“Design, Topology Optimization and Analysis of Prosthetic Foot Manufactured by 3D Printing”

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Abstract: The scope of the work is to design, develop and analyze Prosthetic foot made by using additive manufacturing technique, it also deals with the complete design process of a motion prosthetic foot manufactured by using Poly lactic acid (PLA) material. Along with the fabrication process we also tried to minimize the weight of prosthetic foot by applying topology optimization from ANSYS Workbench. The topology optimized model is printed using a 3D printer. In order to validate the structure many elemental analysis and experiments conducted on the structure. As the weight of the prosthetic directly affects the mobility of patients, the foot should be optimized to weigh on the lesser side. So, by doing what is necessary the weight should be reduced while the structure maintained at a high strength.

Index Terms - *3D printing, FDM technique, Poly Lactic Acid (PLA), Foot prosthetic, FEA, Topology optimization.*

I. INTRODUCTION

Healthy feet are important for comfort, mobility and balance as they Provide contact to the ground, shock absorption and stability during stance, then influencing gait biomechanics by its shape and stiffness. That is because of the trajectory of the centre of pressure (COP) and the angle of the ground reaction forces are based on the shape and stiffness of the foot and needs to match the subject's build in order to produce a normal gait pattern. So, it is obvious that any injury or ill effect to it makes big impact on a persons’ day to day activities. Prosthetic implants replace a missing body part, which may be lost through trauma, disease, or a congenital disorder, restoring the normal functions of the missing body part. Commercially available passive foot prostheses made of either carbon or glass fiber reinforced composites, which are able to store and return a sufficient amount of energy to provide propulsion. Developments in additive manufacturing techniques makes it possible to design 3D-printable foot prostheses having properties of passive feet. Its geometric freedom makes it possible to maximize strength and minimize weight.

When walking, individuals subconsciously use many different control algorithms and compensatory mechanisms in order to walk efficiently. Even after decades of research, many of the control patterns applied during ambulation remain superficially understood. Further adding to the complexity of the problem, gait patterns vary significantly for each individual. However, one identical aspect is minimization of the metabolic cost of walking. The gait cycle starts when one foot makes contact with the ground and ends when the same foot contacts the ground again.[3]

In prosthetic industry, additive manufacturing is still a new dawn and a lot of research is going on in biomechanics, wearable devices, advance prosthetic limbs, bionics etc. This is an experiment to design a light-weight prosthetic foot for low to medium level amputees using advances in additive manufacturing technique.

Designing, analyzing and developing a topology optimized foot prosthetic for amputees which will be easy to manufacture and cost effective; designed by using CAD software, analyzed by Finite Element method, topology optimized by best suited method and made with the help of additive manufacturing for reduction in weight of the component and the cost.

1.1 Additive Manufacturing

Additive Manufacturing refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. Additive Manufacturing techniques are now being used increasingly in Series Production. It gives Original Equipment Manufacturers (OEMs) in different sectors of industry the chance to create a distinctive profile for themselves based on new customer benefits, cost-saving potential and the ability to meet sustainability goals. It uses data computer-aided-design (CAD) software or 3D object scanners to direct hardware to deposit material, layer upon layer, in precise geometric shapes. The FDM (Fused Deposition Modeling) technology has a number of benefits. The geometric freedom of the additive technology makes it possible to maximize strength and minimize weight. The freedom with respect to geometry of the part provided by 3D printing helps customize prostheses to meet the varying needs of patients. The CAD models are adjustable after testing with amputees, based on their feedback. Using this method an optimal geometry can be created for low-volume production or for individual custom prosthetic. The PLA filament plastic with good mechanical properties is used for fabrication purpose.

The PLA (Poly Lactic Acid) material filament plastic with good mechanical properties is used for fabrication purpose. Overall, we can ease out the majority amputees with prosthetics using these techniques with reduced costs [2]

II. METHODOLOGY

2.1 Topology Optimization

Topology optimization is an approach that determines the best material distribution in a given design domain that can minimize a given cost function while satisfying a series of constraints. In topology optimization, the design domain is modelled using finite elements. The material property (e.g., Young’s modulus or cross-sectional dimensions) of each finite element is controlled. If the material in a certain region needs to be removed, then the corresponding material property will approach zero. Methods that use link/beam elements to discretize the candidate design domain are classified as discretization topology optimization methods. Topology optimization that is performed based on continuum discretization (e.g., bilinear quadrilateral element) is classified as continuum topology optimization.

