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Analysis of Ankle-Foot Design for Transtibial Prosthesis Components to Increase The Flexibility using the Finite Element Method

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Abstract

The finite element method (FEM) has been identified as a tool that can be used to analyze stress and strain behavior occurring in prosthetic components of the lower extremities. The main objective of this study was to analyze the structure of the alternative ankle foot designed for the transtibial prosthesis component. The ankle-foot is designed and simulated for strength using Solidworks software. There are two alternative designs of the ankle-foot that are designed. Each design is named alternative designs 1 and 2. The material used is AISI 304 with Young's Modulus of 193000 MPa and Poisson's Ratio of 0.29. Based on the design results, the lowest weight is owned by alternative design 1 of 491.69 grams. The simulation was carried out under normal running conditions in the midstance phase. The applied load is 1000N. Three data were obtained from the simulation results in the form of von Mises stress, deformation, and strain energy. Based on the simulation results on alternative ankle foot design 2, the value of von Misses stress is lower. Even so, the two alternative designs that have been designed are still within safe limits because they still meet the predetermined safety factor value.

Keywords : *Ankle Foot; Transtibial Prosthesis; AISI 304; Midstance; FEM*

1. Introduction

Every year, lower extremity amputations occur in the United States with more than 100,000 patients (Leung & Lee, 2012). Then, according to national statistics, 2 million upper and lower limb amputations occur in China (Ismawan et al., 2022). Prosthetic feet are medical devices to relieve the amputated part of the leg due to an accident or disease. The choice of the prosthetic device must be made wisely because it has an important impact on the amputated part (Pasquina et al., 2006). The global market today offers various prosthetic devices with various materials and designs. The prosthetic must be light enough to move more flexibly than the original functions. In addition, the prosthetic must also be stiff enough to support the user's body properly. A material reduction in the prosthetic foot design can reduce the product's weight but will impact the product's structural strength. Several prosthetic foot designs that are widely circulated in the market include energy storing and return (ESAR) devices and Solid Ankle Cushioned Heel (SACH) feet (Turcot et al., 2013). So far, the most considered to be able to cover footwork that almost mimics the original footwork is the ESAR type of ankle-foot prosthesis. The ESAR feet has shown a better clinical effect than SACH when used by transtibial amputees in terms of power absorption in the prosthetic ankle during weight bearing and increasing foot range of motion (RoM) (Hsu et al., 1999; Orthopaedics, Torburn et al., 2017; Underwood, Tokuno, & Eng, 2012).

In terms of the amputee, the behavior of the biomechanical prosthesis is influenced by several factors, including the weight of the prosthesis components (Bateni and Olney, 2004), the dimensions of the prosthesis (Lee & Turner-Smith, 2003; Friberg, 1984), the mechanical properties and alignment of the prosthetic limb (Xiaobing et al., 2005; Fridman, Ona, & Isakov, 2003), and the alignment of the prosthesis (Geil & Lay, 2004; Jia et al., 2005; Kang, Kim, & Roh, 2006; Chow et al., 2006). Gait cycle analysis is widely used for performance evaluation of prosthetic walking (Gard, 2006). Research on prosthetic behavior is very important in designing prosthetics and prosthetic balance. Most of the studies reported are related to the contact interface between the amputated residual limb and the prosthetic

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socket (Kang, Kim & Roh., 2006), assessment of gait kinematics (Bateni and Olney, 2004), and plantar foot pressure.

Along with the development of computational techniques, numerical methods are increasingly being used to obtain detailed and complex information about prosthesis behavior, such as the interactions between the prosthesis and the amputated part. The most widely used numerical analysis method for analyzing prosthetic legs is finite element analysis (FEA) (Zhang, Mak, & Roberts, 1998). Through this analysis method, it is possible to know the distribution of stresses and strains in the prosthesis components, which are analytically or experimentally tricky. In addition, FEA can also be used to analyze design, material, and alignment effects. Current research has succeeded in presenting a more accurate foot prosthetic model that resembles its original function, non-linear material model, mechanical contact as occurs in prosthetics and amputated surfaces, and interface elements that allow slip contact conditions (Zhang, Lord, Turner-Smith, 1995). Another research showed the influence of inertial loads (Lee et al., 2004) and the pressure applied to the ankle-foot (Jia, Zhang, & Lee, 2004). Although there are many literatures discussing the FE modeling of the socket-amputee interaction, there still needs to be more that discusses the behavior of the ankle-foot component as part of a prosthetic foot.

