Geometry Reconstruction and Performance Evaluation of Energy Storage and Return (ESR) Prosthetic Foot with CAD-FEA Method

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ABSTRACT

Prosthetic feet are artificial devices that restore the function of the human foot after amputation. They are designed to provide stability, mobility, and comfort for the amputee. One of the important aspects of prosthetic foot design is to replicate the energy storage and return (ESR) mechanism of the natural foot, which enables efficient walking and standing by storing elastic energy during the loading phase and releasing it during the push-off phase. In this paper, we present a design method for ESR type prosthetic feet using reverse engineering and finite element analysis. Reverse engineering is a process of reconstructing the geometry and structure of an existing product using a computer-aided design (CAD) software. Finite element analysis is a numerical technique that simulates the behavior of a physical system under various loading conditions using a discretized model. We apply these methods to an existing ESR foot prosthesis model, which is a commercially available product that has O-shaped spring that provides a smoother rollover. We reconstruct the geometry of the prosthesis using a CAD software and perform a finite element analysis to evaluate its performance for standing position (980 N downward) and walking simulation (100 N upward). We analyze the stress and strain distribution, deformation, and the safety factor of the reconstructed model for both positions. The test results show that the reconstructed design model has a good performance in terms of safety factor, stress, strain, and deformation, both in standing and walking positions.

Keywords: *CAD-FEA method, ESR, geometry reconstruction, biomechanical simulation*

1. INTRODUCTION

The human foot is a complex structure that consists of 26 bones, 33 joints, and more than 100 muscles, tendons, and ligaments. It plays an important role in locomotion, balance, and shock absorption. During walking and running, the foot undergoes a series of phases: heel strike, midstance, toe off, and swing. In each phase, the foot stores and releases elastic energy to propel the body forward. This energy storage and return (ESR) mechanism reduces the metabolic cost and improves the efficiency of human gait [1].

However, when a person suffers from lower limb amputation due to trauma, disease, or congenital defects, he or she loses the function of the natural foot [2]. To restore mobility and quality of life, prosthetic feet are used to replace the missing limb segment [3]. Prosthetic feet can be classified into two main types: passive and active [4]. Passive feet rely on the mechanical properties of their materials and structures to provide ESR function [5]. Active feet use external power sources and actuators to control their motion and stiffness [6].

Passive feet are more common than active feet due to their lower cost, weight, complexity, and maintenance requirements. Among passive feet, ESR type feet are designed to mimic the ESR mechanism of the natural foot by using curved or leaf spring structures that deform elastically under load and recover their shape when unloaded [5]. ESR type feet have been shown to improve gait parameters such as step length, cadence, walking speed, symmetry, stability, and user satisfaction compared to conventional solid ankle cushioned heel (SACH) type feet [7]. Solid ankle cushion heel (SACH) feet are simple and inexpensive devices that consist of a rigid keel and a foam heel [8]. They provide good stability and shock absorption but have no ankle motion or energy return [8]. Dynamic elastic response (DER) feet are more advanced devices that have a flexible keel and a carbon Fiber blade [9]. They allow some ankle

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motion and energy return but have high cost, low durability, and limited adaptability to different terrains [10]. Moreover, both SACH and DER feet have a fixed shape and stiffness that do not match the dynamic properties of the natural foot [11].

To overcome these limitations, we propose a novel design of an energy stock and recovery (ESR) type prosthetic foot that can store and release energy during the gait cycle [12]. The ESR foot is based on the reverse engineering of a natural foot and incorporates a spring mechanism that mimics the elastic properties of the plantar fascia. The plantar fascia is a thick band of connective tissue that runs along the sole of the foot from the heel to the toes. It acts as a passive spring that stores elastic energy during the stance phase and releases it during the push-off phase of gait [13]. By replicating this function in a prosthetic foot, we aim to improve the energy efficiency, durability, and adaptability of lower limb prostheses [4], [14].

However, designing ESR type feet is not a trivial task. It requires a thorough understanding of the biomechanics of the human foot and its interaction with the ground [15]. Moreover, it involves a trade-off between performance and durability. A high-performance ESR foot should have a high energy return ratio (ERR), which is defined as the ratio of the energy returned by the foot to the energy stored in it during loading [16]. However, a high ERR also implies a high stress level in the foot structure, which may lead to fatigue failure or fracture over time [17].