Topology optimization is used to make design even better with same characteristics. It is design optimization formulations that allow for the prediction of the lay-out of a structural and mechanical system. That is, the topology or "landscape" of the structure should be an outcome of the procedure. In principle, the result of a topology optimization procedure is also optimal with respect to size and shape, but it is here essential to note that fundamental differences in the design parameterization means that direct comparisons are difficult in practice. Moreover, topology optimization is often restricted to design situations with a moderate number of constraints. One should always consider topology optimization as a companion discipline that provides the user with new types of designs that may be processed directly or which may be further refined using size and shape optimization [1].

Ole Sigmund in their paper presented a method for optimal design of compliant mechanism topologies. It is demonstrated that the maximum stress in a compliant mechanism can be controlled by introducing a displacement constraint at the input port. It is shown that the optimal compliant mechanism topology is highly dependent on the work task considered [8].

2.2 Finite Element Analysis

Finite element analysis is a computational tool that allows for displacement and stresses to be calculated for a complex shape. This technique creates a finite element, or mesh where the individual elements can vary in size and shape. An FEA model contains information regarding the complex shape's geometry, material properties assigned to the shape, magnitude and direction of forces being applied to the shape, and constraints or fixtures of the complex shape. This information is needed to determine the displacement and stresses that occur when external forces are applied to the complex shape. The nodes of the elements found within the mesh represent the corners of the finite elements. Each of these nodes in a structural problem exhibits 6 degrees of freedom, translations in three directions and rotations about these three directions. Most nodes in the mesh are unconstrained, with the fixtures of the shape being the only elements that are constrained. These fixtures are known as the boundary conditions. The finite element analysis software then solves for all of the unknown nodes. A three-dimensional finite element consists of at least four nodes which do not lie in the same plane. The three possible finite elements in a three-dimensional analysis are the tetrahedron, pentahedron, and hexahedron. When hundreds or thousands of these finite elements are required to represent complex shapes, hundreds or thousands of unknowns and equations are created. Computer finite element software arranges these unknowns and equations into a matrix, and perform the iterative process of solving for the unknowns to determine the displacements at every node in the complex shape.

2.3 Mechanism compliances:

The mechanical systems related to compliant mechanisms uses a flexible or elements with large-displacement, opposing the utilization of the elements which are exceptionally inflexible and rigid. Rigid-body mechanisms are those are traditional and commonly used in the manufacturing field. They engage solid linkages joined by joints which permit relative motion linking them. Compliant equal in values of such mechanisms are replaced by the linkages and joints by means of a particular portion of material having rigid and flexible parts. The compliant mechanisms are relatively a recent study in design and research field, but it is one which has increase in its significance due its potential utilization and benefits over the mechanisms of rigid-body. The property of the flexible part returning to its actual position after being released is a resilient advantage. The mechanisms described here are generally lesser on weight basis and having requirement of low expenditure than the rigid-body mechanisms without compromise in strength. As these mechanisms are generally built in a single piece, the modelling techniques and manufacturing is greatly simplified, because of these things even in the absence of rigid-body links, where the parts of machine persistently come in contact against each other, there is decrease in wear significantly.[5]

III. DESIGN OPTIMIZATION PROCESS

In Design and Development phase of the prosthetic foot at this stage a number of CAD Models were drawn in CATIA and their adjustments and structural analysis were followed by FEA using ANSYS, to increase the ground area contact heel was kept of same width as of Front end of designed foot in some cases. Topology optimization of few of the models is done to check feasible options for further reduction and developments in the designed model

To help increase stability of the foot during increased activity, most dynamic-response feet have a split toe design. The split toe feature enables the toes to apply a uniform force to an uneven surface without rotating the heel. This is particularly critical when ambulating over rough or uneven terrain, such as sand or grass. Further reducing the size of the "dead spot" so that individuals experience a smooth motion from heel strike to push-off. This design is currently the closest biomechanical representation of a natural foot.[6]

3.1 Materials:

Materials selection for prosthetic and orthotic devices has traditionally focused on 6 characteristics including yield strength, stiffness, durability, density, corrosion resistance, and ease of fabrication. Yield strength refers to the maximum stress a material can withstand before permanent deformation occurs, which is very important in a load-bearing prosthetic device.