FE modeling was carried out to analyze the performance of the SACH foot prosthetic (Saunders et al., 2003). FE is also used to validate the experimental results of prosthetic limb testing. The finite element method (FEM) has been used to address various orthopedic problems. This research aims to create an alternative design of the ankle-foot prosthesis for a lightweight but strong. The strength of the ankle-foot prosthesis design was tested using the finite element method under normal walking conditions. AISI 304 was selected as a material option as they are widely available and popular. Two major factors were considered in deciding the prosthetic materials: cost and the nal product's weight. The applied load follows the predetermined criteria, which is 100 kg or 980 N. Simulation is done statically. A safety factor between 2 and 2.5 where the material and load limits have been determined.

2. Material and Method

The research method carried out in this study begins with a literature study to study the ankle-foot designs that are already on the market. In addition, it is also studied related to the needs of prosthetic limbs users, which are then used as a reference in determining design criteria. The following criteria must be met in designing a foot prosthesis by referring to human ankle biomechanical behavior: (1) the prosthesis must provide the structural strength to support the amputee's weight and daily activities; (2) the weight of the prosthesis designed must be proportional to the amputated limb; and (3) the prosthesis must provide sufficient shock tolerance to walk comfortably and prevent mechanical damage (Debta & Kumar, 2018).

Furthermore, this study's target of the prosthesis design is related to size and weight. The size of the prosthesis must match the size of the missing limb. The desired mass of the prosthesis should be 2.5% of the amputee's total body mass. Systematically, the research flow is shown through the flow chart in Figure 1.

2.1 CAD Model

This study aimed to produce an ankle foot design for a lightweight but a strong transtibial prosthetic component. Strength analysis was performed with the Finite Element Method (FEM) to predict the behavior of the prosthesis with an approximation to the actual application. FEM is a computational analysis method based on the idea of constructing a very complex object with several simple blocks or by dividing a very complex object into smaller ones and arranging the

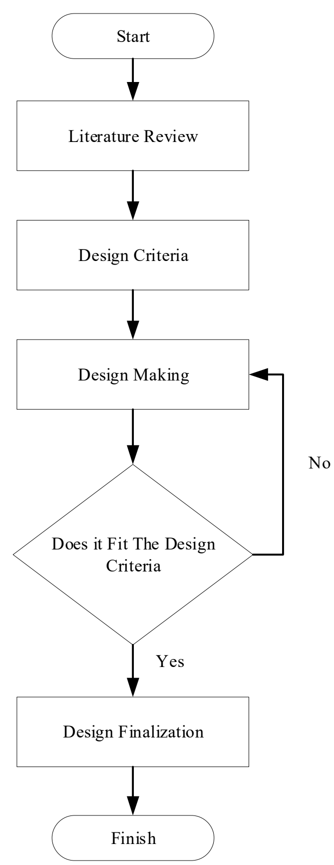

Figure 1. Research flowchart

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pieces (Lestari et al., 2016; Lestari & Ismail, 2017; Lestari & Jamari, 2017).

Before carrying out the simulation process with FEM, the geometry obtained from the artificial foot design process was first designed using SolidWorks CAD (Computer Aided Design) software (Lestari, 2022). The design process in this study begins with a scanning process to obtain the foot profile and size. The scanning results are then used as a reference in designing the ankle foot. The steps in designing the ankle-foot are shown in Figure 2.

