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Analysis and Evaluation of Optimized Lower Limb Prosthetic Device

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Abstract. Transtibial prosthetic devices or below-knee prosthetic devices are used as assistive devices in replacing the part of the leg below the knee joint in case of amputation. The different builds in amputees require the need for the accessibility to custom-made lucrative prosthetic devices in order to reintegrate the amputees into society. The goal of this study is to design a personalized transtibial prosthetic device that closely mimics the human gait by the use of topology optimization. Additive manufacturing is used to reduce the fabrication time of a traditional transtibial prosthetic device. The creation of the transtibial prosthetic device model is through computer-aided drawing (CAD) and afterwards simulated using ANSYS for the comparison and contrasting of the optimized design. The materials used in the design of the transtibial prosthetic device are polypropylene and titanium alloy. Simulation works reveal that there is a 12.8% reduction in the minimum equivalent (von-Mises) stress and a 51.29% reduction in the minimum equivalent elastic strain of the benchmark socket, and titanium alloy is the superior material in the fabrication of prosthetic foot as it greatly reduced the total deformation, equivalent (von-Mises) stress and equivalent elastic strain of the SACH foot as compared to polypropylene in the initial contact, midstance and the push-off phases of the gait cycle. Topology optimization of both the socket and foot models reduced the stiffness and density of material volume up to 60%. Voronoi pattern developed on the socket and foot models mirrors the reduction done on material volume by topology optimization.

1. Introduction

A prosthetic device, or a prosthesis, is defined as an artificial substitute for a part of a body that is damaged or lost. Statistically, it is found that 30 million people internationally depend upon prosthetic limbs to execute their day-to-day tasks [1-2]. It is found that there are two leading causes that result in the need for amputations [3]. Firstly, vascular diseases and diabetes. Secondly, a wound caused by an external force, or a trauma [4-5]. All segments of the prosthetic device perform an important part in order to mimic the immensely complex mechanisms of a natural leg. The shear force acting on the residual limb and the metabolic expenditure of the patient is reduced with a lightweight lower-limb prosthetic device [1]. Therefore, it is crucial that the optimal design and material used in the fabrication of transtibial prosthetic device is determined. Customization and the optimization of the transtibial prosthetic device would reduce the costs of its manufacturing while providing comfort to the users. This could be achieved by integrating topology optimization and additive manufacturing.



Topology optimization is a structural optimization method where the specification of design factors allows for a prediction of a material and load distribution. Topology optimization recommends the best material distribution by continuous iterative calculations based on specified constraints and preserve regions in order to attain excellent structural performance. Topology optimization is an optimization method that allows users to define loads and supports on a volume of material which in areas where stresses are not applied are henceforth reduced in stiffness and density [6]. The optimal structure of a solid is found through this process as the shape is often times organic and counterintuitive.

Additive manufacturing is a technology that builds three-dimensional (3D) objects by adding material layer by layer according to a pre-determined path. Additive manufacturing has the capability to produce more complex components compared to traditional manufacturing processes like milling and casting. In additive manufacturing, an object is first designed in computer-aided drawing (CAD) software like Inventor, Catia and SolidWorks. The CAD file is then converted into a Standard Triangle Language (.STL) file, which is the standard used in the industry.

2. Methodology

The optimisation of the socket and foot of transtibial prosthetic device, where the optimisation of socket is focused on its design and the optimization of the foot of transtibial prosthetic is done by altering its design as well as finding the optimal material to be used in its fabrication. Captured data of a transtibial prosthetic device is used to create a standard model of the socket and foot using CATIA and Autodesk Fusion 360. This would be the benchmark for the comparison of stresses in the designing of an optimised model of socket and foot prosthesis. The dimensions and material of this benchmark model uses the patellar-tendon bearing (PTB) socket [7-9] and the Otto Bock solid ankle cushion heel (SACH) foot [10-12].

Optimized designs of both the socket and the foot are drawn as three-dimensional (3D) drawings using computer-aided drawing (CAD) programs, which are CATIA and Autodesk Fusion 360. These drawing are exported as (.stl) and (.stp) files in order to be used in simulation work using ANSYS. Simulation work is done using ANSYS software, where a load of 600 N is applied to all models of the socket and foot prosthesis. Cylindrical and fixed support were specified at positions where the models would be attached to the pylon. ANSYS runs multiple iterations in order to simulate stresses like total deformation, equivalent (von-Mises) stress and equivalent elastic strain. The results of these structural analyses are then fed into topology optimization [6][13] module, emphasis is on regions where stresses occurred and other regions are excluded in order to reduce the structure volume and density. Lastly, the result of the topology optimization analysis is then reflected on the generated Voronoi pattern models [14] that is done using Autodesk Meshmixer. Prior to generating this pattern, refinement and reduction of mesh is made by using the sculpt function in Meshmixer. This step is done by referring to the topology optimization and refining mesh at structurally critical areas and reducing the mesh, which increases the mesh dimension at lesser critical areas. These Voronoi patterned models are then ready to be fabricated by 3D printing.