Not only does the device need to withstand the individual's bodyweight, but also the increased forces during walking, running, and jumping. Another characteristic related to strength is the stiffness of the material. Stiffness refers to the stress-to-strain (or Young's Modulus) ratio. A material will stretch or compress a certain distance whenever a force is applied. The ultimate strain of a material refers to the amount of bending deformation, compression, or elongation a material exhibits before failure. The durability of the device refers to the ability of the selected materials to withstand repeated force loading and unloading while maintaining material integrity. Many materials degrade or become fatigued after repeated exposure to loading and unloading. Once a material is fatigued, the force required to reach failure is reduced. Since a prosthetic device is loaded and unloaded with every step, repeated hundreds to thousands of times per day, fatigue strength is an important material characteristic in prosthetics. The density, or mass per unit of volume, is a concern for all prosthetic users because a low density reduces the overall device weight. Decreasing the weight of the prosthetic system or increasing the device's energy storage and return minimizes the metabolic energy required to ambulate, allowing increased mobility. Corrosion resistance and ease of fabrication are important characteristics pertaining to the life cycle and fabrication of the device. Additional characteristics to consider are material costs and availability. Consideration of all of these characteristics guides material selection.

Another measure of a materials ability to withstand a load is the factor of safety. Factor of safety is a ratio used in structural applications to determine the ratio of the maximum working stress to the maximum stress the material can withstand. The final design is the product of numerous designs and testing iterations until a finalized product with a sufficient life expectancy is created.

3.2 Different Designs of Foot

In this phase we developed a model based on previously known models and the work up forth by previous researchers. In development of the CAD Model a number of different models have been drawn and designed based on the measurement of human foot and the data also collected by measuring feet.

All adjustments of the model were followed by FEA techniques, hence optimizing its strength. The front support points are positioned according to the human foot. The heel is robust just like the human heel. Back end of the rib had to be implemented due to high stress at the heel area; also, the heel was of same width as front end in order to increase the area that is in contact with the ground. In first solid structure drawn the model is completely solid so having maximum material used and it would be heavy for the amputee to use for light work applications and day to day use for low level activities as well, then changes were followed on the models to make preferred model for 3D printing.

We changed that model to accommodate the stress strain results found out by doing ANSYS Calculations. Few of these ANSYS results were shown in figures below.

Model Dimensions: Model I: L = 265 mm H = 90 mm
Other Models: L = 250 mm H = 80 mm width = 75 mm