Two alternative designs were obtained from this study, namely alternative designs 1 and 2, shown in Figure 3. This alternative design is carried out to obtain the most optimal design based on predetermined criteria. The main criteria of this research are light but strong. Based on the calculations that have been done previously with reference to the anthropometry of the Indonesian people, the transtibial prosthesis that is made must weigh no more than 2.3883 kg. So for the weight of the foot prosthesis made in this study, it must have a weight far below the predetermined criteria so that when

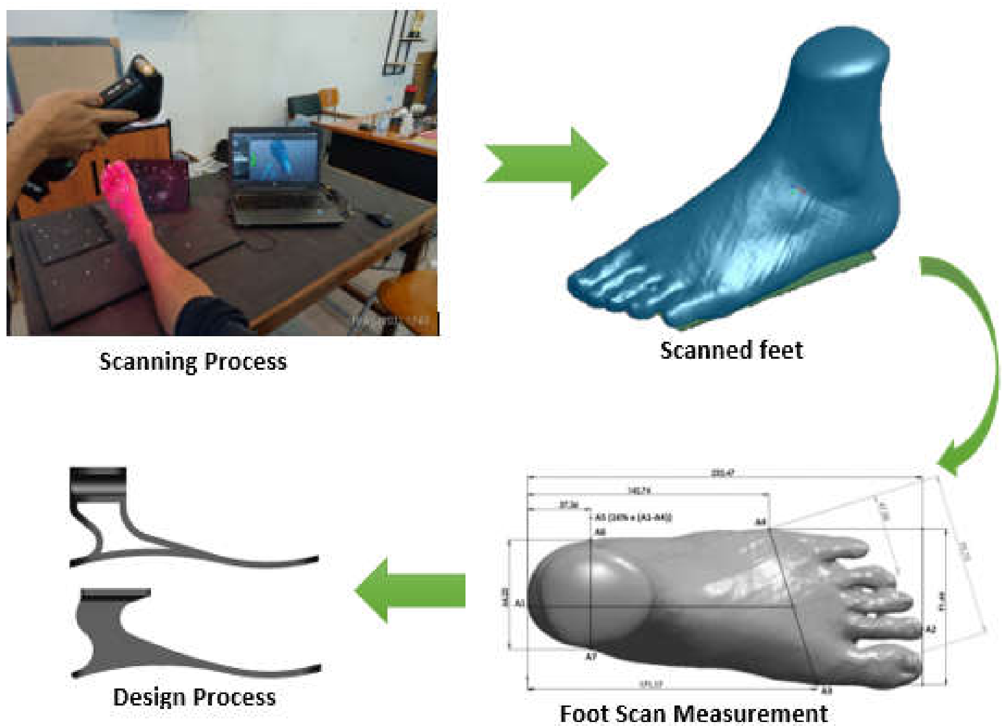
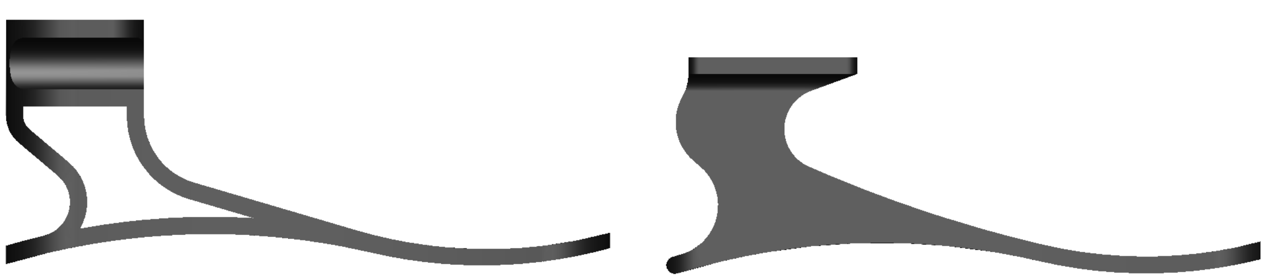


Figure 2. CAD Design Process



(a) (b)

Figure 3. Ankle foot model generated from Solidwork for (a) alternative ankle foot design 1 and (b) alternative design 2

