situated between the metacarpal bone and the proximal phalange of the finger.

In this study DP and MP bones are modelled from computerized tomography (CT) images. Finger prosthesis was designed based on the kinematic analysis. Optimised finger prosthesis design was manufactured by using a 3D printer. Gripping capabilities of manufactured finger prosthesis was tested. 40mm diameter cylinder was used for full griping tests and smaller objects were hold with fingertips.

2. MATERIAL and METHOD

This study aim to design personalised, easy to apply finger prosthesis. CT images (taken to the corresponding author) were used in order to make the design personalised. Distal and middle phalanx bones are removed at the solid modelling stage to simulate finger loss. It's not possible to get a solid model directly from medical images. Therefore different image processing programs were used. First of all hand model created from CT images by using MIMICS software and saved as a point cloud. From point cloud, shell model was formed by using Geomagic Software. The design stages of the finger prosthesis were shown in Figure 2.

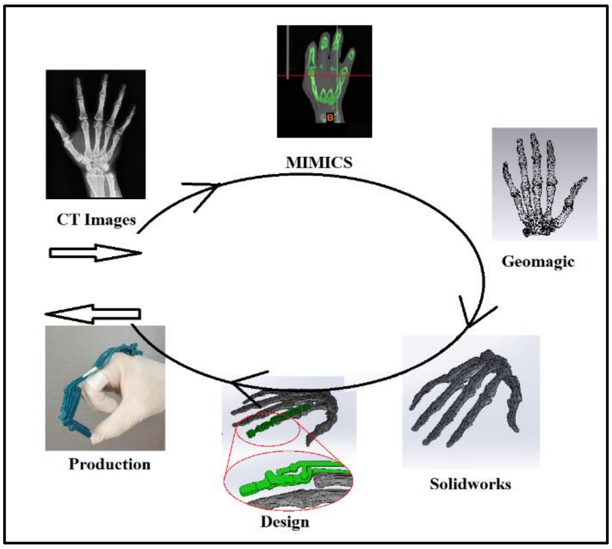

Figure 2. The design stages of the finger prosthesis

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

The image processing stage is required to personalise the prosthesis design. Finger parts of the prosthesis measurements were determined according to bone models. Therefore, bone models must be accurate to successfully measure prosthesis finger parts. Results of the 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 an accurate model is the most important stage of image processing. If there are sharp points, spikes or cracks, getting the 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).

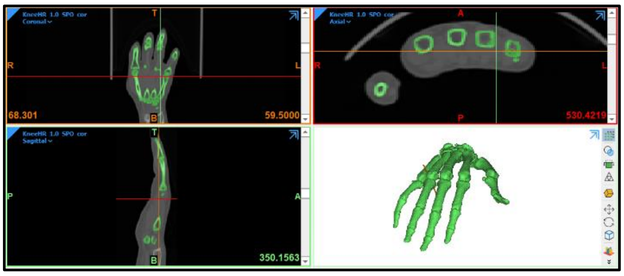

Figure 3. Created hand model at MIMICS

Point cloud data was opened in Geomagic software to create the surface model shown in Figure 4a. After the surface model was created, spikes, holes and cracks in the surface model was fixed carefully prior to creating of 3D surface model that seen in Figure 4b. The 3D solid model was created from the surface model as seen in Figure 4c.

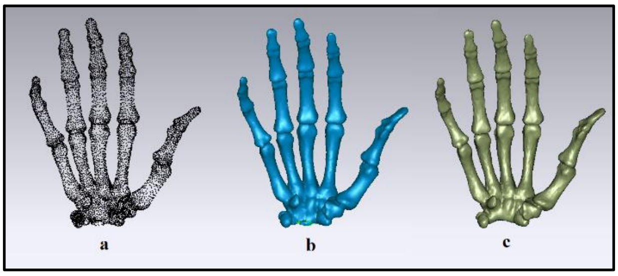

Figure 4. Creating surface model at Geomagic (a. Point cloud, b. surface model, c. 3D solid model).

2.2. Prosthesis Design

3D solid model transferred to SolidWork program for prosthesis design. In order to simulate finger loses, the index finger (distal and middle phalanges bones) was removed from the 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 the target group of this study. The target group of this study has a finger losses and for designed model, it is assumed that the user has index finger loss. For this reason, ring finger measurements (length of the ring finger distal and middle phalanges bones) were used for index finger prosthesis design. In other word index finger prosthesis was modelled based on ring finger size. After the completion of the 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.

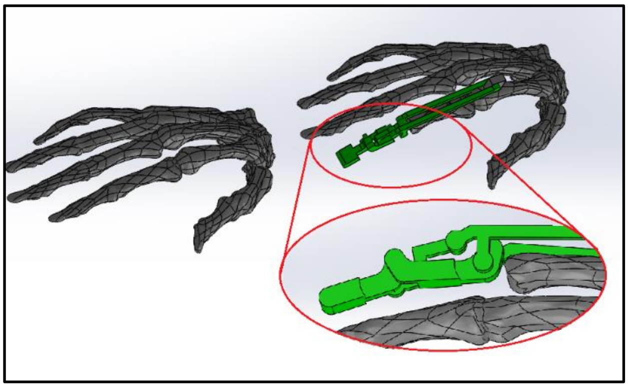

Figure 5. hand model and assembled finger prosthesis design

2.3. 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 a newly designed prosthesis is painless and easy, does not required surgical operation. The designed prosthesis has 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 the 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.

