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Design and Analysis of Finger Prosthetics Using Finite Element Methods

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ABSTRACT

According to data from the Badan Pusat Statistik (BPS), the number of physically disabled people in Indonesia reached 22.5 million people by 2020. However, only 18% use assistive devices. The role of prosthetics as a replacement for lost body parts is very important for carrying out daily activities. The presence of 3D printing technology in healthcare can be used to print prosthetic materials. However, many functional prosthetic designs are still conventionally fabricated and do not consider prosthetic standards and quality. This research aims to produce a functional prosthetic finger design tested for strength through computational simulation using the finite element method. The tools needed in this study include a ruler for finger measurement and a computer or laptop with Fusion 360 software. The analysis results show that this model can withstand a load of up to 100 N with deformation, stress, and safety factor values of 0.016 mm, 27.605 MPa, and 7.49, respectively. The prosthetic model is considered safe because the stress value is below the yield strength of the material used, which is 30.00 MPa. The safety factor exceeds the minimum safety factor limit of 1.00.

1. INTRODUCTION

Physical disability or quadriplegic is a condition where a person experiences abnormalities in the muscle, bone, and joint system, disrupting mobility coordination and development [1]. According to data from the Badan Pusat Statistik (BPS), the number of physically disabled people in Indonesia continues to increase, reaching 22.5 million by 2020. With only about 18% using assistive devices [2] Prosthetics play a crucial role in replacing lost body organs, essential for daily activities. The availability of prosthetics as walking aids for people with leg disabilities in Indonesia is quite varied, such as wheelchairs, crutches and other support

The role of prosthetics as a tool to replace lost body organs is very important for quadriplegics to carry out daily activities[3]. In Indonesia there is a wide variety of prosthetic available as walking aids for people with foot disabilities, including wheelchairs, cradles, support, and more.[4]. However, for quadriplegics who have only lost part of their fingers due to woek accidents or congenital birth defects, the available option are limited [5]. Finger prosthetics in Indonesia predominantly focus on aesthetic functions or serve as accessories. These prosthetics are typically made from silicon to achieve a realistic appearance [6]. The complex construction required to produce functional finger prosthetics contributes to their high selling price.

The presence of 3D printing as a rapid prototyping technology provides many benefits, particulary in the health sector [7] [8]. 3D printing technology can be used to print prosthetic materials [9]. However, many previous functional prosthetic designs were still fabricated conventionally and did not meet the necessary the standards and quality, making them uncomfortable during direct testing. Testing prosthetics after molding without considering the strength aspects can be time-consuming and expensive

[10]. As a result,the prosthetics tend to be more expensive due to the additional material costs. One way to overcome this is by testing prosthetic prototypes through computational simulation before fabrication [11]

One computational testing method that can be employed to assess prosthetic strength is the finite element method (FEM). FEM is a computational simulation method to analyze and evaluates structures and components for their ability to withstand specific capacities [12]. This method is widely utilizied in engineering to numerically analyze design [13] The values analyzed include deformation values, maximum stress, and strain. This analysis aims to determine components and structures that can safely withstand the specified load strength [14]

The aim of this research is to produce a functional finger prosthetic design whose strength has been tested through computational simulations using the finite element method. This approach aims to minimize prosthetic production costs, making the resulting prosthetics more affordable.

2. METHOD

The research begins with a literature study to gather references from previous or similar studies. Then the next stage involves anthropometric measurements. The tools needed for this research include a ruler for measurements and a computer or laptop with Fusion 360 software. The research was conducted at the Physics and Instrumentation Lab at PGRI University, Yogyakarta.

2.1 Study of Literature

Literature studies are conducted by collecting information from various sources such as journals, articles, and YouTube. From the data search, several references were obtained, one of which is Keaton's prosthetic, as shown in Figure 1. This prosthetic uses a cross-cable mechanism as the propulsion system. The cross-cable mechanism is a propulsion system for prosthetic fingers that relies on ropes to actuate the prosthetic [15].