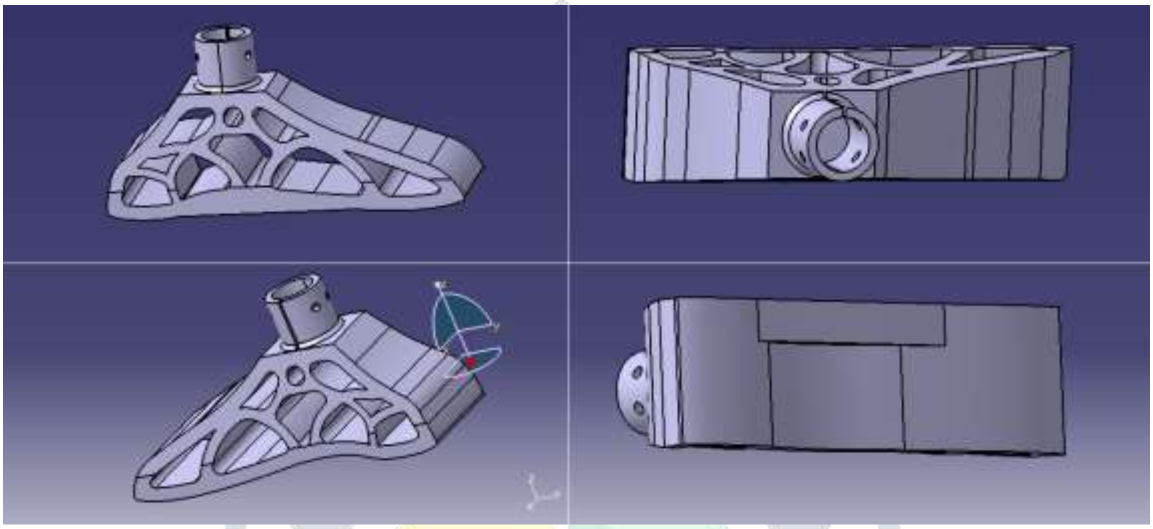

Fig 3.1 Model

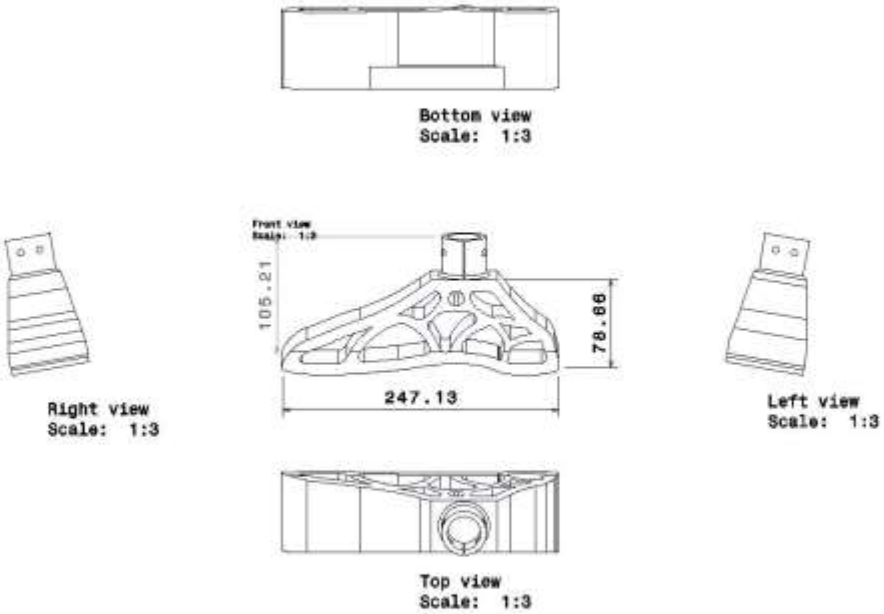

Fig 3.2 Detailed View of Model

3.3 Static Structural Analysis

The static structural analysis of the model showing equivalent (von-Mises) Stress results from the downward loading applied on them. The Static Structural Analysis of few models is shown here to show the results of the stress and deformation analysis the models have been through.

These different models and their analysis given here shows that after even a slight modification the results will be different due to the change in parameters of the process. This is the main reason behind all these different simulations and varying parameters in this study. In most of these models we can see the maximum stress is taking place at position where the load is applied and small number of deflections are observed here and there in the structure. If the deflection is more and would it harm the structure, we added some support to the structure making it robust for such scenarios.

