In Silico of PLA and ABS Materials and Kinematics Analysis of 3D-Printed Transtibial Prosthetic Leg: A Patient-Specific Design

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Abstract: *Lower limb amputation is a type of physical disability associated with the loss of a lower extremity body part that has restricted mobility. Nowadays, three-dimensional (3D) printing technology gives new hope to the developer in manufacturing affordable prosthetic sockets. However, it is very limited literature on the study of suitable materials for 3D-printed sockets. Therefore, the aim of this study is to simulate 3D prosthetic socket with two different commonly used materials; polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), and later investigate the 3D-printed PLA socket via kinematics assessment. A 3D scanner was used to scan the residual limb and later the data was used design socket using computer-aided design (CAD) software. A 3D printer was utilised to print the socket using PLA filament. The material properties of Young's modulus and Poisson's Ratio have been assigned according to the material used. In addition, the boundary condition for the simulation was an axial load applied on the top surface of the residual leg to indicate the bodyweight forces, and the fixed support was applied at the foot in contact with the ground, to represent the midstance phase. For the results, the PLA materials demonstrated the lowest value of maximum stress (2.508MPa) at the socket region and the lowest displacement (1.393mm) compared to the ABS. In terms of kinematics finding, the 3D printed socket of PLA gives promising results for limb symmetry index (LSI), which is 98.42% for cadence and symmetry function (SF), which is 1.6% for stride time. In conclusion, the analysis results indicate that PLA has good potential material to be implemented in prosthetics leg socket fabrication, but it is only limited to low-level activity.*

Keywords: prosthetics leg; transtibial prosthetics; amputation, 3D socket; assistive device; finite element

1. INTRODUCTION

International Classification of Functioning, Disability and Health (ICF) stated that lower limb amputation is a type of physical disability that contributes to the impairment in body structures and consequently restricts the involvement in many activities [1]. The main causes of defined amputation are Diabetes Mellitus (DM), Peripheral Vascular Disease (PVD), and trauma [2]. In fact, Varma et al [3] in their study revealed that there is a high trend of lower limb amputations due to DM complications and the most common amputation level is the transtibial amputation. The amputation will bring negative impacts to the affected patients such as a disability in physical functionality and performance, social interaction, vitality, and general health [4, 5]. The World Health Organization [1] reported that the percentage of disabled people in low and middle-income countries who have access to any rehabilitation or assistive services is only 5-15%. A study conducted by Razak et al. [6] on 37 lower limb amputees in a single region in Malaysia found that 58% disabled people used prosthesis devices. This indicated that many disabled people are still not using proper devices for rehabilitation and daily activities and none of literature reported the reason behind it. As far as author's aware, there are several factors that will be considered for using a prosthetics leg such as comfortability, ease of use in donning and removing, lightweight, durable, aesthetically pleasing, well-functioning, and minimal maintenance requirement [7, 8]. To achieve that, it involves a higher cost of manufacturing and results in a financial burden to the amputees.

The current widely used method of fabrication is tedious and time-consuming [6, 9]. The amputees need to wait for a long period to obtain the fitted prosthetic. Besides, it will require the certified prosthetics and orthoptist to conduct all the manual procedures to fabricate the prosthetics leg. According to Ariffin et al. [10], there is limited access to certified prosthetics and orthoptist in Malaysia as most of them resided in West Malaysia. The amputees in other regions may face difficulty in getting the prosthetics leg and result in inhibition in their rehabilitation progress. The manual process includes many steps like creating the positive cast around the residual leg of the patient for the socket, continue by filling the negative impression with a plaster mixture of Plaster of Paris (PoP) and adding different material at the residual leg [9, 11]. To overcome the problem, advanced technology which is automatic scanning using a three-dimensional (3D) scanner could be utilized to create a customize socket of prosthetics leg according to the personalized configuration and structures of the amputee's residual leg [12-14]. In this case, 3D printing technology have been suggested for the fabrication of the prosthetics leg. The material selection for 3D printing will also be cost-effective and affordable. In fact, the process will be more efficient and less time-consuming as engineers will use a computer-aided design (CAD) software during the design process [14]. However, there are limited literature on the study of different materials of 3D printing filament for prosthetics leg design and socket. Apart from that, there is very limited resources of study on the kinematics behaviour of 3D printed prosthetics leg [15]. Then researchers and users could not justify the best materials for the prosthetics leg socket. Therefore, this study was proposed to evaluate the performance of different materials of polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) for the application of 3D printed prosthetics leg socket. The results from here are not only for the sake of design improvement, but it may contribute enough for researchers and industry players to choose the best materials for prosthetics leg socket when they consider 3D printing technology to develop the product.