3. Results & Discussion

The optimisation of the socket of the transtibial prosthetic device is mainly focused on its design, keeping the material of the socket the same as the standard, which is polypropylene.

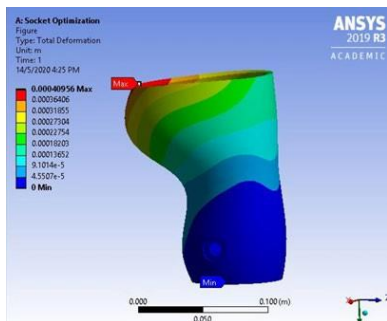


Figure 1. Total deformation of standard PTB socket.

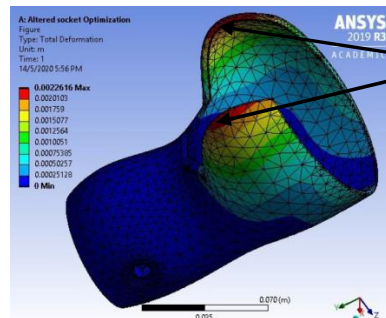


Figure 2. Total deformation of optimized socket.

A load of 600 N is applied on the inner part of the socket and support is defined at the hole area where pins would be located in the donning of the transtibial prosthetic device. The comparison between the benchmark model and the optimized model can be seen in the structural analysis results in Figure 1 to Figure 6.

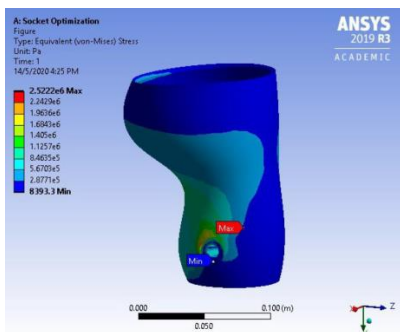


Figure 3. Equivalent (von-Mises) stress of standard PTB socket.

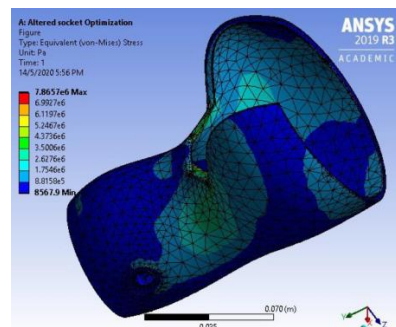


Figure 4. Equivalent (von-Mises) stress of optimized socket.

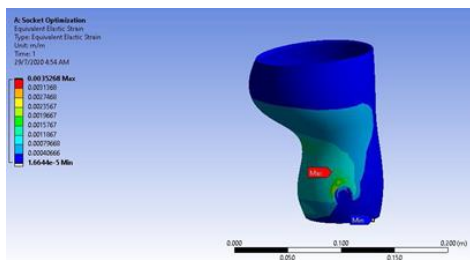


Figure 5. Equivalent elastic strain of standard PTB socket.

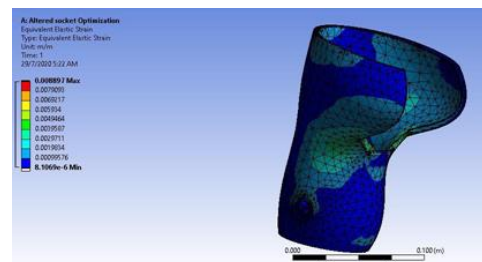


Figure 6. Equivalent elastic strain of optimized socket.

Table 1. Comparison of structural analysis between standard socket design and optimized socket design.

	Standard socket		Optimized socket	
Total deformation (m)	Min.	0	Min.	0
	Max.	0.40961×10^{-3}	Max.	2.261×10^{-3}
Equivalent (von-Mises) stress (Pa)	Min.	8378.5	Min.	7303.1
	Max.	2.5201×10^6	Max.	8.0133×10^6
Equivalent elastic strain (m/m)	Min.	16.644×10^{-6}	Min.	8.1069×10^{-6}
	Max.	3.5268×10^{-3}	Max.	8.897×10^{-3}

From Table 4, it can be noted that the optimized socket model has a larger maximum total deformation as compared to the standard socket design, which is 2.261×10^{-3} and occurred at the near region as shown in Figure 2. This need to be reinforced during the design of a new socket. The Voronoi pattern generated on the optimized socket in Figure 7 to Figure 9 reflects the topology optimisation done on it using ANSYS.



Figure 7. Voronoi pattern of optimized socket (Side view).

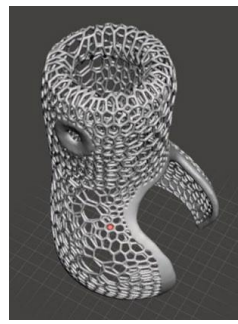


Figure 8. Voronoi pattern of optimized socket (Isometric view).