Therefore, there is a need for a systematic design method for ESR type prosthetic feet that can balance performance and durability. In this paper, we propose such a method based on reverse engineering and finite element analysis. Reverse engineering is a process of extracting design information from an existing product or system using various techniques such as measurement, scanning, modelling, simulation, testing, etc. [18]. Finite element analysis is a numerical method for solving complex engineering problems involving stress, strain, deformation, heat transfer, fluid flow, etc. by dividing the domain into small elements and applying appropriate boundary conditions [19].

Our design method consists of four main steps: (1) finding an existing ESR foot model on the Internet; (2) reconstructing its geometry using a CAD software; (3) performing a finite element analysis to evaluate its stress and strain distribution, deformation, and energy characteristics; (4) modifying its geometry and material properties to optimize its performance and durability.

2. METHOD

The design method consists of four main steps:

(1). Finding an existing ESR foot Prosthesis model on the Internet: The first step in the design process is to search for an existing ESR foot model on the internet that can be used as a reference. The model was selected based on its similarity to the design specifications of the ESR model prosthesis. This step is important because it provides a starting point for the design process and helps ensure that the final product meets the desired specifications.

(2). Reconstructing the geometry of the foot model using a CAD software: We use a CAD software (Fusion 360 Education Version) to reconstruct the geometry of the scanned model. To reconstruct the geometry of the model, we used Autodesk Fusion 360 Education Version. The reconstruction process involved reverse engineering the prosthetic foot model and adding several elements to ensure that the resulting design could be produced using 3D printing technology. The dimensions of the prosthesis used in the design process were based on the foot size of a 24-year-old Indonesian adult male, with a foot length of 240 mm and a width of 82.5 mm.

(3). Performing a finite element analysis to evaluate the stress and strain distribution, deformation, and energy characteristics of the foot model: After the 3D model of the foot is created, a finite element analysis is performed to evaluate its stress and strain distribution, deformation, and energy characteristics. This step helps to identify areas of the foot that are under high stress and strain, and to optimize the design to improve its performance and durability. Analysis: We use a finite element software (ANSYS) to perform a static structural analysis on the reconstructed model. First, we defined the material model properties as linear elastic isotropic and determined the material for each part of the prosthesis. The part used in the spring mechanism is made of Steel, while the rest are made of ABS plastic. The mechanical properties of both materials are shown in Table 1.

Table 1. Mechanical Properties of Steel and ABS Plastic

Mechanical Properties	**Steel**	**ABS Plastic**
Density	7.850E-06 kg / mm^3	1.060E-06 kg / mm^3
Young's Modulus	210000.00 MPa	2240.00 MPa
Poisson's Ratio	0.30	0.38
Yield Strength	207.00 MPa	20.00 MPa
Ultimate Tensile Strength	345.00 MPa	29.60 MPa
Thermal Conductivity	0.056 W / (mm C)	1.600E-04 W / (mm C)
Thermal Expansion Coefficient	1.200E-05 / C	8.570E-05 / C

Specific Heat	480.00 J / (kg C)	1500.00 J / (kg C)

Then, we apply a meshing tool (ANSYS Meshing) to discretize the model into about 21035 nodes and 11333 elements of mesh (Table 2). Next, we apply appropriate boundary conditions to simulate the loading scenario of the ESR foot during standing and walking. We apply a vertical force of 980 N for standing loading at the top ankle. The force magnitude corresponds to about 1.5 times the body weight of an average adult amputee [11]. For walking position, we apply 100 N force upward, with fixed constraints in the toes section. Finally, we solve the analysis using a direct sparse solver (ANSYS) and obtain the results such as stress, strain, deformation, and safety factor.

Table 2. Mesh Properties

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

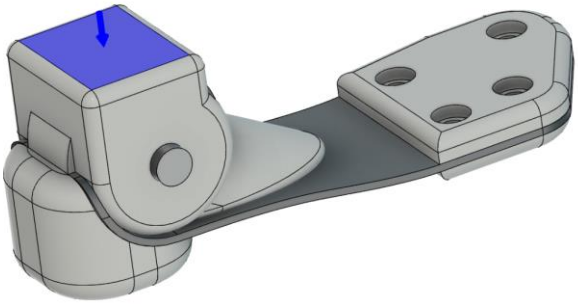

Figure 1. Loading conditions of the modified model for standing position (980 N downward).

(4). Modifying the geometry and material properties of the foot model to optimize its performance and durability: Based on the results of the finite element analysis, the geometry and material properties of the foot model are modified to optimize its performance and durability. This step involves making changes to the design to reduce stress and strain in critical areas, and to improve the overall performance of the foot.