2. MATERIALS AND METHODS

2.1 Patient Recruitment

In this study, all procedure and protocol have been approved by UTM Research Ethics Committee with an approval number UTMREC-2023-24. A volunteer transtibial amputee (gender: male, age: 52 years old, limb: transtibial residual limb) was recruited in this study. The volunteer has read all the protocols and agreed to contribute to this study where a consent form have been signed before the study begin.

2.2 Three-Dimensional Scanning and Modelling

The first process was the image acquisition from a subject who had undergone below-knee amputation on the right leg. A Sense three-dimensional (3D) scanner (3D Systems) had been used to record the topology of the subject's residual limb. The 3D scanning technology can configure the size and shape of the patient's leg stump perfectly and invasively [16]. Fig. 1(a) shows the raw data of the subject's leg from the 3D scanner machine. For the 3D modelling, it was started with importing the raw data into Computer-Aided Design (CAD) software, Autodesk Meshmixer. In the software, a custom-fit socket had been designed with reference to the exact size and shape of the residual leg. The dimension of the socket was fixed based on the dimension of the stump and the offset of 2 mm had been applied between the interface of the socket and the residual leg. In the final design of socket as shown in Fig. 1(b), the thickness was 5 mm. Next, the socket design was then imported into the SolidWorks software (Dassault, USA) to further design the socket base and socket-pylon adaptor [8]. The adaptor was used to connect between the socket and pylon. From here, the adaptor was designed as one single body with the socket and attached to the socket base. For the socket base, the diameter was set at 8mm as shown in Fig. 1(c).

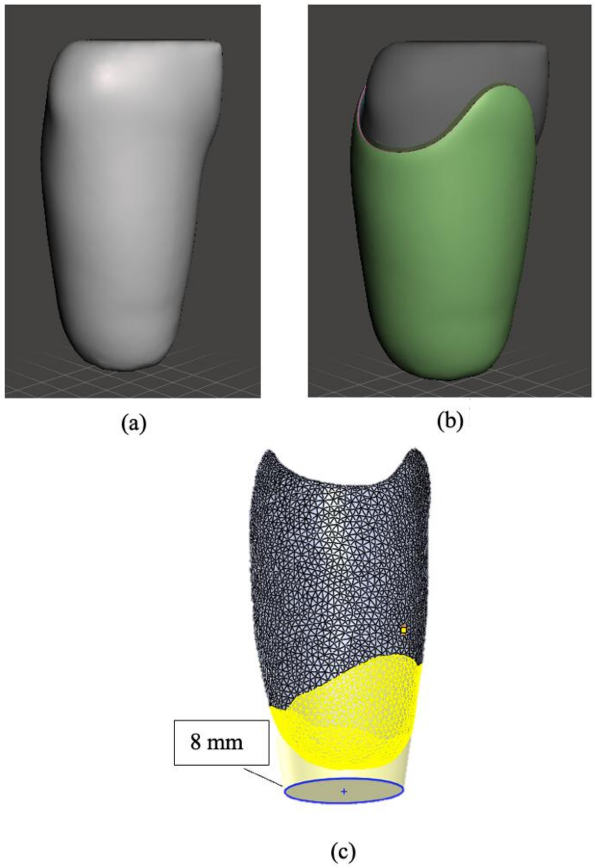

Fig. 1. The 3D model of (a) raw data of residual limb, (b) prosthetics leg socket (green), and (c) prosthetics leg socket with 8mm base thickness.