Figure 9. Voronoi pattern of optimized socket (Back view).

The optimization of the transtibial prosthetic foot is done by altering the design of the foot and finding the optimal material to be used in its fabrication. The structural analysis done on the foot models where the benchmark foot model has an interface plate made of maple hardwood and a cushion heel made of polyurethane foam [10][12], and the optimized foot model is set to be made of titanium alloy and polypropylene [11][15]. A load of 600 N is applied on all foot models and the directions force determines the walking phase that the foot is in, whether it is going through heel strike, standing, or toe off phase [16]. The results of the structural analyses of the foot models can be seen in Figure 10 to Figure 12.

Table 2. Comparison of structural analysis between foot models during heel strike.

	Standard SACH foot		Optimized foot (Polypropylene)		Optimized foot (Titanium alloy)	
Total deformation (m)	Min.	0	Min.	0	Min.	0
	Max.	6.8834×10^{-3}	Max.	18.081×10^{-3}	Max.	0.18476×10^{-3}
Equivalent elastic strain (m/m)	Min.	1.5896×10^{-6}	Min.	1.0447×10^{-8}	Min.	7.2632×10^{-11}
	Max.	8.533×10^{-3}	Max.	37.442×10^{-3}	Max.	0.32539×10^{-3}
Equivalent (von-Mises) stress (Pa)	Min.	14.109	Min.	8.1868	Min.	6.0938
	Max.	5.3272×10^7	Max.	1.6142×10^7	Max.	1.6175×10^7

Table 3. Comparison of structural analysis between foot models during standing phase.

		Standard SACH foot	Optimized foot (Polypropylene)	Optimized foot (Titanium alloy)
Total deformation (m)	Min.	0	Min. 0	Min. 0
	Max.	6.8834×10^{-3}	Max. 74.765×10^{-3}	Max. 0.7496×10^{-3}
Equivalent elastic strain (m/m)	Min.	1.5896×10^{-6}	Min. 4.8616×10^{-6}	Min. 0.03641×10^{-6}
	Max.	8.553×10^{-3}	Max. 37.442×10^{-3}	Max. 0.32539×10^{-3}
Equivalent (von-Mises) stress (Pa)	Min.	14.109	Min. 3230.9	Min. 1940.1
	Max.	5.3272×10^7	Max. 3.3822×10^7	Max. 3.086×10^7

Table 4. Comparison of structural analysis between foot models during toe off.

		Standard SACH foot	Optimized foot (Polypropylene)	Optimized foot (Titanium alloy)
Total deformation (m)	Min.	0	Min. 0	Min. 0
	Max.	6.8839×10^{-3}	Max. 108.08×10^{-3}	Max. 1.0847×10^{-3}
Equivalent elastic strain (m/m)	Min.	1.188×10^{-6}	Min. 6.2949×10^{-6}	Min. 0.034627×10^{-6}
	Max.	8.5909×10^{-3}	Max. 58.05×10^{-3}	Max. 0.50576×10^{-3}
Equivalent (von-Mises) stress (Pa)	Min.	14.159	Min. 1766.9	Min. 1696.7
	Max.	5.3743×10^7	Max. 5.2448×10^7	Max. 4.7977×10^7

The Voronoi pattern generated on the optimized foot below reflects the topology optimization done on the optimized foot model using ANSYS.

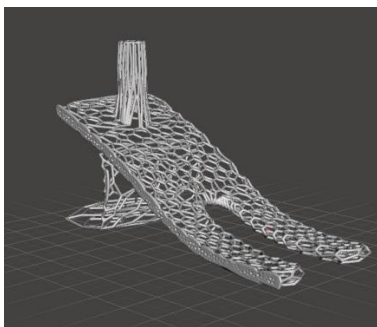


Figure 10. Voronoi pattern of optimized foot model (Isometric view).

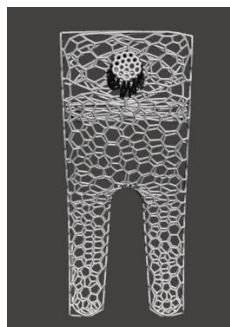


Figure 11. Voronoi pattern of optimized foot model (Top view).

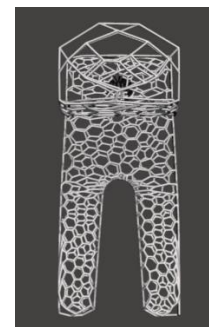


Figure 12. Voronoi pattern of optimized foot model (Bottom view).

4. Conclusion

From the comparison made in the socket model simulations, the design needs further alterations in order to achieve the optimal structure that would further reduce cost and time of the fabrication of transtibial prosthetic device. The comparison in the foot models however, shows that the titanium alloy optimized

foot has greatly reduced the prosthetic foot's stresses. This can be proven by further testing the models using experimental methods.

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