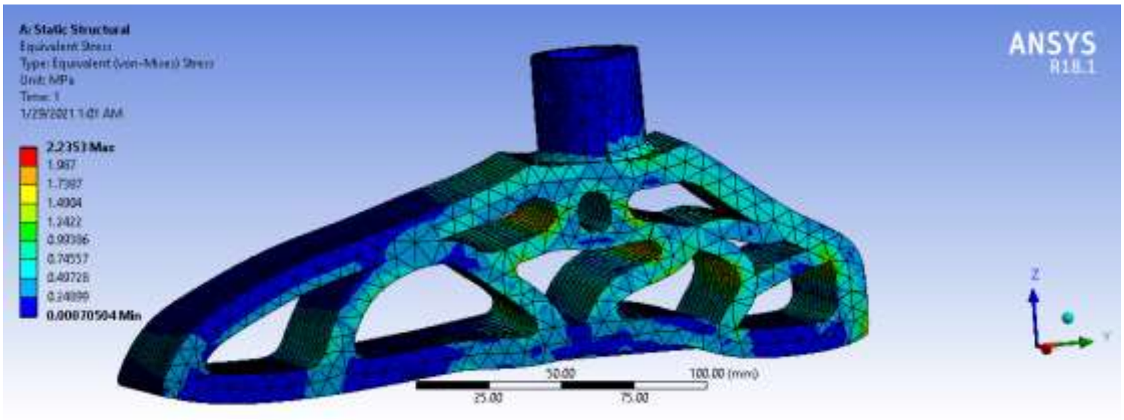

Fig 3.3 Model: Static Structural, Equivalent Stress

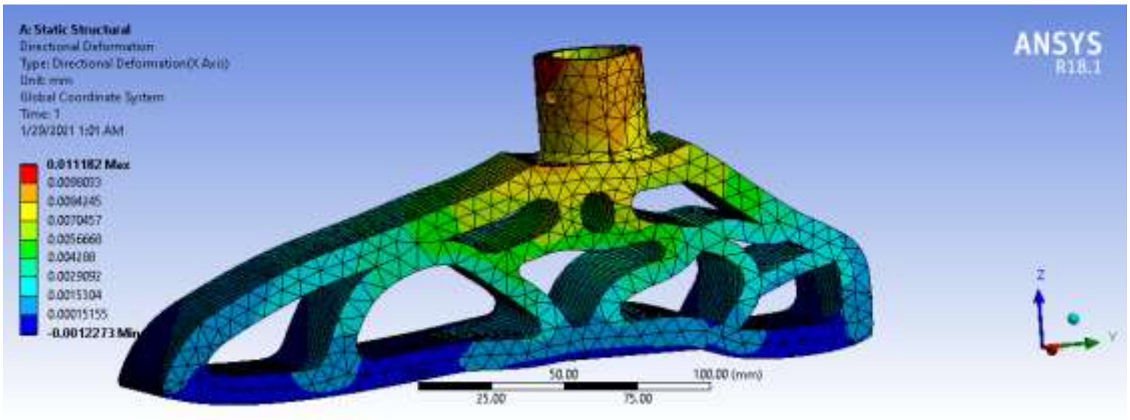

Fig 3.4 Model: Static Structural, Directional Deformation

3.4 Topology Optimization

Here in Ansys Workbench 18.1 we got topology optimization of the structure option and while trying out the feature found that this shows material can be removed which is not necessary for keeping the strength intact while performing the same task. So, we checked this for some of our designs and found out how to improve them at some extent.

In this way we studied various models and analysed their structure using ANSYS Software and it will help to choose further modifications and necessary changes to the model we will finalize on the way for production using additive manufacturing.

The Static Structural analysis shows maximum equivalent (Von-Mises) stress of 2.235 MPa and following the same results doing analysis for topology optimization we found out the topology suitable to print considering other results. The topology optimized by mass reduction and objective was to keep strength intact while removing the extra material possible via various iterations.

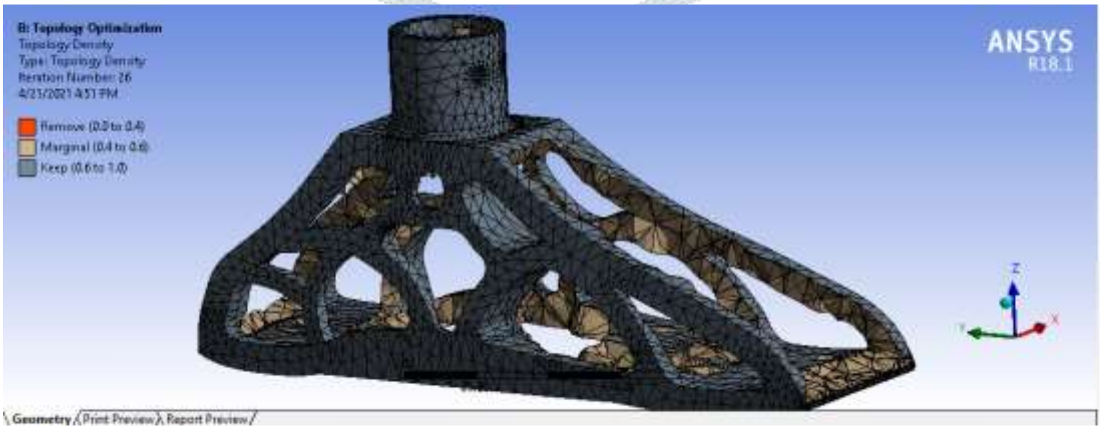

Fig. 3.5 Printed models' Topology optimization

IV. PRINTING IN 3 DIMENSIONS

Even though, many materials like poly lactic acid, acrylonitrile butadiene styrene (ABS), and nylon 6 are used for fabrication using fused deposition modelling (FDM) and conventional injection moulding, this foot is fabricated completely by using PLA material because of its strength and stiffness than ABS and also seems to be readily and cheaply available.[4]

Material: (Polylactic acid) PLA

- Biodegradable Polymer, Soluble in chlorinated solvents, hot benzene, dioxane etc.

