3D Printed Lower-Limb Socket for Prosthetic Legs

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***Abstract*—The statistics of lower limb amputation is rising across the globe and continues to be a major threat to morbidity and mortality. In Malaysia, amputation prevalence has been increasing in which several main components of service delivering aspects should be anticipated to accommodate the increasing demand, such as service intervention and prosthetic personnel. The objectives of this project are to (i) design a lower limb socket for amputated leg according to size of residual limb, (ii) analyze the performance of the socket at different materials and (iii) fabricate the lower limb socket using 3D printing technology. Several phases of design process were conducted including product development and computational analysis and fabrication. The design stage had modeled the socket layers, which can be obtained from 3D scan or CT-scan images. The analysis stage will evaluate the performance of the product based on the material used and the set-up procedure conducted. Resulting stress and deformation were measured to propose the best design and will be fabricate using 3D printing technology by considering the best suit of material and set-up as per obtained in the analysis.**

***Index Terms*—Amputation, Lower Limb Socket, Prosthetic Leg, 3D print.**

I. INTRODUCTION

Lower-limb amputation is the removal of a part or multiple part of the lower limb. Though there is some discrepancy in literature regarding exact distal boundaries, it is generally accepted that “major” amputations include those which are at or proximal to the ankle [1]. There are a few main sites of amputation which are just below the knee or transtibial, through the knee and through the thigh or transfemoral.

After amputation process, the patients need to undergo rehabilitation for him or her to adapt with the new body condition. The goal of rehabilitation after an amputation is to help the patient return to the highest level of function and independence possible, while improving the overall quality of life in physically, emotionally, and socially. Prosthetic rehabilitation goals should be set in advance which is at the very beginning of the process and should come as a result of an agreement between the patient and the rehabilitation team members, while further pursuance of the specific goals is to be left at the discretion of experts of referent backgrounds. The goals discussed above should be set in writing and should be specific, measurable and realistic.

In respect with this, the merge between technology and medical helps to fasten the process thus help the patient to gain their confidence in no time. The 3D printing technology became widely known in biomedical and biomechanical field. From dental products to prosthetics and tissue engineering, 3D printing is also helping address some of today’s biomedical challenges [2].

Prosthetics was one of the first biomedical areas to be revolutionized by 3D printing and continues to grow as the technology becomes more advanced, making replacing limbs easier and cheaper. Hence, in this project our objectives will be firstly is to design a lower limb socket for amputated leg according to stump size. Secondly, analyze the performance of the socket at different thickness and infill settings and lastly fabricate the lower limb socket using 3D Printing technology.

II. METHODOLOGY

This project involved four main phases which are (i) the data collection and processing, (ii) product design and technology implementation, (iii) analysis and parametric study and (iv) fabrication using 3D printing technology.

A. *Data Collection and Processing*

To achieve the first objective, the process that takes place are firstly, the patient will undergo an MRI process or 3D Scanning in order to obtain perfect shape of the leg stump. After getting the results, the file will be converted into STL file. The file then uploaded into Computer Aided Design software to design the socket for the prosthetic legs. A few designs will be made to check its suitability and rendered for documentation process.

i) MRI Process

Magnetic resonance imaging (MRI) is a type of scan that uses strong magnetic fields and radio waves to produce detailed images of the inside of the body. For residual limb, ground reaction force (GRF) measurements were taken by means of two force sensors located between the bottom of the socket and the MRI's patient table, to ensure continuous load transfer through the residual limb while it was scanned by MRI at the load-bearing experimental mode. The contact pressure distribution around the residual limb was acquired before the MRI scan [3]. The process is described as in Figure 2.1 and the data processed example is described in Figure 2.2. A scheme of the imaging configuration at the open-MRI, where

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the residual limb of the subject is (a) unloaded and (b) statically loaded.