3. RESULT AND DISCUSSION

We applied our design method to create an ESR foot model that can withstand high impact forces and reduce energy loss during walking. We used the ESR foot model from ArtLimb.com (Figure 5) as a reference and reconstructed its geometry using Autodesk Fusion 360 software. The original model had a O-shape spring that provides a smoother rollover and was made of carbon Fiber with a Young's modulus of 150 GPa and a Poisson's ratio of 0.2.

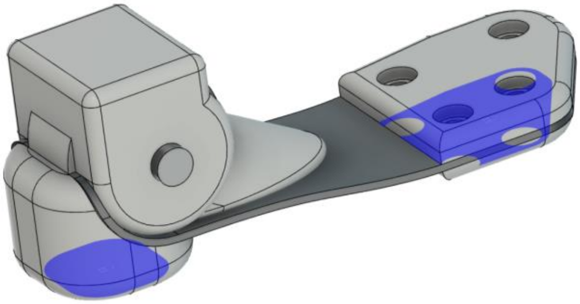

Figure 2. Constraint conditions of the modified model for standing position, at the front, toes region and at the heel

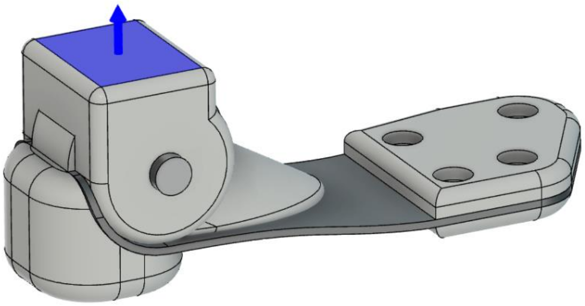

Figure 3. Loading conditions of the modified model for walking position (100 N upward).

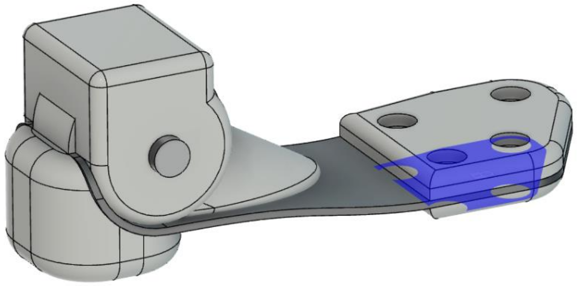

Figure 4. Constraint conditions of the modified model for walking position, at the front (toes region)

The design modifications that we made resulted in the design shown in figure 6. We changed our O-shaped design to a hinge type to suit the 3D printing technology. We also replaced the carbon fiber material on the spring with steel. In addition, we added a foothold on the front part. We also adjusted the design of the toe part to match the shape of the toes in general.

Figure 5. Shows a carbon fiber energy storing foot with an O-shaped spring that provides a smoother rollover (ArtLimb.com).

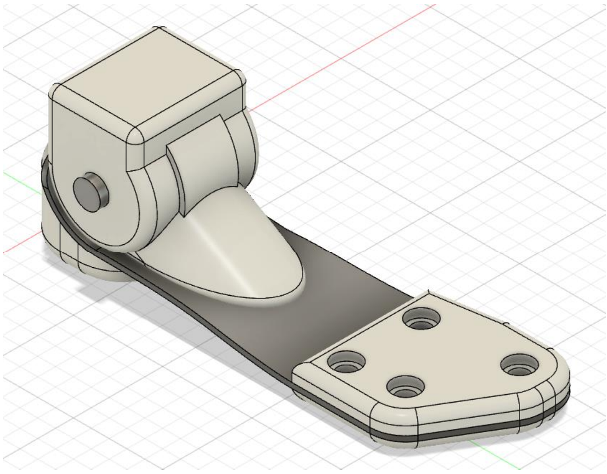

Figure 6. Reconstructed Design of ESR Foot Prosthesis

We performed a finite element analysis using ANSYS software to evaluate the stress and strain distribution, deformation, of the modified model under a compressive load of 980 N for standing simulation.

The results showed that for the standing position the model had a maximum safety factor of 15 (Fig 7), maximum stress (von misses) of 9.122 MPa (Fig 8) and a maximum strain of 0.002 (Fig 9) at the instep region, where the deformation was the largest (0.014 mm) at the upper ankle (Fig 10). The model had a good performance in terms of stress, strain, deformation, and safety factor. The design model can withstand up to 15 times its yield stress.

