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FABRICATION OF SINGLE-AXIS PROSTHETIC FOOT USING 3D PRINTING AND RESIN INFUSION METHOD

FABRIKASI TELAPAK KAKI TIRUAN SINGLE-AXIS PROSTHETIC FOOT MENGGUNAKAN 3D PRINTING DAN METODE INFUS RESIN

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ABSTRAK

Prototipe telapak kaki tiruan jenis single-axis diusulkan sebagai salah satu alternatif alat bantu kaki tiruan bagi pasien difabel untuk melakukan aktivitas sehari-hari. Tiga posisi utama dalam 0- 64% dari gait cycle yaitu posisi heel strike, midstance dan toe-off yang digunakan sebagai boundary condition. Finite Element Method mampu menganalisis suatu pemodelan untuk mengukur nilai deformasi, tegangan dan regangan yang terjadi secara detail. Penelitian ini bertujuan untuk fabrikasi produk atau prototipe telapak kaki tiruan yang optimal dan mengetahui batas kekuatannya sehingga dapat menahan beban berat badan pengguna untuk memberikan kenyamanan dan keamanan sebelum difabrikasi menggunakan 3D printing dan metode infus resin. Fabrikasi prototope telapak kaki tiruan ini menggunakan software Fusion 360 dan dilanjutkan dengan simulasi pengujian menggunakan software ABAQUS 6.14. Model prototipe didesain dan dianalisis untuk mendapatkan kekuatan dan kelayakan sebelum difabrikasi dengan mesin 3D printing DLP tipe Anycubic Photon Mono X dan metode infus resin. Hasil yang diperoleh pada penelitian ini menunjukkan bahwa prototipe telapak kaki tiruan single-axis prosthesis foot mampu menahan beban berat badan pengguna dengan pembebanan level P3 atau 60 kg, level P4 atau 80 kg, level P5 atau 100 kg sesuai ISO 10328. Massa prototipe atau produk telapak kaki tiruan single-axis yaitu sebesar 657 gram, sesuai kriteria tidak melebih 1,7% dari total berat badan pengguna dengan nilai kekerasan 55,5 HA dan dapat bertahan pada 50.000 siklus dalam pengujian fatigue.

Kata kunci: *Telapak kaki tiruan; Gait cycle; 3D printing; Prototipe; ISO 10328.*

ABSTRACT

A prototype of a single-axis prosthetic foot is proposed as an alternative prosthetic foot for patients with disabilities to perform daily activities. Three leading positions within 0-64% of the gait cycle are heel strike, midstance, and toe-off positions used as boundary conditions. The Finite Element Method can analyze a model to determine the values of deformation, stress, and strain that occur in detail. This research is conducted to fabricate an optimal prosthetic foot product or prototype and determine its strength to support the weight of the user's body and provide comfort and safety before being fabricated using 3D printing and resin infusion methods. The fabrication of the

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prosthetic foot prototype used Fusion 360 software and continued with simulation testing using ABAQUS 6.14 software. The prototype model was designed and evaluated to obtain strength and feasibility before being fabricated with an Anycubic Photon Mono X type DLP 3D printing machine and resin infusion method. The results obtained in this study show that the prototype of a single-axis prosthetic foot can support the human body's weight with loading level P3 or 60 kg, level P4 or 80 kg, and level P5 or 100 kg according to ISO 10328. The mass of the prototype or single-axis prosthetic foot product is 657 grams, according to the criteria, not more than 1.7% of the user's total body weight, with a hardness value of 55.5 HA, and can withstand 50,000 cycles in fatigue testing.

Keywords: *Prosthetic foot; Gait cycle; 3D Printing; Prototype; ISO 10328*.