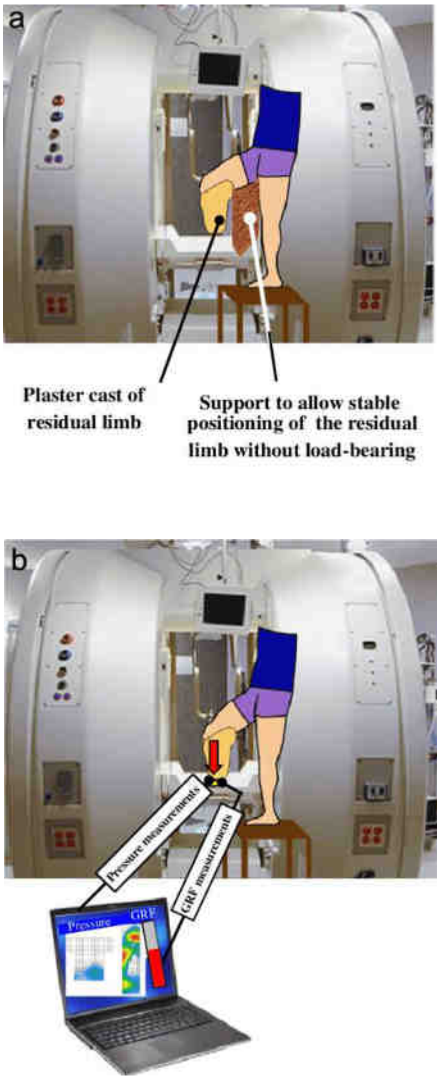

Figure 2.1 Process involved when taking MRI of residual limb

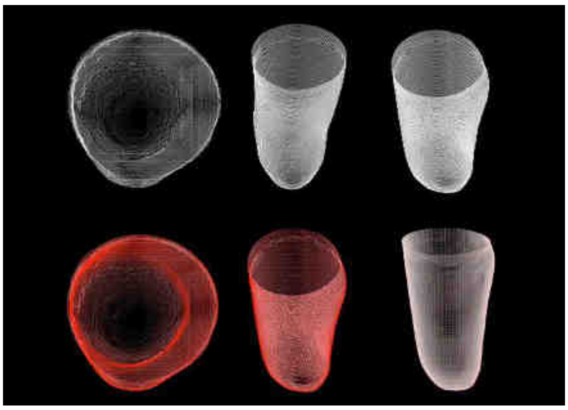

Figure 2.2 Parametric scheme of MRI digital file and ATS data collector. ATS data plotted to calculate tissue stiffness along residual limb [4]

ii) 3D Scanning

3D Scanning process was performed to configure the size and shape of residual limb. 3D laser scan technology can give quick results with high resolution. From that, the outside contour of the residual limb is viewed from different angles as shown in Figure 2.3.

Figure 2.3 3D scanning process [5]

B. Product Design and Technology Implementation

The data collected will undergo a few stages of design accordingly to the shape and size of the residual limb. There will be a few stages involved which are construction of sock layer, inner layer and outer layer

i) Sock Layer

Construction of sock layer was made as close as possible to the real shape and size of the residual limb to make it as a mold for next processes. The layer made should not overlap with the 3D model of the residual limb so that the socket will be well fitted. The thickness is 1.0 mm.

ii) Inner layer

After the sock layer is designed, the initial sketch was made accordingly to size and shape. The sketches then used as a guideline to make sure the inner layer does not overlap with sock layer. The sketch was as in Figure 2.4.

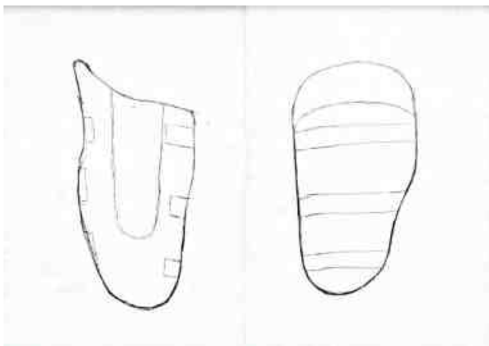

Figure 2.4 Initial sketches of the socket

iii) Outer Layer

The outer layer was designed to even out the outer surface so that the surface finishing will be better. It took quite a long time to complete this process because we want to make sure all area has almost same thickness and give a better surface finishing.