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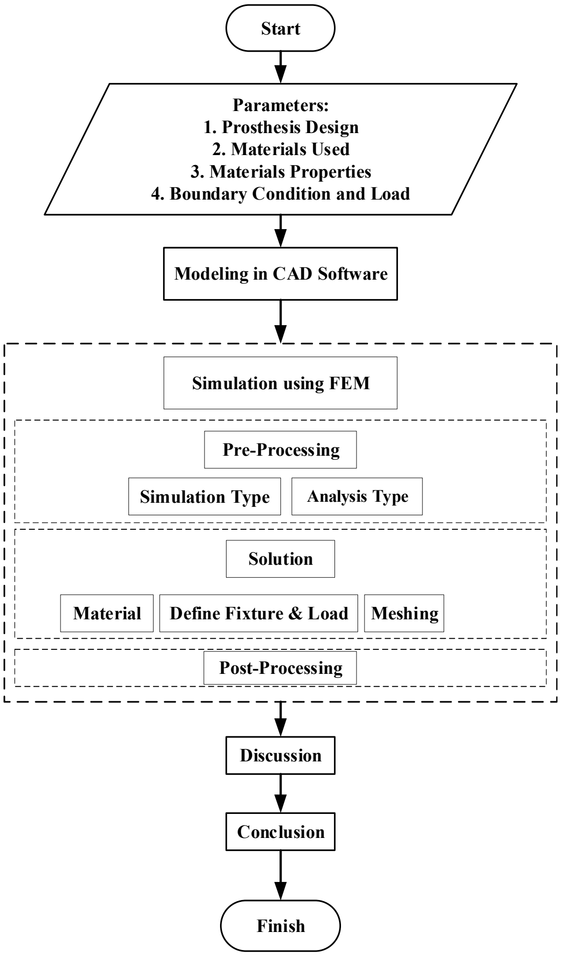

Figure 3. FEM simulation flowchart

combined with other components, the weight is still following the criteria. The material chosen to be adopted in the ankle-foot design is AISI 304. From the modeling results, the weight of each alternative 1 and 2 prosthetic design is 491.69 grams and 742.39 grams.

2.2 Static Structural Analysis

The ankle-foot design needs to be tested by FEM with static loading to see the strength of the material and safety standards from failure. The simulations carried out in this study are in the form of static simulations on Solidworks software. The material used is AISI 304 with Young's Modulus of 193000 MPa and Poisson's Ratio of 0.29 (Lestari, 2022). Structural statistical analysis was performed after appropriate meshing. The simulation process using FEM in this study is shown through the flow diagram in Figure 3. The simulation was carried out under normal walking conditions in the midstance phase. The applied load is a vertical load of 1000N, following predetermined criteria where the prosthesis must withstand 100kg. The load is applied vertically to the legs by continuously working downwards. The simulation procedure is shown in Figure 4.

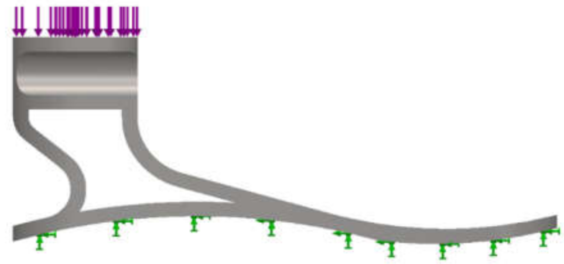

Figure 4. Simulation procedure using FEM

3. Results and Discussion

Validation is needed, either analytical, computational, clinical, or experimental, to determine the accuracy of the simulation process being carried out. In this study, validation was carried out by in-line production tests of mechanical uniaxial loading on the blades as cantilever beams, simulated and compared with measured values. This comparison proves the assumptions made on material properties.

The foot prosthesis must be adjusted to the function, such as regular walking, going ascent and descending stairs, or sports. In general, prostheses are designed to be used in normal walking. For this reason, it is necessary to test both simulations and experiments so that the prosthesis can perform according to its function. A simulation of human movement in normal walking is called a gait cycle. This walking cycle has 8 phases: initial contact, loading response, mid stance, terminal stance, pre-swing, initial swing, mid swing, and terminal swing. In this study, the simulation of ankle foot loading was carried out in the midstance position. In this position, the ankle-foot forms an angle of 0^0 with the ground so that they will immediately receive the load from the body when standing perfectly using one foot. The data taken are in the form of von Misses stress, displacement, and strain.