INTRODUCTION

In recent years, disability has become a problem in Indonesia because of accidents or diseases. According to the Indonesian Central Agency on Statistics (BPS) in 2010, there were around 3.1 million people who could not move their lower limbs because of amputation [1]. The population with functional disorders in difficulty walking is 2.432.000 people, and the severe category is 656.000 [2]. Several factors can physically lead to disability, especially lower extremity amputations, such as diabetic ulcers or the condition of the patient's feet that are infected, ulcerated, or have damaged the deepest skin tissue, reaching 85% [3]. In 2020, 88% of the total demand for medical devices in Indonesia was still imported, including prosthetic feet [4]. Considering the substantial needs and opportunities, more and continuous research is needed to develop products that can later become a reference, especially for medical devices for people with lower limb disabilities. The prosthetic foot is also often used by most people who have been amputated, so the prosthesis must have high stability and flexibility when in contact with the heel.

Therefore, it required a material structure composition that can minimize the fatigue factor. The prosthetic used to replace an amputated lower foot is called lower limb prosthetics. According to research, lower limb prosthetics are categorized into exoskeletal and endoskeletal [5]. Various types of prosthesis models have been researched previously such as prosthetics with a surface that looks similar to a human foot [6], prosthesis models that have a small, thin and affordable design [7], prosthesis models that use control devices and electric power sources [8] as well as prosthesis models that use springs, couplings and motors [9]. However, several similar studies still have the disadvantages of being too complex, difficult for users, heavy, and expensive. Although various types of foot prosthetics have been developed, they are still costly and unaffordable for the middle to lower level of amputation survivors [10].

The Finite Element Method (FEM) approach was used to reduce trial and error in the fabrication of the prosthetic foot, to increase time efficiency and to minimize the amount of energy expended when testing the strength of the prosthesis model. FEM is used to analysis a modelling to measure the values of deformation, stress and strain that occur in detail [12]. Static load deflection testing with a gait cycle is performed to identify the mechanical property changes and eliminate the complex load on the prosthetic foot [13]. Problem solving with FEM will provide a faster calculation process than manual theoretical mathematical calculations or laboratory experiments with close to real values.

Single-axis prosthetic foot testing in compliance with ISO 10328 is very crucial. Testing is used to measure the prosthesis's performance, but it requires the availability of the necessary equipment. The complexity of this equipment is an advantage, as it causes the cost of testing to be expensive. Simulation of prosthesis testing with referring to the ISO 10328 standard using the FEM is a solution that can solve this problem. The use of FEM to analysis engineering problems is considered to have several advantages, such as being able to define irregular element shapes easily, set up various types of boundary conditions, and various element sizes as needed.

The human foot consists of 26 bones and 33 joints, and more than 100 muscles and ligaments [14]. The foot is a structural segment of the musculoskeletal system with complete statolocomotor and morpho-functional capabilities supporting a person's motor functions [15]. The prosthesis treatment aims to enable the amputee to perform basic ambulation and various advanced and normal daily activities.

Therefore, there is a requirement for a foot model that is feasible, user-friendly, and affordable in a cost-effective manner. Making prosthetic feet with 3D printing is easier and faster than conventional manufacturing [11]. The experiment of manufacturing a prosthetic foot with full and solid 3D printing has been performed. However, the results obtained are not completely optimal because there are many incomplete defects, so there is a need for other alternative methods to get ideal prototype results.

Method

The main steps of this research are model design and prosthetic foot model analysis. Model design using CAD software and analysis of the model using CAE software. The step of the design model is to obtain a single-axis prosthetic foot that has advantages compared to the existing designs. The next step is the model analysis, which aims to analyze how the design can be fabricated using a 3D printing machine and resin infusion method as a prototype. Before using this resin infusion method, we must know the ratio of resin to be used and the level of hardness to be achieved from the prototype to be fabricated. The tools used are divided into two categories: models and simulations, and secondly, tools used to make prototypes. Model and simulation tools are divided into hardware and software. The hardware used in this research is a laptop for model and simulation.

Furthermore, software includes Autodesk Fusion 360, ABAQUS 6.14, and Anycubic Photon Workshop. The prototype fabrication tools include an Anycubic Photon Mono X type DLP 3D printing machine, an Anycubic 2.0 type wash and cure machine, a Shore A Durometer Hardness test tool, a Fatigue test holder, a Fatigue test machine, and Digital Scales. Meanwhile, the materials used to fabricate prototypes are ESUN Photopolymer Resin, TMPU Resin A and B, Anycubic Clear Resin, and 90% Alcohol Liquid.