2.3 Assemble and Alignment

The socket, adaptor, pylon and foot were then assembled and aligned together to complete the prosthetics leg model before analysis (Fig. 2(a)). The components have been imported into the CAD software using the stereolithography (STL) file. A total of four bodies for the alignment; the residual leg, the socket, the pylon and pylon-foot adaptor and foot have been merged in the software [12]. Each of them was aligned properly to avoid the overlapping surface between the components.

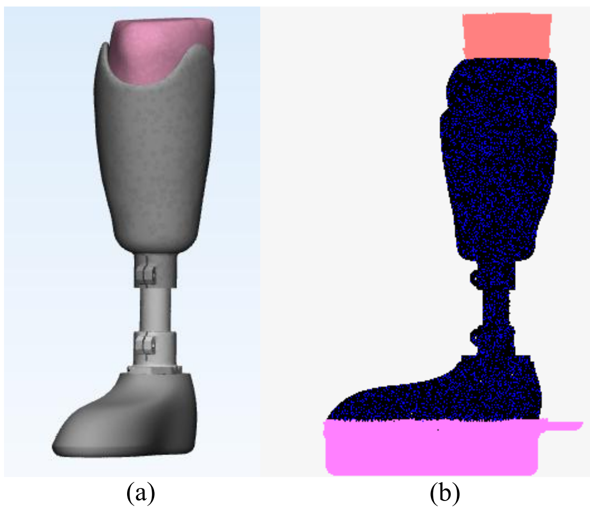

Fig. 2. Complete set of (a) 3D model of prosthetics leg and (b) boundary condition of finite element analysis.

2.4 Finite Element Analysis

The biomechanical analysis of the transtibial prosthetics leg had been conducted in the Marc. Mentat (MSC. Software, Santa Ana, CA) software [17]. Firstly, the material properties of the different bodies have been categorised. The customised transtibial prosthetics leg has four bodies: the residual leg, the socket, the pylon, and the foot. For the simulation, the properties of the material that need to be considered are the Young's Modulus and the Poisson's Ratio. The material properties of the residual leg and the foot has been kept constant throughout the analysis which is the skin and the polyurethane respectively. On the other hand, the material properties for the socket and the pylon are between the PLA and ABS interchangeably. All the material properties were set as homogeneous, isotropic, and linear elastic. The mechanical properties of each material had been presented in Table 1. From the finite element analysis (FEA), parameter of stress distribution and displacement were recorded and analysed.

Table 1. Material properties for different materials simulated in the finite element analysis

Properties	Material	Value
Young's Modulus	PLA	3500 MPa [12]
	ABS	2600 MPa [12]
	Polyurethane	1600 MPa [18]
	Skin	20 MPa [18]
Poisson Ratio	PLA	0.36 [12]
	ABS	0.35 [12]
	Polyurethane	0.4 [18]
	Skin	0.48 [18]

Secondly, the essential aspect of the FEA is the boundary condition. The boundary condition had been divided into the load and the fixed displacement as shown in Fig. 2(b). The type of load used in this study was the axial load as demonstrated by other study [14]. For all the simulations, the load was applied similarly which is normal towards the surface of the residual leg cut in the transverse plane to indicate the body weight. The bodyweight of the subject for this study was 70 kg, where it is equivalent to 700N. During the simulation, half of the body weight was used to indicate the subject is standing and it was assumed at the midstance phase [19]. In addition, the parameter used in the simulation for the axial load is the pressure, then the pressure was obtained by dividing the load (N) with the surface area (mm^2) of the top surface at the residual leg. For the fixed displacement, it has been positioned at the whole area of the foot sole when the subject was assumed at the midstance phase. The geometric properties of all the bodies had been set as solid body during the simulation and the contact type between the bodies has been set as glued. At the end of the simulation, the parameters of equivalent von Mises stress and displacement were observed and recorded.