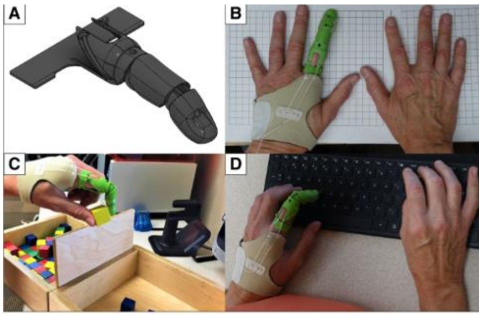
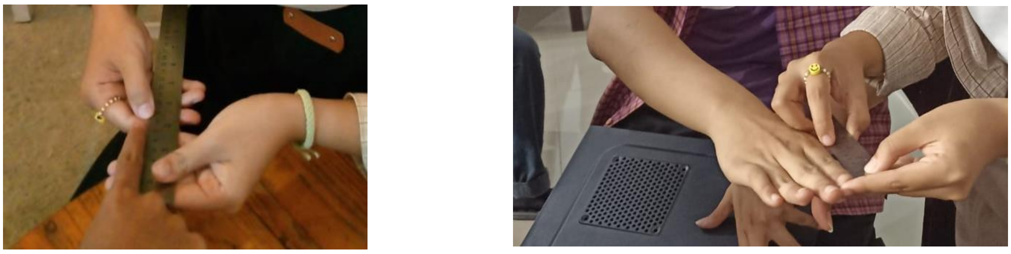


Figure 1. Keaton's Reference Design
Source: Assessment of body-powered 3D printed partial finger prostheses: a case study

The disadvantage of this prosthetic is its complex design, lacking prior computational simulations have not been carried out. There for, initial testing requires printing, which can be time-consuming and costly. Keaton's prosthetics are crafted from Polyclatic Acid (PLA) material. This design inspired the movement mechanism of the prosthetic finger, which underwenr subsequent strength testing using the finite element method.

2.2 Antrophometric Measurement

The dimensions chosen for this prosthetic design correspond to the length of an adult's index finger, specifically 7 cm. This measurement was determined based on anthropometric studies of finger conducted at at Universitas PGRI Yogyakarta, as depicted in Figure 2.



(a) (b)

Figure 2. Anthropometry measurements

The data involved collecting 40 finger samples, comprising 20 male and 20 female finger samples, from individual age between 17 to 30 years. This age range was selected because physical growth and proportions tend to stabilize during this period [16]. Measurements were taken using a ruler. The anthropometric data obtained from the samples can be found in Table 1 below:

Table1 Anthropometric Data of Finger Measurements

No	Male	Female	No	Male	Female
1.	8.5cm	7.5cm	11.	7.5cm	6.5cm
2.	8 cm	6.5cm	12.	8.4cm	8 cm
3.	8.2cm	7.5cm	13.	7.3cm	7.3cm
4.	8.4cm	7 cm	14.	7.5cm	8.2cm
5.	7 cm	7 cm	15.	7 cm	6.7cm
6.	7.4cm	7 cm	16.	7.5cm	7.8cm
7.	7.5cm	7.9cm	17.	8 cm	7.4cm
8.	7.9cm	8 cm	18.	8 cm	7 cm
9.	7.7cm	7.1cm	19.	8 cm	7 cm
10.	7 cm	7.7cm	20.	8.5cm	7.5cm

Based on the results of the data collection is the average length of female's fingers is 7.3 cm, with quartile 1 (Q1) at 7 cm and quartile 3 (Q3) at 7.6 cm. The average length of male's fingers is 7.8 cm, with quartile 1 (Q1) at 7.4 cm and quartile 3 (Q3) at 8.1 cm. Due to the spesific focus of this research on designing finger prosthetics for adult women, a standardized length of 7 cm was chosen. This decision is based on aligning with the average finger length observed among women in the collected data.

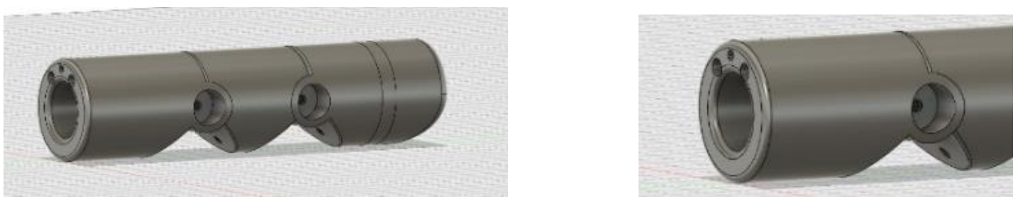
2.3 Model Design and Analysis

Prosthetics are designed to replicate the shape and function of missing body parts, particularly the anatomy of the human hand and fingers is depicted in Figure 3. Each human finger comprises three joints, which guide the design into three main components that mirror the human finger's structure. The proximal phalanges is the segment of the finger closest to the body, the medial phalanges is the middle segment of the finger, and the distal phalanges is the tip of the finger, which includes the nail. This version is more concise and clearly outlines the components of the finger prosthetic.