RESULTS AND DISCUSSION

A single-axis prosthetic foot is designed with a single axis that can be moved upward and downward. The ankle part of the prosthetic foot is also designed with two small holes with a diameter of 8 mm and one center hole with a diameter of 15 mm so that it can provide elastic force again if given a load from above and used in the gait cycle (Figure 1).

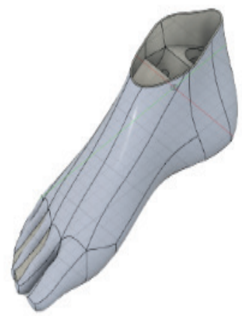

Figure 1.
Single-axis prosthetic foot design
Source: Author's documentation (2023)

Based on the test simulation results of the ISO 10328 method, the single-axis prosthetic foot is applied with a load of 60 kg, 80 kg, and 100 kg in the positions of heel strike loading, midfoot loading, and toe offloading, where the load can be resisted in each loading position, according to the user's needs.

Table 1.
Resultant load force of level P5*

Position	Components	X	Y	Z	Resultant
Heel strike loading	Reaction force (N)	-0.00130504	100.005	0.00313941	100.005
	Reaction moment (N.m)	0	0	0	0
Midstance loading	Reaction force (N)	-0.00103685	100.008	0.00188854	100.008
	Reaction moment (N.m)	0	0	0	0
Toe-off loading	Reaction force (N)	-0.00242773	100.01	0.00358826	100.01
	Reaction moment (N.m)	0	0	0	0

Source: Author's analysis (2023)
*Stress Analysis Level P5 or about 100 kg

The stress distribution values shown in Figure 2, for the heel strike loading and mid-stance loading positions, have a critical area next to the bottom hole indentation of the prosthetic foot. Furthermore, for the toe-off loading position, there is a critical area near the toes of the prosthetic foot. Therefore, it can be seen that the position and component that has the highest stress distribution is mid-stance loading of 7.514e+05 $N/m2$ with a total of 61274 nodes.