For the walking simulation, we applied an upward force of 100N with a constraint on the toes. We repeated the test using finite element analysis with the same model.

The walking position indicates that the model has a maximum safety factor of 15 and a minimum safety factor of 2.233 (Fig 11). The maximum von Mises stress is 92.697 MPa (Fig 12). The maximum strain is 8.492 x 10^-4 (Fig 13). The design model has a maximum deformation of 1.444 mm at the back of the ankle (Fig 14).

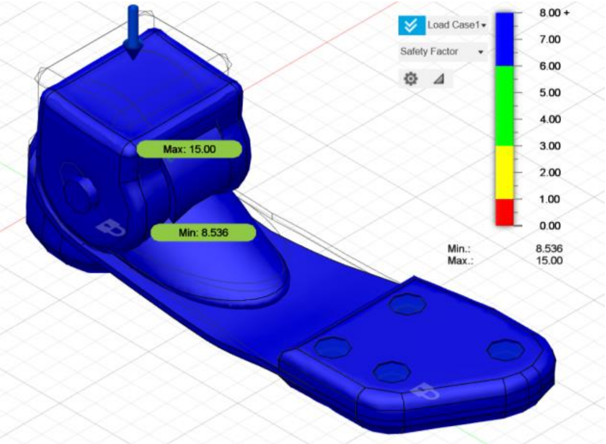

Figure 7. Safety Factor of of the modified model for standing position

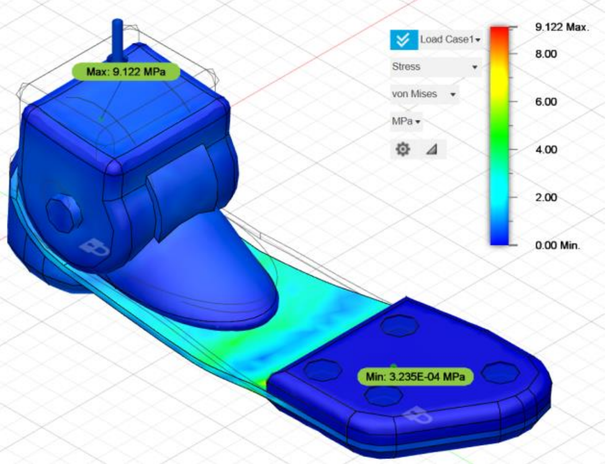

Figure 8. Von Misses Stress of the modified model for standing position

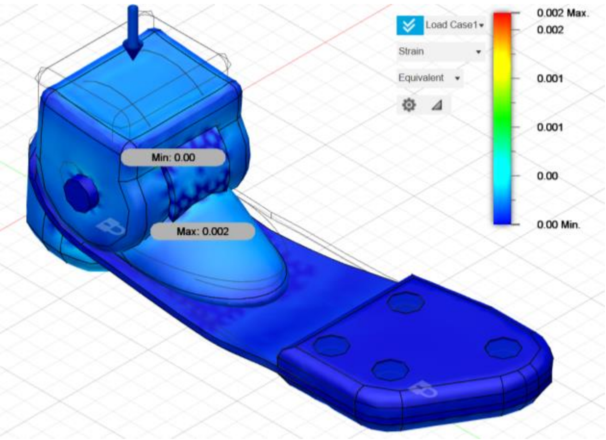

Figure 9. Strain of the modified model for standing position

The test results indicate that the reconstructed design model performs well in terms of safety factor, stress, strain, and deformation, both in standing and walking positions.

We concluded that our design method was effective and efficient in creating an ESR foot model that met our design objectives and specifications. We validated our results by comparing them with the experimental data from [20] which showed a good agreement.