Figure 3. Human Finger Anatomy
(Source: Teton Hand Surgery)

In this research, finger prosthetics were designed and analyzed using Fusion 360 software. The simulation capabilities of the software are useful for evaluating the validity of a design [17]. Which can save time and reduce costs before creating a physical prototype [18]. The procedure for analyzing the stress values in this prosthetic is divided into several stages:

First, create a design featuring a cross cable mechanism. This type of prosthetic uses an elastic rope as the drive system, which is attached to the distal phalanges component. Each component has small holes at the top and bottom. Serving as passage for the connecting straps and prosthetic actuation. The total length of the design is 7 cm based on existing antrophometric data. The autocontact method used is contact detection with a tolerance of 0,1 mm. The autocontact method used is contact detection with a tolerance of 0,1 mm. All contacts are bonded with symmetric penetration type. The prosthetic design utilizes basic features in Fsuion 360 including sketch, sweep, fillet and extrude. For detailed prosthetic design drawings, see Figure 4.



(a) (b)

Figure 4. (a) Hole Design for Rope (b) Design Details

The design is divided into three components. Each prosthetic component will be connected using a small iron rod with a diameter of 1.5 mm. Therefore, a hole is made adjacent to each prosthetic component to accommodate the connecting rod as shown in Figure 5.

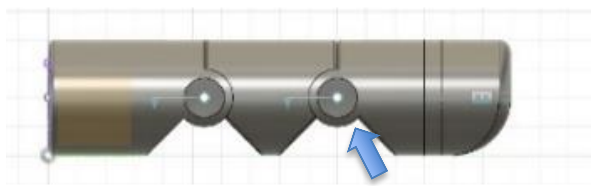


Figure 5. Connecting Hole Design

The attached elastic rope will be connected to a bracelet worn on the wrist. The prosthetic's movement is powered by the user's body. When the wrist is moved up or down, the connecting strap on the bracelet moves the end of the strap attached to the distal phalanges, allowing the prosthetic finger to perform opening and closing movements.

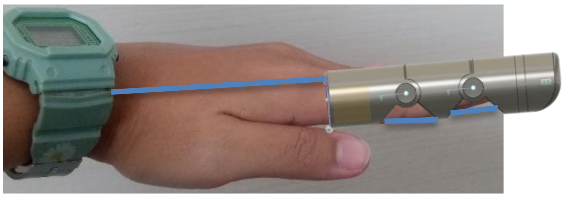


Figure 6. Construction and Use of Prosthetics for Human Fingers

Second,determine the type of material used. The chosen material is PLA (Polyclatid Acid) plastic filament, which has a yield strength of up to 30.00 MPa. The material characteristics are detailed in Table 2 below:

Table 2. PLA Material Characteristics (Source: Autodesk.com)

Density	1.290E-06 kg/mm^3
Young's Modulus	709.00 MPa
Poisson's Ratio	0.40
Yield Strength	30.00 MPa
Ultimate Tensile Strength	40.00 MPa
Thermal Conductivity	2,500E-04 W/ (mm C)
Thermal Expansion Coefficient	4.190E-05/C
Specific Heat	1750.00 J / (kg C)

Third, determine the load applied. The maximum load for this research is 10 kg. This load is converted to Newton by multiplying it by the gravitational acceleration (9.81 m/s2) to become 98.1 N, which is rounded to 100 N. .According to Helen, for daily activities such as writing, holding a bag and holding a bottle, the load received tends to be smaller than the maximum grip strength, which is 5-10 kg, In contrast, lighter activities such as holding a pen only require a load of around 1-2 kg [19]. The load is placed on the underside of the distal phalanx, as indicated by the arrow in Figure 6. This area is crucial for grip strength, making it essential to analyze its structural integrity [20]

Figure 7. Load placement

Then, perform the meshing process. The meshing process is carried out to minimize errors during the simulation [21]. As shown in Figure 6, the plane of the component is divided into small elements. These elements will serve as parameters during the surface is analysis. This step is crucial to ensure the accuracy and reliability of the simulation results [22]

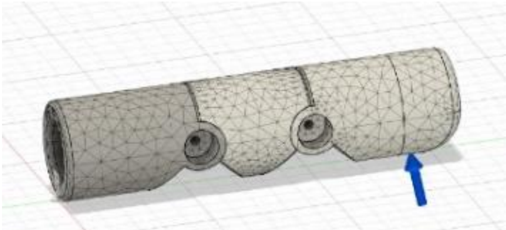


Figure 8. Meshing Process

The results of the meshing process can be seen in the Table 3:

Table 3. The Meshing Result

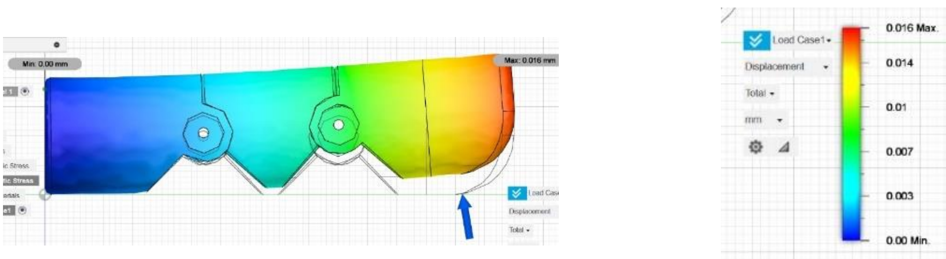
Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Fifth, the design is analyzed by running a simulation program using Fusion 360 software. This simulation will produce values for von mises stress, deformation (displacement) and safety factors.

3. RESULTS AND DISCUSSION

3.1 Deformation

Deformation parameters are used to determine changes in model shape that occur when a load is applied. The load that the fingers can accept for gripping can vary depending on several factors such as individual strength, duration of grip and type of activity. By referring to this research, a load of 100 N or 10 kg is used. Deformation can be an important indicator to determine whether the material used is strong enough to withstand the desired load [23]. The results of material deformation (displacement) with load variations of 100 N can be seen in Figure 7. The maximum deformation value for a finger prosthetic with a length of 7 cm is 0.016 mm.



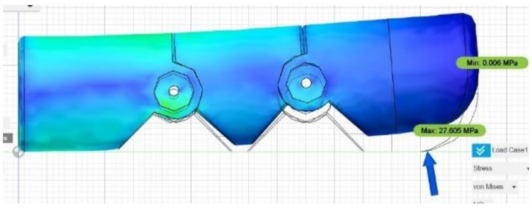
(a) (b)

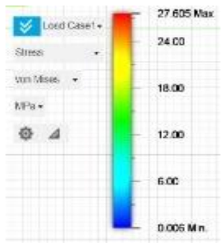
Figure 9. (a) (b) Deformation Analysis Results

The largest deformation occurs at the upper right part (component tip) which is colored red. In practice, the tip of the component moves more, resulting in the greatest deformation [24]. Based on the above analysis, it can be concluded that the design has significant variation in deformation values, and the part with maximum deformation needs special attention to ensure the structural integrity of the entire component.

3.2 Stress

Stress analysis aims to determine the maximum stress that occurs in finger prosthetics when subjected to load and moment. This value is a determining factor whether the material design is safe or will fail. The analysis results show that the maximum stress value is 27,605 MPa with a minimum stress of 0.006 MPa.





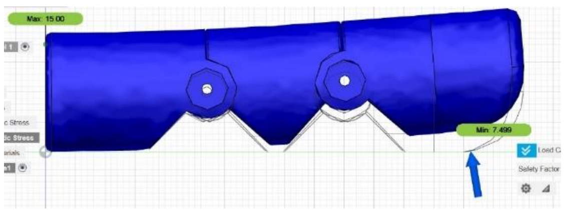
(a) (b)

Figure 10. (a) (b) Stress Analysis Results

Based on the color parameters, the design shows safe stress analysis values as they are below the maximum value of 27.605 MPa. Most components show relatively low stress values with blue color parameters. The area around the hole shows slightly higher stress values but they are not critical. This part is marked with green.

3.3 Safety Factor

The safety factor is commonly used metric in evaluating the safety of an element [25]. A safety factor value is considered safe if it is above 1 [26]. The safety factor helps prevent failure and determines the suitability of the prosthetic for production [27].



(a) (b)

Figure 11. (a) (b) Results of Safety Factor Analysis

Each component shows a blue color, indicating that every area has a high safety factor value. A high safety factor value indicates that the component has a low likelihood of failure. In this design, the minimum safety factor value produced is 7.49, or 8 when rounded. This value is considered very safe because it is greater than 1.

4. CONCLUSION

The finger prosthetic model is designed and analyzed before fabrication to determine its strength and feasibility. Based on the analysis results, the model can withstand loads of up to 100 N with deformation, stress and safety factor values of 0.016 mm, 27,605 MPa and 7.49 respectively.

This prosthetic model can be considered safe because the resulting stress value is below the yield strength of the material used, wich is 30.00 MPa. Additionally, the resulting safety factor value has exceeds the minimum safety factor limit of 1.00. Therefore, it can be concluded that this finger prosthetic design is advantageous in being easy to use, safe and flexible. The design has been analyzed using the finite element method, wich can save costs in prosthetics manufacturing by allowing testing before the fabrication process.

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