3.1 Deformation

The total deformation analysis parameter is used to determine the design changes that occur when it is given a load. The value of displacement that occurs at the midstance position for each design is 0,04726 mm and 0.03489 mm for alternatives 1 and 2. The form of deformation that occurs at that position can be illustrated in Figure 5. The deformation value can be used to determine the stiffness value of the model form with the following equation.

$$K = F/d \quad (1)$$

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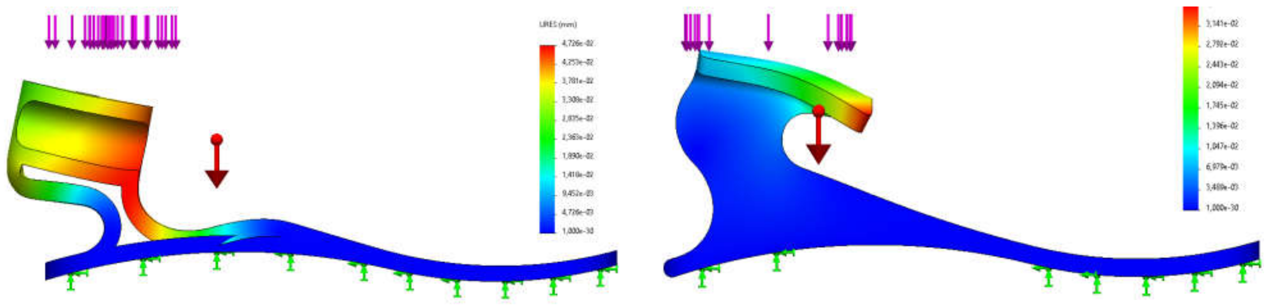
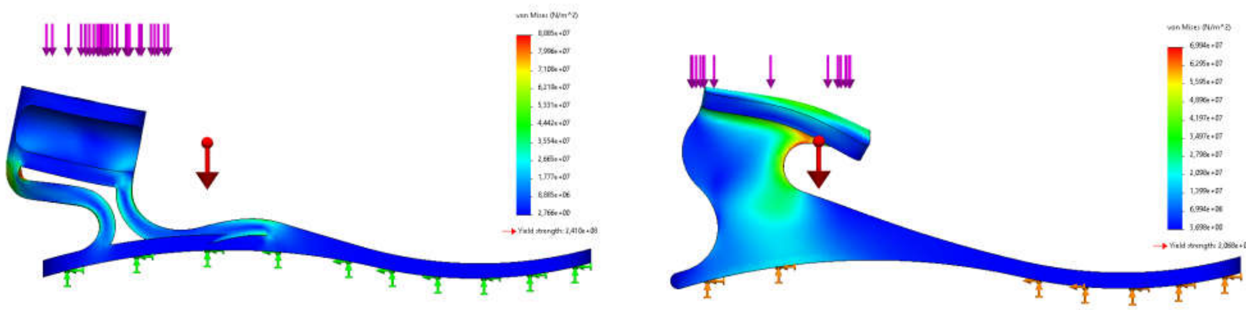


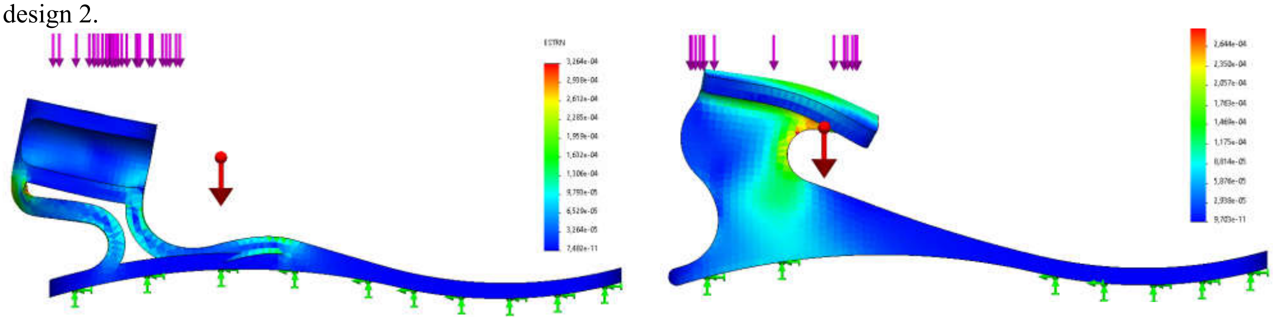
(a) (b)

Figure 5. Illustration of deformation simulation results on (a) alternative ankle foot design 1 and (b) alternative design 2.