2.5 Three-Dimensional Printing and Assembling

The Ender 5 Plus (Creality, Shenzhen, China) in Fig. 3(a) was used to print the model of prosthetics socket where PLA material was chosen for the filament. The choice of PLA is based on the FEA results showed better performance in terms of stress distribution and displacement, as compared to the ABS material. Before the printing procedure, the stereolithography (STL) file format of the socket was first imported into Ultimaker Cura software (version 5.10) for a slicing purpose. In this software, the parameters of layer height, line width and infill density were set as 0.2 mm, 0.56 mm and 30%, respectively. Other parameters were set as a default setting. Once the model was sliced, then the file in g.code format was then imported into the Ender 5 Plus (Figure 3(a)) for printing. The time taken for printing the prosthetic socket was 35 hours and 27 minutes. The model was 3D-printed without considering the additional support since the bottom of the socket was perfectly touched the printing bed, and no other hanging/floating features from the design.

In the assembling process, other components such as socket adapter, pylon, foot adapter, and foot were assembled. These components were resources from local prosthetics and orthotics service providers. Later, the assembled part was fixed with the 3D printed socket according to the subject's leg alignment and height as shown in Fig. 3(b).

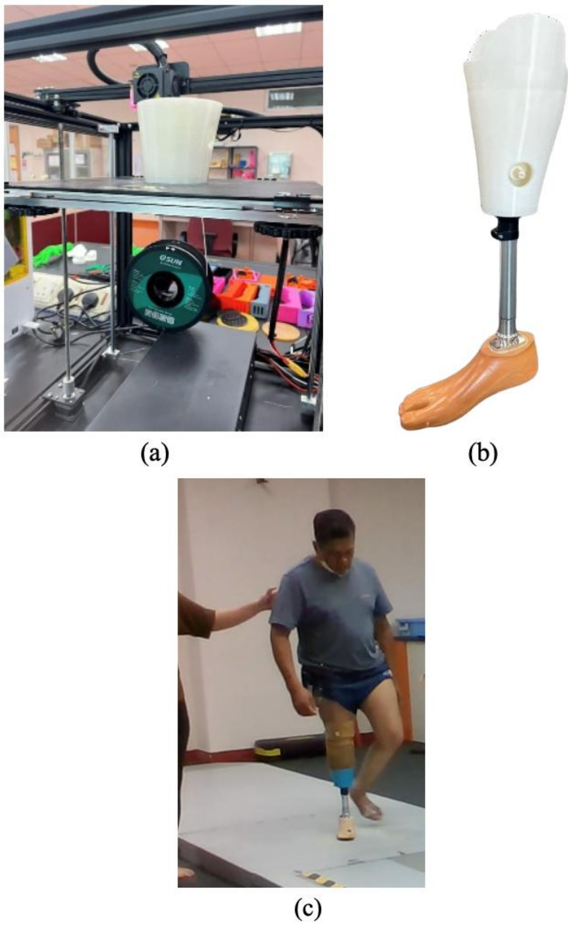

Fig. 3. A flow that illustrated the process of thermal imaging assessment

2.6 Kinematics Analysis

The same subject as reported in 3D scanning process section was agreed to participate in the kinematics study. A total of six (6) infrared (IR) or optoelectronic cameras (Vicon Motion Capture systems) was used to detect the movement of the subject while wearing the prosthetics leg during walking condition. In the data requisition, two trials were recorded for walking from starting to ending point. Figure 3(c) shows the subject was walking on the platform during the kinematics analysis. From the kinematics analysis, parameter of cadence, stride time, stride length, step length and walking speed were recorded for both intact and prosthetic limb. Later, the Limb Symmetry Index (LSI) and Symmetry Function (SF) were calculated for comparison between both limbs.