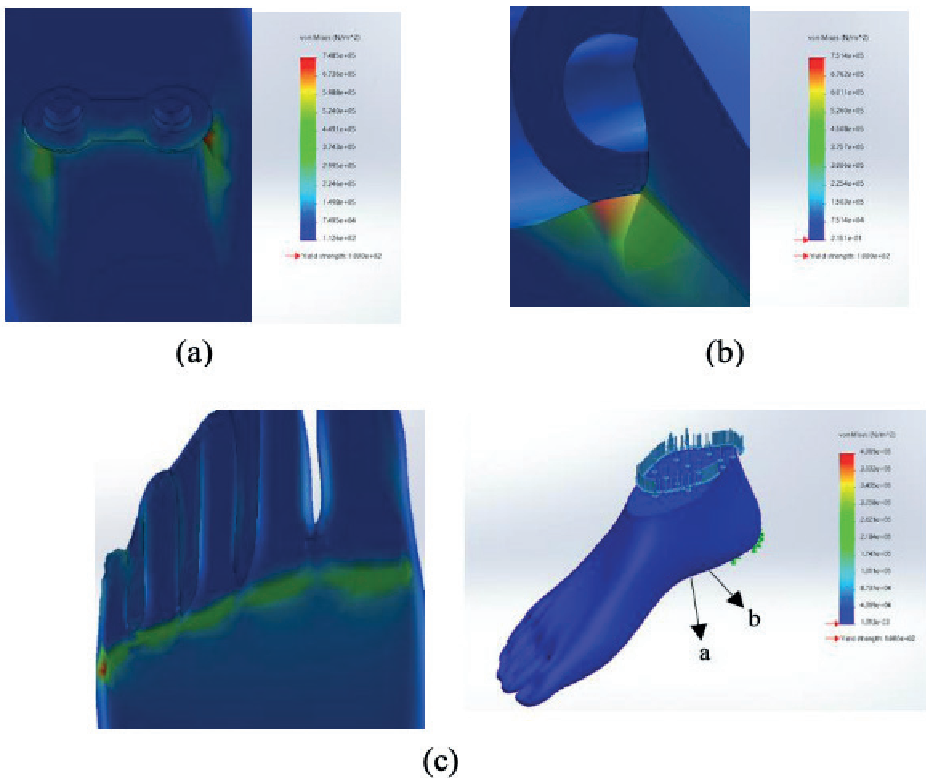

Figure 2.
Von Mises stress results 100 kg
(a) heel strike loading, (b) Midstance
(b) loading, (c) toe-off loading
Source: Author's Analysis (2023)

Figure 3 shows the total deformation value. For the heel strike loading and midstance loading positions, a critical area is at the back of the prosthetic foot's ankle. Furthermore, for the toe-off loading position, a critical area is at the tip of the toes. Therefore, the position and component with the highest deformation value is midstance loading of 7.389e-03 mm with a total of 1335 nodes.

The simulation results of von Mises stress distribution testing at a load of 60 kg show that the position with the highest stress distribution is a midstance loading position of 4.508×105 MPa, with a total of 61274 nodes. Furthermore, the von Mises stress distribution value at a load of 80 kg indicates that the highest stress distribution position is midstance loading of 6.00×105 MPa with 61274 nodes. Meanwhile, the von Mises stress distribution value at a load of 100 kg indicates that the position has the highest stress distribution, which occurs at the midstance loading position of 7.514×105 MPa, with a total of 61274 nodes (Figure 4).

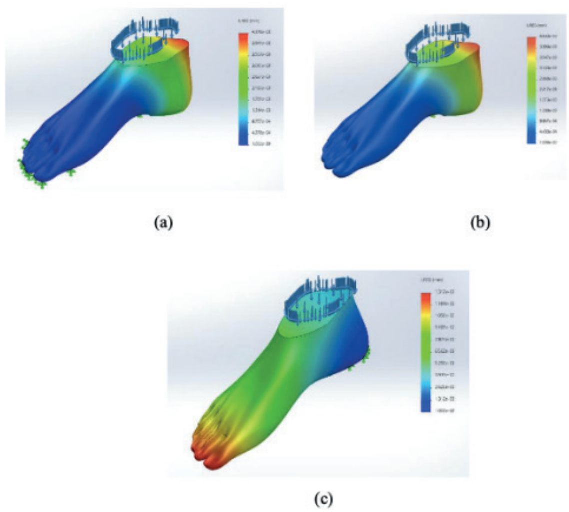

Figure 3.
Total deformation result of 100 kg
(a) heel strike loading, (b) Midstance loading, (c) toe-off loading
Source: Author's Analysis (2023)

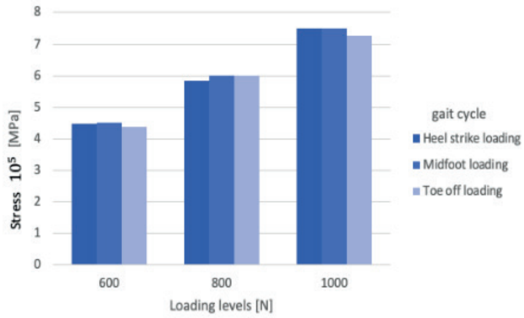

Figure 4.
Diagram of von Mises stress simulation result.
Source: Author's analysis (2023)

The simulation results of testing the total deformation at a load of 60 kg show that the position with the highest total deformation, which occurs with the toe-off loading position of 4.433 ×10−3mm, involves a total number of 1335 nodes. Furthermore, the simulation results of testing the total deformation of an 80 kg load show that the highest total deformation occurs in loading with a toe-off loading position of 5.911 ×10−3mm with a total number of 1335 nodes. Meanwhile, the simulation results of testing the total deformation at a load of 100 kg show that the position with the highest total deformation occurs in the toe-off loading position of 7.389 ×10−3mm with the number of nodes 1335 (Figure 5).