Table 1: Material properties of PLA (Polylactic Acid) [4]

Material Properties	
Youngs' Modulus	$3.54\ GPa$
Poisons Ratio	0.33
Density	$0.01054\ {}^{kg}/_{mm^3}$
Tensile yield strength	$60.4\ MPa$
Compressive yield Strength	$23\ MPa$
Tensile Ultimate Strength	$35\ MPa$
Compressive ultimate Strength	$2600\ - 13600\ PSI$
Melting Temperature	$173 - 178$℃

To limit divergence from design to execution, it is important to plan correctly and find out the optimum orientation of the model, slice the model into sufficient layers and generate supporting materials, which must support the addition of subsequent layers and can easily be removed after printing. Freedom of design, mass-customisation and the ability to print complex structures with minimum waste are the main benefits of 3D printing.[7]

In additive manufacturing, a digital file is converted to a solid object by converting the file to instructions for a machine that creates the model by adding one layer of material on top of another. Two of the most popular styles are fused deposition modeling (FDM) and stereolithography (SLA). FDM involves a machine pushing coil of plastic having small diameter through a nozzle that melts the plastic and deposits it on a print surface as it moves in a programmed pattern. As it moves, it creates layer upon layer of material, forming a model. SLA involves a small vat of liquid resin and using a moving laser to cure the resin as the model bed moves up, away from the liquid, forming layer upon layer of cured resin.[9]

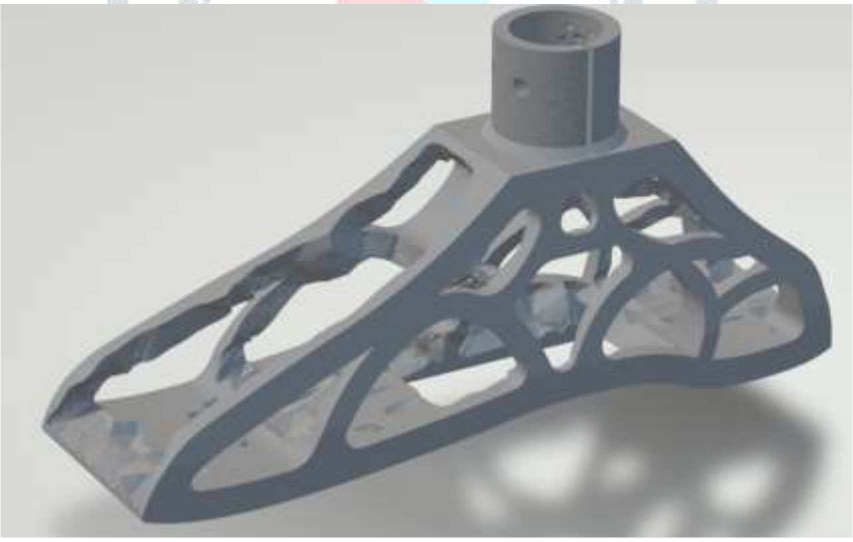

Fig. 4.1 Model for 3D Printing

The size of the models to be produced is determined by the size of the print bed surface, and models must be large enough to appreciate foot and ankle pathology. Larger build volumes correlate with increased prices of 3-D printers. Leveling the print bed allows the height of the nozzle to be set and the machine then to be able to predict where the bed will be. This can be a painstaking process and is vital to print success. A print must stick to the bed without moving to produce a successful print but also must release with ease at the completion of the print. The print bed also may be heated. This is a feature that greatly enhances the adhesion of some materials and may be necessary for some materials to print successfully.

4.1 Filament

One of the most important factors in producing a high-quality foot and ankle model is filament selection. The pliability of the material, melting point, ease of printing, and toughness are factors that vary from material to material. We chose polylactic acid (PLA) as it meets the needs. PLA has a relatively low melting point and extrudes through an FDM machine well. It is stiff and resilient enough for a model while being cost-effective. It does not require a heated bed to adhere well and it releases well from the bed when the prints are complete. Polyethylene terephthalate glycol and ABS are other options;

4.2 Model Creation

The final step is to convert the model file into instructions that the 3-D printer can understand.