3. RESULT AND DISCUSSION

3.1 Von Mises Stress

The stress contour band for each component is observed separately by arranging the contour bands in the same manner as shown in Fig. 4.

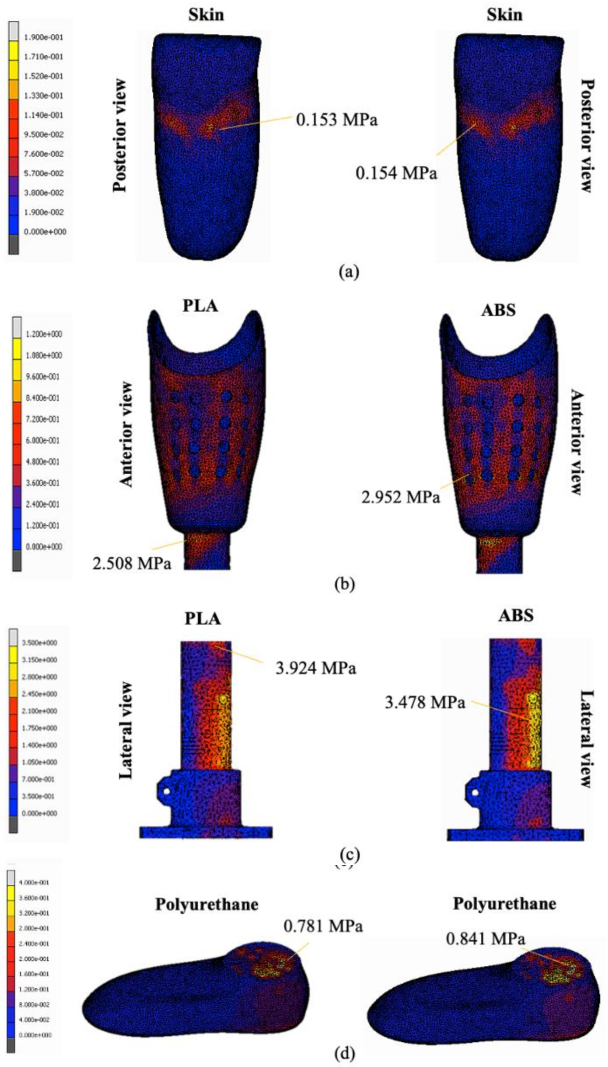

Fig. 4. Stress distribution and peak stress at the (a) skin, (b) socket, (c) pylon and (d) foot of the model.

The maximum stress location on the bodies had been marked for easier comparison between the two different materials. For easy comprehension, the first analysis is referring to the analysis with PLA materials at the pylon and socket while the second analysis is referred to as ABS materials applied also at the pylon and socket. The peak stress on both residual leg (Fig. 4(a)) has shown a similar peak stress value since they have the same properties of the skin. Next, a lower value of peak stress is detected at the adaptor region of the PLA socket as shown in Fig. 4(b) (2.508 MPa) while higher peak stress is observed in the ABS socket (2.952 MPa) at the posterior area. In contrast, a higher value of max stress is experienced by the PLA pylon as shown in Fig. 4(c) (3.924 MPa) at the top surface while a lower value of max stress is detected at the middle region of ABS pylon (3.478 MPa). Lastly, both foot (Fig. 4(d)) had shown a high concentration of stress at 0.781 MPa for the first analysis and 0.841 MPa for the second analysis. Based on the above findings, it is found that the stresses are not exceeding the yield strength of that materials, where this indicating that the design and model are safe in mechanical environment.

3.2 Displacement

Fig. 5 below illustrates the contour bands of overall displacement distribution on the prosthetic leg for two different materials. It should note that the PLA materials have a lower maximum displacement at 1.393 mm located at the top of the residual leg while the ABS has a higher maximum displacement of 1.769 mm at the same region. In fact, the displacement distribution for all the socket materials had shown a similar pattern where the maximum displacement was detected at the top region of the residual leg.