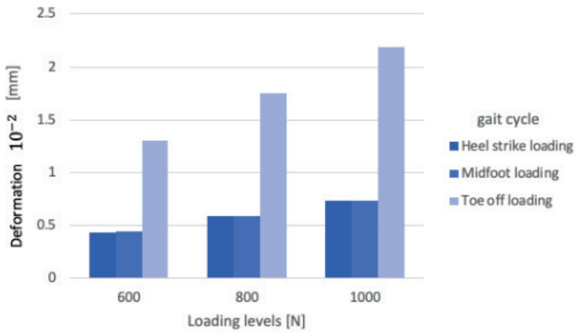

Figure 5.
Diagram of total deformation simulation results.
Source: Author's analysis (2023)

The simulation results of strain testing at a load of 60 kg show that the position with the highest strain distribution is loading with a toe-off loading position of 1,157 × 10-4mm, with a total of 4562 nodes. Furthermore, the results of the strain simulation at a load of 80 kg show that the highest strain occurs in the toe-off loading position of 1,813 × 10-4mm with a total number of nodes of 21549.

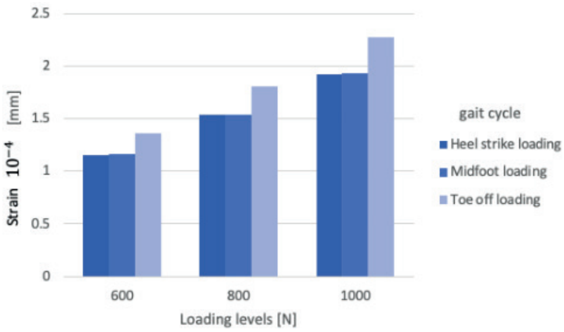

Figure 6.
Diagram of strain simulation results
Source: Author's analysis (2023)

Meanwhile, the results of the strain test simulation at a load of 100 kg show that the highest strain position occurs at the toe-off loading position of 2,267 × 10-4 mm with a node count of 21549 (Figure 6).

Product Failure Criteria

The single-axis prosthetic foot can perform the loading conditions with heel strike loading, midstance, and toe-off loading. Specifically, the gait cycle with the most significant load is during the foot flat or midstance loading phase, where the foot supports the entire body mass with the surface of one sole flat.

Furthermore, the gait cycle with the most significant load also occurs in the toe-off loading position, where one of the feet pushes the body with the front end of the foot and then rests on the heel of the other foot. The failure criteria for the prototype are that the mass of the single-axis prosthetic foot product should not exceed 1,7% of the user's total body mass (Krishnan et al., 2016). Therefore, the following can be summarized:

Product mass = 1,7% × user body weight
Product mass = 1,7% × 60 kg
= 1,02 kg or about 1.020 grams

So, the mass of a single-axis prosthetic foot product for a user with a 60 kg body weight should not exceed 1.02 kg.

Hardness test results

After getting the results of the single-axis prosthetic foot skin using a 3D printing machine, the next step is hardness testing of the resin specimens that will be used to fabricate this prototype. Before using the resin infusion method, it is necessary to know the ratio of TMPU resin that will be infused into the skin of the 3D printed prosthetic foot and the hardness level approximately close to the hardness of the prosthetic foot product, after having the results of the skin of a single-axis prosthetic foot using 3D printing machine. The Shore Hardness test in this research aims to determine the level or value of comparative hardness of TMPU resin specimens A and B to get the same hardness value as Chinese prosthetic foot products.

This testing also refers to the ASTM D2240 standard using six specimens with TMPU A and B resin comparisons shown in Figure 7, including 1:1, 1:2, 1:3, 2:3, 3:1, and 2:1. The specimen dimensions are 49 mm x 12 mm x 8 mm and marked at five different points with a distance of 6 mm between points on the specimen by ASTM D2240 standard.