C. Analysis and Parametric Study

To achieve second objective, the final design will undergo strength analysis according to their variables which is the percentage of infill to find Von Mises Stress, stress and strain limits and total deformation. The natural frequency of the product also will be obtained. The analysis started by applying 600N load inside the socket and placed fixed support at the bottom of the socket as in Figure 2.5.

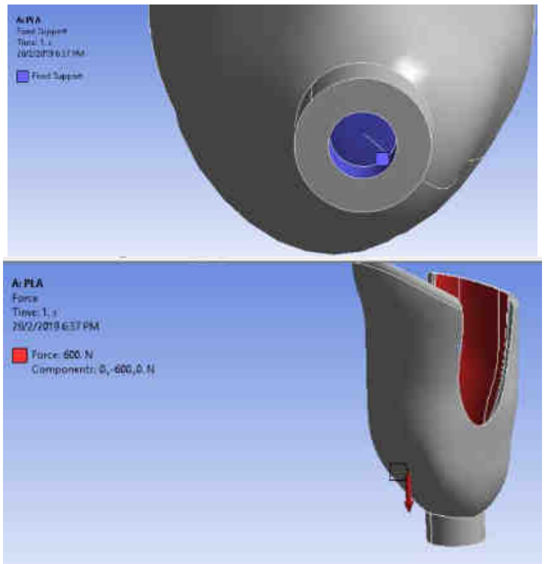

Figure 2.5 Application of load

The parameters for the 3D printing process were set as:

Thickness: 15mm
Weight of patient: 600N (60kg)
Printing Speed: 60mm/s
Layer height: 0.20 mm
Temperature: 195°C
Infill pattern: Linear
Number of shells: 2

D. Fabrication

For the last objective, the fabrication of the model will be made using 3D printer on different infill density and material to compare the strength, smoothness of surface and time taken to fabricate. Modification will be made on the design if it has printing failure or has any defects on it. The slicing process is visualized in Figure 2.6.

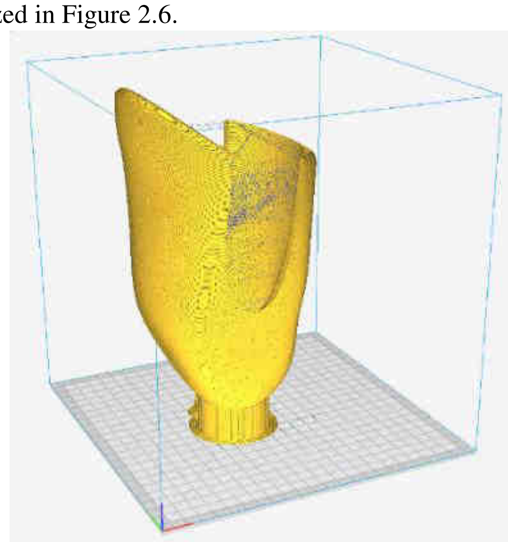

Figure 2.6 Slicing Process inside Ultimaker Cura

III. RESULTS AND DISCUSSION

Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are typical materials used when in additive manufacturing process. The material properties are as shown in Table 1 and Table 2 for PLA and ABS, respectively.