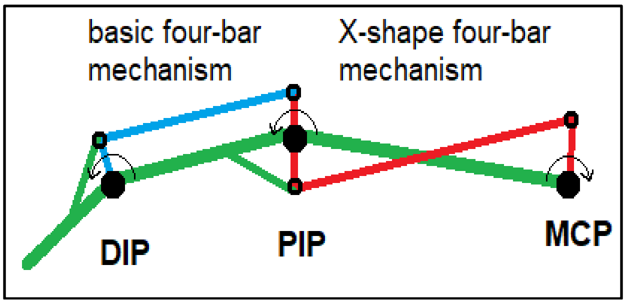

Figure 6. Cross (x) and basic bar mechanism

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.

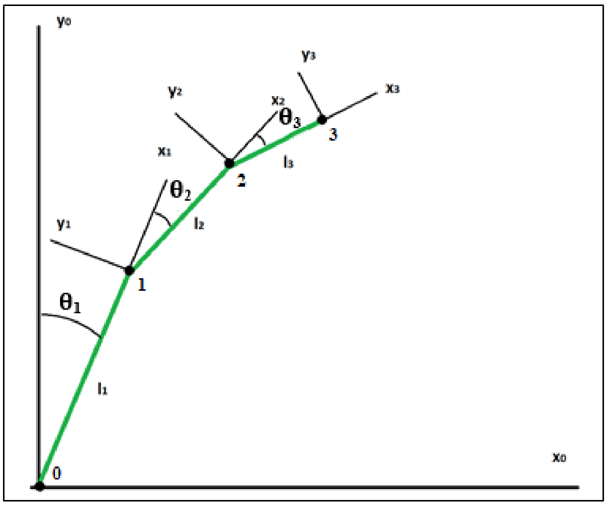

Figure 7. The link structure of the 3-pieced prosthetic finger

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 ($\boldsymbol{ai}$), part twist ($\boldsymbol{\alpha i}$), joint offset ($\boldsymbol{di}$) and joint angle ($\boldsymbol{\theta i}$) [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	$\boldsymbol{ai}$	$\boldsymbol{di}$	$\boldsymbol{\theta i}$
1	l_1	0	$\boldsymbol{\theta_1}$
2	l_2	0	$\boldsymbol{\theta_2}$
3	l_3	0	$\boldsymbol{\theta_3}$

By determining the parameters, transfer matrices can be obtained. Transfer matrices enable each part of the prosthetic finger to be expressed relative to the center of the previous coordinate system. The transfer matrices (A_i^{i-1}) used to associate the coordinate system (i'th) 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. At the equations sine and cosine functions are shortened as "s" and "c".

$$\boldsymbol{A_1^0} = \begin{bmatrix} c\,\theta_1 & -s\,\theta_1 & 0 & l_1\,c\,\theta_1 \\ s\,\theta_1 & c\,\theta_1 & 0 & l_1\,s\,\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$\boldsymbol{A_2^1} = \begin{bmatrix} c\,\theta_2 & -s\,\theta_2 & 0 & l_2\,c\,\theta_2 \\ s\,\theta_2 & c\,\theta_2 & 0 & l_2\,s\,\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$\boldsymbol{A_3^2} = \begin{bmatrix} c\,\theta_3 & -s\,\theta_3 & 0 & l_2\,c\,\theta_3 \\ s\,\theta_3 & c\,\theta_3 & 0 & l_2\,s\,\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

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 center 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 i^{th} coordinates into the coordinates defined in the system's root coordinates [12]. Equation 5 and 6 show to obtaining transfer matrix for root coordinates.

$$T_3^0 = A_1^0 A_2^1 A_3^2 \tag{4}$$

$$T_2^0 = A_1^0 A_2^1 = \begin{bmatrix} c(\theta_1+\theta_2) & -s(\theta_1+\theta_2) & 0 & l_1\,c\,\theta_1 + l_2\,c(\theta_1+\theta_2) \\ s(\theta_1+\theta_2) & c(\theta_1+\theta_2) & 0 & l_1\,s\,\theta_1 + l_2\,s(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$T_3^0 = \begin{bmatrix} c(\theta_1+\theta_2+\theta_3) & -s(\theta_1+\theta_2+\theta_3) & 0 & l_1\,c\,\theta_1 + l_2\,c(\theta_1+\theta_2) + l_3\,c(\theta_1+\theta_2+\theta_3) \\ s(\theta_1+\theta_2+\theta_3) & c(\theta_1+\theta_2+\theta_3) & 0 & l_1\,s\,\theta_1 + l_2\,s(\theta_1+\theta_2) + l_3\,s(\theta_1+\theta_2+\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

In order to replace the fingers and give a realistic sense of use, the designed prosthesis 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.