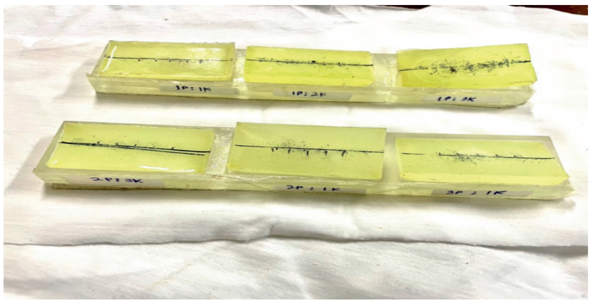

Figure 7.
Hardness testing specimens
Source: Author's personal documentation (2023)

Figure 8.
Hardness testing results
Source: Author's documentation (2023)

Based on the hardness test results, the ratio of TMPU A and B resin specimens was obtained, which is 1:1, to be used as material for the resin-infused method on the skin of the prosthetic foot. The prototype of a single-axis prosthetic foot has an average hardness value of 55.5 ± 0.3 HA, shown in Figure 8. The hardness value obtained exceeds the design criteria for Chinese prosthetic foot products with a Shore hardness value of 50-55 HA or Hardness of Shore A.

Prototype fabrication result by resin infusion method

The resin infusion method aims to obtain a solid prosthetic foot prototype. Therefore, the method was performed because of the limitations of the 3D printing machine, which cannot print solid complex geometries with elastic Polyurethane resin.

(a) (b)

Figure 9.
Results of the resin infusion method: (a) Top View, (b) Side View
Source: Author's documentation (2023)

The prototype that has been printed is infused with TMPU A and B resin with a 1:1 ratio because the dimensions of the Anycubic Mono X 3D printing machine are not able to print when in a solid condition. So, the infusion process was performed and allowed to stand for 32 hours so that the results obtained were solid. After that, the resin pigments were mixed to match the skin colour (Figure 9).

A single-axis prosthetic foot prototype

The result of the fabrication prototype of this single-axis prosthetic foot is a mass of 657 grams using polyurethane. The mass has fulfilled the criteria with the maximum mass of the foot of the total body weight of the user, which cannot exceed 1,7% by using the P3 level body weight, or equal to 60 kg, the result is 1,02 kg. The dimensions are 245 mm x 75 mm x 75 mm, or a size 39 shoe according to the Indonesian woman's foot size. First, the foot mold was made using a 3D printing machine for 11 hours and 49 minutes, then inserted into the curve and wash machine for 5 minutes. After that, the finished mold was filled with TMPU A and B in a ratio of 1:1 and allowed to settle for 32 hours, and there was a joint in the middle of the prototype because the dimensions were large enough that the design had to be divided into two and reconnected (Figure 10).

Figure 10.
Polyurethane material prototyping results
Source: Author's documentation (2023)

Meanwhile, the result of an overall prototype using PLA material or Anycubic clear resin with dimensions of 210 mm x 65 mm x 65 mm, or according to the shoe size of 35 Indonesian women, shown in Figure 11, without joints, was printed using a 3D Printing machine for 12 hours and 10 minutes, inserted into the curve, and washed in a washing machine for 5 minutes.

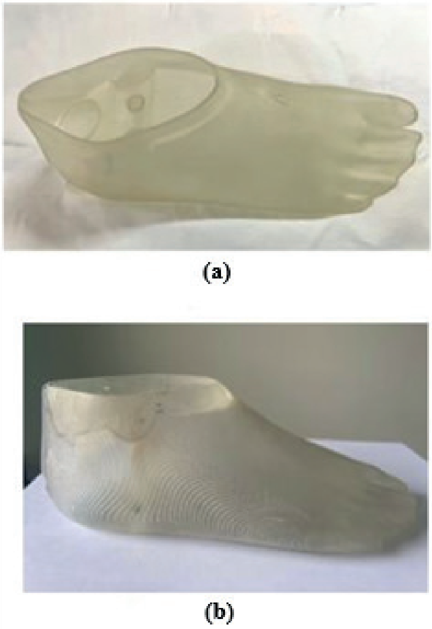

Figure 11.
PLA material prototype result,
(a) Top View, (b) Side View
Source: Author's documentation (2023)