Table 1 Material properties of PLA [7]

Density	1240 kg/m³
Elastic modulus	3500 MPa
Shear modulus	1360 MPa
Poisson's ratio	0.36
Yield strength	70 MPa
Ultimate tensile strength	73 MPa
Modulus of elasticity	3750 MPa

Table 2 Material properties of ABS [7]

Density	1530 kg/m³
Elastic modulus	2600 MPa
Shear modulus	1287 MPa
Poisson's ratio	0.35
Yield strength	75 MPa
Ultimate tensile strength	22 MPa
Modulus of elasticity	2600 MPa

The PLA material show higher stiffness and stronger physical properties where it also has higher tensile strength and tensile modulus. Yet, it lacks in surface quality where it provides rougher surface compared to ABS. Yet, it can be improved with usage of cushion or gel padding inside the socket for the patient comforts and thus prevent blisters from happening.

i) Von Mises Stress

Based on the results, it is proven that PLA had higher tolerance toward force compared to ABS which was the focus of the 3D Printing of prosthetic limb socket. Figure 3.1 shows the stress distribution of the socket at isometric view for PLA and ABS materials.

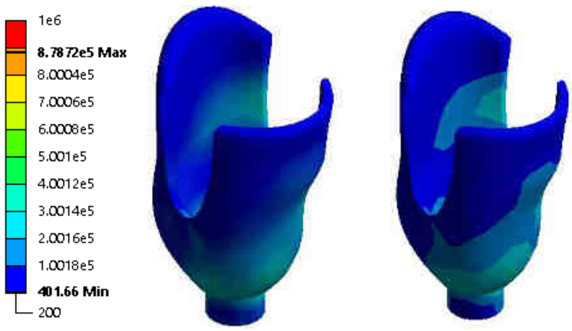

Figure 3.1 Stress distribution in the socket at Isometric view for PLA (left), ABS (right)

The variation of maximum von mises results is shown in Figure 3.2. The maximum von mises stress for PLA is 0.879MPa while for ABS is 0.877MPa. the maximum stress is compared to the yield strength of each material to suggest the best performance. In this respect, ABS socket indicate better safety factor as compared to the PLA socket. In both cases, the fracture is expected to initiated at bottom where the lower part of prosthetic leg is attached. Yet, the critical area is small which will be safe for the patient to wear it.

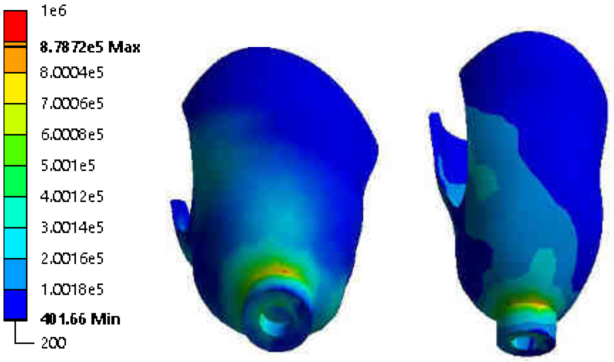

Figure 3.2 Critical Area PLA (left), ABS (right)

ii) Shear Stress

For shear stress, the maximum value for PLA is 0.4993 MPa which is higher than ABS which is 0.4991 MPa. The material properties which are the Shear Modulus shows that PLA is higher than ABS. The Figure 3.3 shows comparison of shear stress findings between PLA and ABS socket.

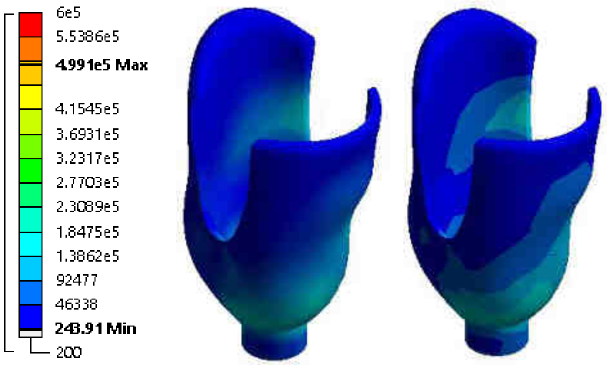

Figure 3.3 Shear stress distribution in the socket for PLA (left), ABS (right)

The critical areas are also the same which it occurs at the bottom of the socket. It happened due to the vertical loading from the load of the patient. Figure 3.4 shows the maximum value and place it occurs with comparison between PLA and ABS socket.