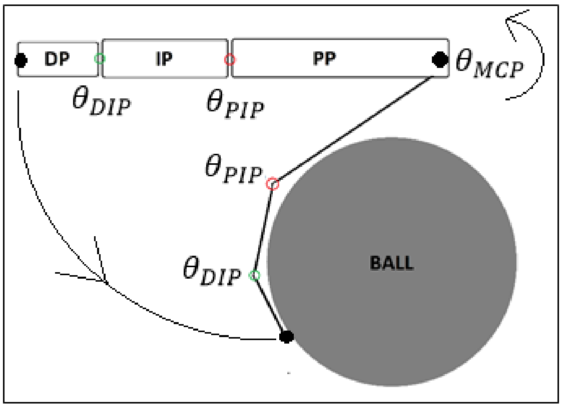

Figure 8. Human finger gripping path

Figure 8 shows the path of the human finger follow while gripping a ball. Variables of the $\theta_1, \theta_2, \theta_3$ at the Equation 6 are MCP, PIP, DIP joints rotation angles, respectively.

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 are measured from the bone models (from ring finger), joint angles will be determine at this stage. The route of the joint follows depends on the gripping object diameter. At this point, the 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.

3. RESULTS

Joint rotation is change according to gripping object size, at this study cylinder objects were used. For 20 to 80 mm cylinder objects, finger joint rotations (degrees) were recorded. Figure 9 shows different joint rotation angles for different gripping object diameters.

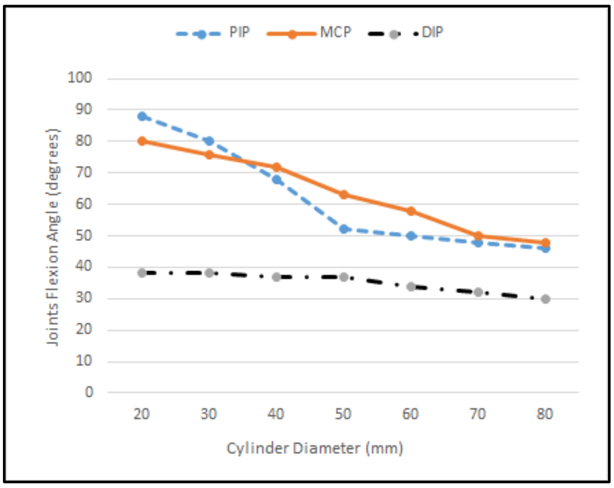

Figure 9. Different rotation angles for different gripping object

Rotation angles of the joints for gripping 40 mm cylinder is used for this study. Reason of this determination is daily life gripping objects such as glasses, remote controllers and mobile phones. Also as it can be seen Figure 9 gripping for bigger objects from 35 mm diameter, MCP joint rotation is getting bigger than PIP angle and this changes the design greatly.

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

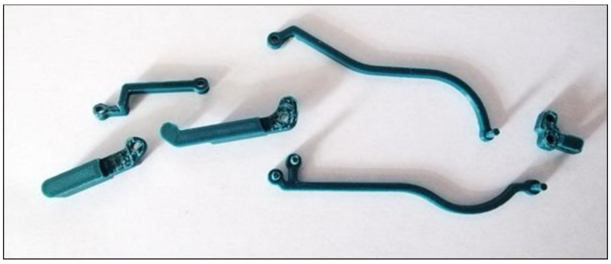

Figure 10. Designed finger prosthesis parts.

1% tolerance used in the 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.

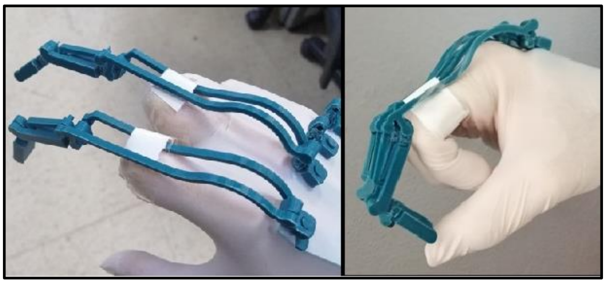

Figure 11. Manufactured finger prosthesis.

4. 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 those 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 personalised design [11-14]. Metal parts were used at the most of the designs [15-18], at this study PLA material used. This material much more cheaper and by the help of 3D technology, it is easy to use for manufacture. As a result of the analysis and the formulas produced, the production of perfectly compatible prostheses has been easy and accessible.

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.

5. CONCLUSION

Personalized, easy to manufactured, economic and accessible finger prosthesis was carried out. In this context finger prosthesis was modelled from CT images and model was manufactured from 3D printer. Kinematic analysis have done to provide design perfect fit to hand and different sized object increased grasp capability. With the help of the created design parameters, personalised prosthesis design was become easy. Determining 2 parameters are sufficient for future designs which are "gripping object diameter" and "finger bones lengths".

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Çağatay TAŞDEMİRCİ: Perofrmed the experiments and analyse the results.,

Arif ÖZKAN: Perofrmed the experiments and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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