We used Cura to accomplish this; these instructions for the printer are a G-code file. The file type is specific for the printer hardware. The print parameters are set within this same software program. This step is different for various printers, and a step-by-step tuning should be performed based on the printer as well as material that is used, prior to attempting to print a model. The settings for the printer are entered, the STL file is imported to the workspace, and the program then is able to slice, or convert, the file. The final instruction set is able to be previewed in Cura to ensure that there are no layers missing or issues with the instructions that are sent to the computer to create the model.

4.3 Printing and Postprocessing

Due to the nature of FDM printing, the models must be stuck to the printing surface. The difficulty of removing the prints depends on how well the bed adheres to the material and the surface area that is printed directly onto the build surface. The parameters for the print that are set up in Cura also play a role in part removal from the print surface. The temperature of the initial layer, as well as the layer height, can affect how well the plastic adheres. Care must be taken to not harm the model or the print surface during this step. Sometimes a reasonable amount of force is required to remove the piece. A thin flexible blade often can be used to begin the removal process. This should not require any prying that may damage the print surface or the model Many factors regarding the supports are determined by the settings in the G-code that are customizable in Cura or another program that converts STL files to G-code. This support material connects to the print surface as well as to the model. It is Important to fine-tune the settings in the software before printing to ensure easy removal of the support material without compromising the model. PVA is a printing filament that is soluble in water. With a dual extruder, this allows printing the model directly on the support material with no gap. When the PVA is dissolved, the model is not susceptible to the scarring from the removal of the support.[9]

We used WOL 3D's YUVA V2 printer to make the prototype. The 3D Printing process took almost 20 hours for two third scale model of the prototype with 100% fill density. We chose the 100% fill density to keep strength intact and make the prototype useful for testing.

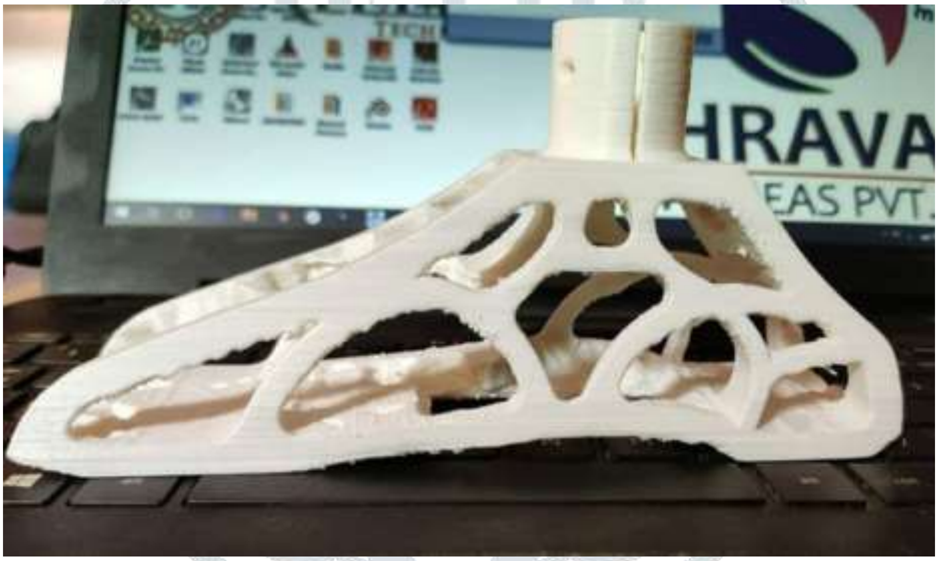

Fig. 4.2 3D printed prosthetic foot

V. CONCLUSION

These are few work-related results and conclusions we have reached at from this study till now:

- Prosthetics based on amputee needs are different from person to person and it is easier to fabricate them using additive manufacturing techniques.
- Developed six different CAD models based on medium sized right foot of human adult male.
- Using trial and error method conducted finite element analysis on some of the models to check their strength and directional deformation using ANSYS Workbench 18.1
- Applied topology optimization on some of the models to check material removal from them to find approach to actual working model.
- Developed a 3D Printed model of prosthetic foot using FDM technology and it helped to understand whole process in a better way.

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