Fatigue testing results

Fatigue testing is conducted to determine the capability of the single-axis prosthetic foot product to withstand cyclic load conditions and is customized to the human walking position. Furthermore, the starting pressure applied is 0,3 MPa on the fatigue testing machine. The fatigue safety factor (FSF) distribution is calculated using the Modified-Goodman relationship's predicted stress and mean stress values. In this test, changes in characteristics will be observed in the state before and after testing. The fatigue test process on the sole of the single-axis prosthetic foot is as shown in Figure 12.

Figure 12.
Fatigue testing process
Source: Author's documentation (2023)

Fatigue testing in the initial cycle did not show any changes. Meanwhile, at cycle 13,496, there was a slight scratch at the top joint of the center of the sole of the single-axis artificial foot. After that, at cycle 49,875, a small tear was observed on the forefoot or near the toes, shown in Figure 13. Thus, this section is the same as the simulation results of von Mises stress and strain at the toe-off loading position; there is a critical area near the toes of the artificial foot. Furthermore, at cycle 50,000, it was stopped because a crack occurred on the front of the sole of the single-axis prosthetic foot. The fatigue testing process lasted for 15 hours.

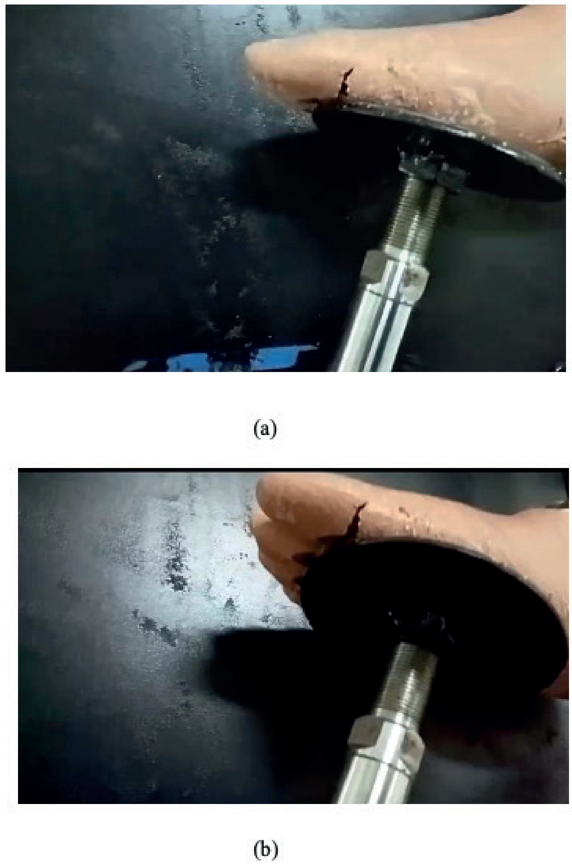

Figure 13.
Fatigue test on prototype
48.875 cles
(a) Side view, (b) bottom view
Source: Author's documentation (2023)

CONCLUSION

The results of research into the fabrication of single-axis prosthetic foot using 3D printing and resin infusion method can be concluded that the single-axis prosthetic foot with Polyurethane material can withstand simulated testing based on ISO 10328 Finite Element Method at loading levels P3, P4 and P5 as well as the three leading walking positions such as heel strike (initial contact), midstance loading and toe-off loading. However, in the deformation value results, parts of the single-axis prosthetic foot have critical points. The product or prototype of the single-axis prosthetic foot has a mass of 657 grams in compliance with the criteria of not more than 1,7% of the mass of the user's body with a hardness value of 55,5 HA. It can withstand 50.000 cycles in fatigue testing.

For future research, this research can be developed by adding variations in loading on single-axis prosthetic foot by international standards of prosthetic foot products and this research can be developed by making single-axis prosthetic foot prototypes using polymeric materials or other elastic materials that have flexible properties but can still withstand the weight of the human body.

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