(a) (b)

Figure 6. Illustration of von Mises stress simulation results on (a) alternative ankle foot designs 1 and (b) alternative design 2.



(b)

Figure 7. Illustration of strain simulation on (a) alternative ankle foot design and (b) alternative design 2.

Where K is stiffness (N/mm), F is force (N), and d is deformation (mm). Based on these equations, the stiffness values for each alternative 1 and 2 are 20.736,35 N/mm and 28.088,277 N/mm. The average stiffness of 121.8 kN/m at midfoot loading was obtained by Taboga & Grabowski (2017).

Prosthetic ankle stiffness is one of the keys in making it easier for users to carry out daily activities (Glanzer & Adamczyk, 2018). In addition, load-carrying loads affect the foot's stiffness and gait, so an adaptive prosthetic foot is essential to meet functional demands (Adamczyk, Roland, & Hahn, 2017). In addition, the user wanted a light and dimensional prosthetic to resemble an amputated limb(Schnall et al., 2019).

Table 1. Safety factor values for each ankle foot design

Design Ankle Foot	Safety Factor (SF)
Alternative Design 1	2.33
Alternative Design 2	2.96

3.2 Stress

Stress analysis is carried out to determine the design's stress distribution when given a load. The stress distribution on the ankle-foot is more even in the midstance position because it rests on two fixed supports in the area of the forefoot and the back of the foot. The maximum stress results in the ankle-foot can be seen in this FEM simulation through the von Mises stress analysis parameter. The analysis results show that the

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ankle-foot design with the lowest stress is an alternative design 2, amounting to 69.8 MPa. As for the stress value for an alternative design 1 amounting to 88.85 MPa. A 3D illustration of the stress simulation results in each design can be seen in Figure 6. In the second design, the greatest stress occurs in the bending area of the forefoot. The stress is due to a material reduction in the middle in alternative design 1 and a concave shape like the letter C on the front in alternative design 2. This stress condition also occurs in the Ankle Foot Orthosis design (Surmen & Arslan, 2021), where stress is concentrated around the lateral and medial sides during walking and the stress level increases due to the pruning process. The safety factor value can be calculated based on the maximum von Misses results. The safety factor value can be calculated through the following equation.

$$SF = Fu/Fi \quad (2)$$

Where SF is the safety factor, Fu is the yield strength, and Fi is the allowable stress. The yield strength value of AISI 304 material is known to be 206,8 MPa. The safety factor value for each alternative design can be seen in Table 1. Based on the table, it can be seen that from the two alternative designs, the ankle-foot is still categorized as safe because it still meets the safety factor requirements; namely, the safety factor value must be more than 1.5.

3.3 Strain Energy

Strain energy is used as an analytical parameter to measure the stored strain energy. Calculations on the energy storage of prosthetic feet are usually done conventionally (Hansen et al., 2010). The results are very dependent on the model, so it has limitations in analyzing the prosthetic feet design. Some researchers calculate strain energy using FEM based on certain gait cycles (Bonnet et al., 2012). Based on the amount of load given, the design that saves the most energy is the alternative ankle foot design 2. A 3D illustration of the energy strain simulation for each alternative design is presented in Figure 7.

4. Conclusion

This study focused on developing a foot design for a transtibial prosthesis component that supports increased ESAR and flexibility. In addition, design development also aims to create products that are strong, cost-effective, and suitable for use by Indonesian anthropometry. The design is then simulated as its strength using FEM. Based on the design results and ankle foot simulations, the results show that the design is still in the light and safe category when receiving a predetermined load. This is because the von Mises value of the two designs that have been produced is still below the yield strength value of the material. The results of this study can contribute to the local industry to develop an artificial foot manufacturing process for domestically made transtibial prosthetic components. For further research, simulations can be carried out for all phases of each design's normal walking cycle to determine the model function's similarity to the original leg.

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