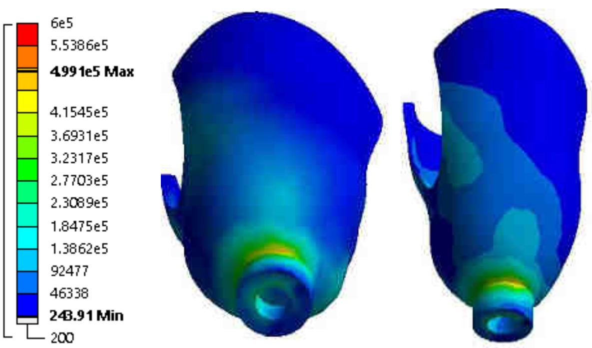

Figure 3.4 Critical Area PLA (left), ABS (right)

iii) Total Deformation & Natural Frequency

The total deformation for PLA is lower than ABS which makes the PLA is the safest and suitable material for printing the socket for prosthetic leg. The maximum deformation on PLA is 8.62×10^{-5}m while ABS is 0.000124 m. The Figure 3.5 shows findings for both socket model. The critical area occurs at the front part of the socket which the ABS has bigger critical area on the socket compared to PLA. This can be related to the modulus of elasticity for each material.

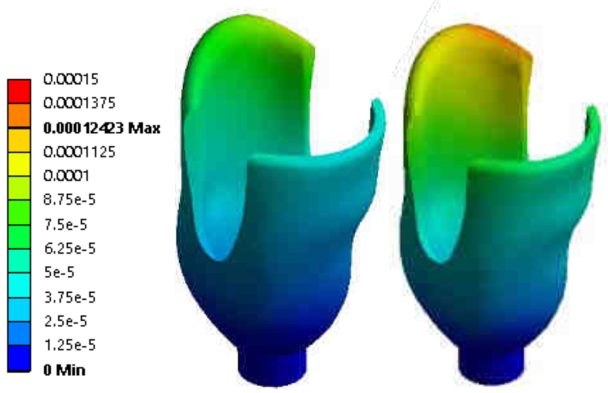

Figure 3.5 Isometric view PLA (left), ABS (right)

It is important to know the natural frequency of the design and how it behaves toward it (mode of shape). When the socket vibrates at the same level of the natural frequency of the design, it will tend to deform according the mode shape. Only the first six natural frequencies were determined from the analysis as described in Figure 3.6. At mode shape 1 which is on natural frequency level of 123.73 Hz, it shows minimal deformation or twisting at the joint around the handle. But as it increases which is on the mode shape 2 and above which is on natural frequency of 263.92 Hz, it started to show twisting and buckling at the column or the critical area. Even though the value is low, it is not to be worried as there are no rotating or vibrating producing element such as walking and running activities that could cause the socket to vibrate until the natural frequency at high level. For the normal usage of socket, it is sufficient to bear the weight of patient.

(I) Frequency 123.73 (Hz)		*(II) Frequency 263.92 (Hz)*	
(III) Frequency 290.02 (Hz)		*(IV) Frequency 364.05 (Hz)*	
	(V) Frequency 431.33 (Hz)		

Figure 3.6 Natural frequency of the socket at mode shape (I) – (V)

IV. CONCLUSION

The maximum value of Von Mises Stress was compared between PLA and ABS where PLA has the highest value which is 0.879MPa. The analysis also performed successfully which were to find Total Deformation and Shear Stress. The material that has highest total deformation is ABS which is 0.000124 m. Hence, the material that has the highest shear stress is PLA which is 0.4993 MPa. With this result, we managed to identify the differences in quality and strength of PLA and ABS and thus determine the suitable material to be used in manufacturing lower-limb socket for prosthetic leg.

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