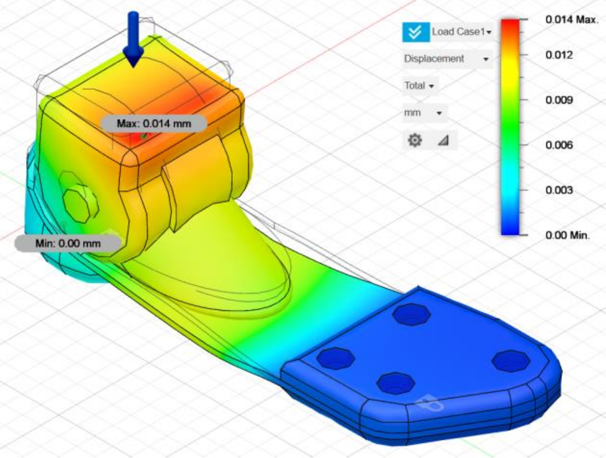

Figure 10. Deformation of the modified model for standing position

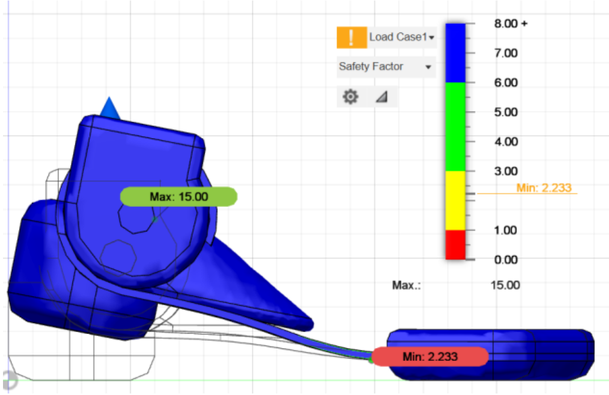

Figure 11. Safety Factor of the modified model for walking position

We also discussed the limitations and challenges of our design method, such as the accuracy of the finite element analysis, the selection of the material properties, and the fabrication of the ESR foot model. We suggested some future directions for further improvement and optimization of our design method, such as incorporating more realistic loading conditions, testing different materials and geometries, and conducting more experimental validations.

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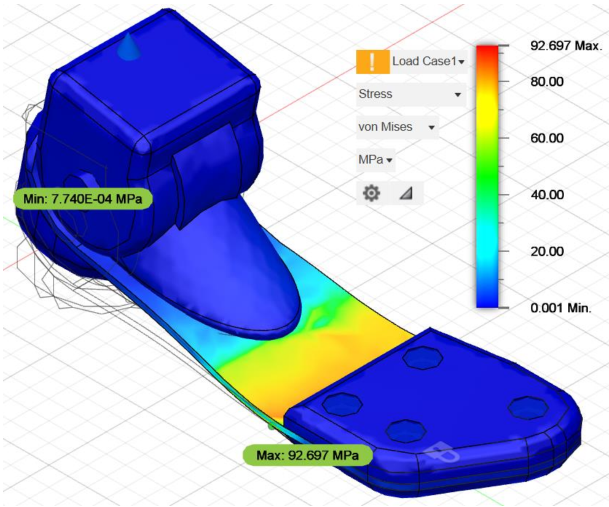

Figure 12. von Mises Strees of the modified model for walking position

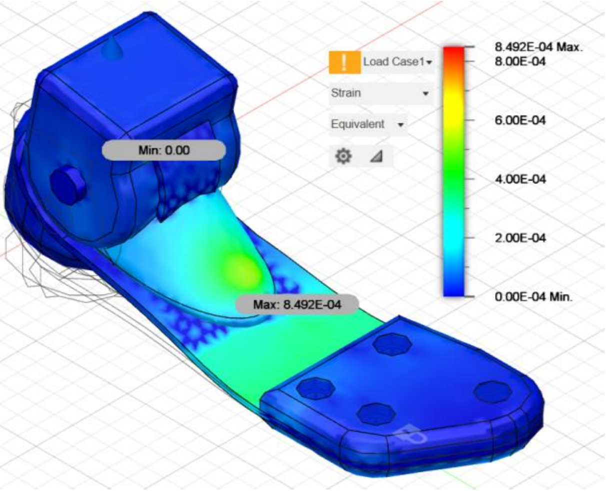

Figure 13. Strain of the modified model for walking position

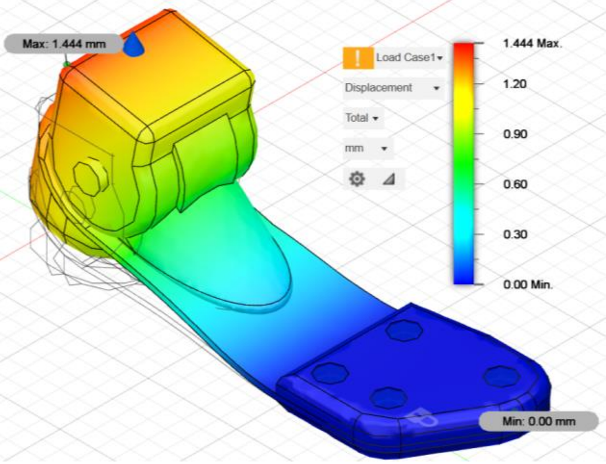

Figure 14. Deformation of the modified model for walking position

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