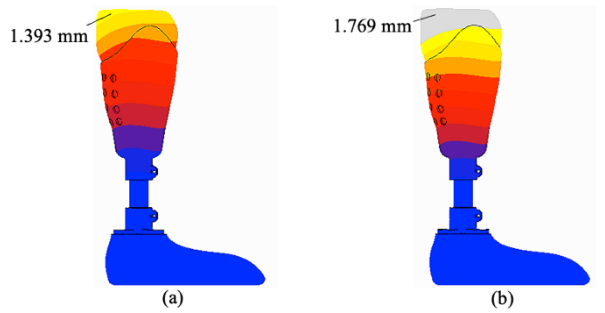

Fig. 5. Displacement contour plot and maximum displacement in the model with (a) PLA and (b) ABS materials.

As demonstrated in this study (Fig. 5), the PLA has shown much lower deformation than the ABS, hence the PLA is indicating better tolerance towards the stress applied and will be less likely to deform. Furthermore, the overall magnitude of von Mises stress for the PLA material results proves that all the components provide adequate strength since the value is below the yield strength [20].

3.3 Limb Symmetry Index (LSI) and Symmetry Function (SF)

The Limb Symmetry Index (LSI) is the ratio performance between left and right side of leg to determine the inconsistency of the lower limb including function, mobility and strength. Next, the symmetry function (SF) used to compare time coursesand detect the asymmetry or symmetry of human motion at specific region. Based on the literature study, most of the contemporary protocol require more than 90% of limb symmetry index for intact andprosthetic limb [15].

Table 2 shows the spatiotemporal results for the intact and prosthetic limb. The range for the healthy people in walking speed range from 1.20m/s to 1.40m/s [21] while amputees with transtibial amputations who have an average walking speed of 1.20 m/s when walking at a normal rate [22]. The amputee has slow walking speed as the asymmetry involve at both prosthetic and intact limb. From the table, it is shows that the stride time for prosthetic leg is 1.26s in which 0.02s slow than the intact limb. LSI in 3D prosthetic leg shows more than 90% in cadence, stride time and stride length.

Table 2. Spatiotemporal results for the intact and prosthetic limb; Limb Symmetry Index (LSI) and Symmetry Function (SF).

Parameter	Intact Limb	Prosthetic Limb	LSI (%)	SF (%)
Cadence (steps/min)	96.77	95.24	98.42	-1.60
Stride Time (s)	1.24	1.26	101.61	1.60
Stride Length (m)	0.90	0.81	90	-10.53
Step Length (m)	0.46	0.39	84.78	-16.47
Walking Speed (m/s)	0.73	0.64	87.67	-13.14

Several limitations have been considered to conduct this study. First and foremost, only one volunteer was recruited in this study. To obtain more comprehensive results, the study should include more volunteers as suggested by other studies [23, 24]. Secondly, the simulation was done for only two different materials (PLA and ABS). It is suggested that more assessment on many materials should be done in the nearest future. Nevertheless, the two materials were chosen in this study due to the fact that both are not only commonly used in the literature, but they are lightweight material and easy to print as compared to other filaments [18, 19]. Next is the activity during the kinematics assessment, where there was only walking condition in this study. It is good to highlight that by combining many activities, such as running, climbing and cycling could enrich the knowledge in the future [25].

4. CONCLUSION

It is concluded that the study achieved the main objective of the research where the finite element analysis found that PLA material showed the best option for prosthetics leg socket, meanwhile the results of LSI and SF show promising outcome when it comes with PLA socket in kinematics assessment. From this study, it could suggest that 3D-printed prosthetic socket with PLA material is becoming a potential replacement to that of conventional polypropylene material in the nearest future. However, further study needs to be conducted to mechanically evaluate the 3D-printed socket in laboratory environments.

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