

Additive Manufacturing and Testing of a Prosthetic Foot Ankle Joint

Yogesh Avula¹, Adi Seshan Mula², Vishal Onnala², Kartheek Merugu²

¹Assistant Professor, ²UG Student

^{1,2}Mechanical Department, Guru Nanak Institute of Technology, Affiliated to Jawaharlal Nehru

^{1,2}Technological University Hyderabad, Ibrahimpatnam, Rangareddy, Telangana, India

How to cite this paper: Yogesh Avula | Adi Seshan Mula | Vishal Onnala | Kartheek Merugu "Additive Manufacturing and Testing of a Prosthetic Foot Ankle Joint" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-3 | Issue-3, April 2019, pp.958-961, URL: <https://www.ijtsrd.com/papers/ijtsrd23216.pdf>



IJTSRD23216

ABSTRACT

Ankle replacement is a fairly new concept and is one of the popular treatments of ankle fractures and arthritis. This project focuses on modelling and 3D Printing of a prosthetic talocrural joint. The standard sizes of tibia which is the larger bone of lower leg and talus being lower part of the ankle joint, are observed and modeled accordingly by using CATIA with standard dimensions. The prototype is made with PLA plastic using an FDM (Fused Deposition Modelling) 3D printer. The analytical tests carried on ANSYS by applying human weight on the tibial surface and physical tests are conducted on Universal testing machine. The compression force is applied on the prototype and observed till failure. Results obtained are compared for static position of the foot, of both analytical and physical outcomes.

KEYWORDS: Talocrural joint; Tibia; Talus; Universal testing machine; static position

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1. INTRODUCTION

Additive manufacturing or 3D printing is the process in which the required material is solidified together to create a three dimensional object under the computer control. The prosthetics can be made using 3D printing by melting of the metal powder using lasers layer by layer. The ankle replacement can be made easy using this process because it has limited number of bones and the bone stock is less [1].

The ankle joint is made of the lower leg and the foot and acts a linkage to connect the lower limb with the ground, it is a key requirement for activities of daily living. The ankle joint consists of subtalar, talocrural, transverse tarsal joint [2]. John Fische et al. [3] explained that the ankle joint is most commonly prone to the osteoarthritis which results in the loss of normal structure and functioning of the articular cartilage. The Ankle Arthrodesis (AA) and Total Ankle Replacement (TAR) are the two methods of treating it. With the recent developments in TAR it is being considered as the most effective way of treating the arthritis [4].

Roxa Ruiz et al. [5] elaborated that the new generation TAR's can be divided into two categories. They are the semi constrained two component design and the unconstrained

three component design. The semi constrained design provides greater stability at the same time the shear forces acting at the tibial bone interface is also high with comes with a great risk. The unconstrained design reduces shear force with the addition of the third part [6].

John E Famino et al. [7] determined the factors to be considered while performing the TAR, they are limb and ankle alignment, bony and ligamentous anatomy of the ankle joint, ankle motion which occurs in coronal, sagittal and transverse planes and the talocrural and subtalar joint motion in the above three planes. Also other factors that are taken into account are the presence of degenerative changes in other joints, such as the subtalar, midtarsal, knee, hip, and the contralateral ankle. The measurement parameters of foot and ankle are very important in the operative planning. In earlier times the 2D weight bearing radiographs were used to get the dimensions. Later computed tomography (CT) was used to get the three dimensional image, the use of CT was restricted to limited extent because of its expense and radiation exposure. With the development of EOS biplanar imaging system, capturing of two orthogonal anteroposterior (AP) and lateral radiographs in a standing weight bearing position spanning from spine to the foot is possible [8]

Nikolaos E. Gougoulas et al. [9] explains about the rehabilitation after the surgery, the process starts with breathing and antithrombotic exercises. The patient will be able to sit in upright position one week after the surgery. The range of motion is restored by doing active and passive exercises in sagittal plane, the mobility of the joint is gradually restored. The minimum estimated time required for total restoration of the gait function is one year after the surgery. This study elucidates the comparison and discussion of the analytical results with the practical test results.

2. METHODOLOGY

The ankle joint is modelled to exact dimensions and then checked before additive manufacturing. The 3D printing involving a series of steps is carried out by finally obtaining the prototype. The prototype which is obtained must be checked for the surface finish and fill. The testing is the next step carried away in the process to obtain the analytical and physical values. The analytic values are obtained by conducting analysis in ANSYS and the physical test is done on universal testing machine (UTM). The ankle prosthesis must be carefully designed as the cases sometimes may cause side effects due to the inefficiency of the design and the material chosen.

2.1 Modeling of Prosthetic Ankle Joint

As the ankle joint is combination of parts which combine to make a prosthetic joint rigid and flexible to replace as well as function the same as talocrural joint. Its parts can be named as follows

1. Tibial Part.
2. Mobile bearing.
3. Talus part.

2.1.1 Modeling of Tibial Part

The Tibial part is in the superior portion when viewed in sagittal plane. Sketch the part as per standard dimensions of the tibial bone. The sketch must be containing the ways to fix itself in the tibial bone with any type of fasteners. Extrude the part up to 17 mm on both the sides and make use of mirror extend option to obtain equally two sided extrusion. Remove the material in between the hook type structure with depth 17 mm on either side. Then Draw a circle of diameter 38 mm on the surface and remove the material from corners by reversing pocket. Fillet the four edges with 1 mm radius. At the distance 10 mm from origin in both axes of the plane plot a hole M3 thread of 5 thread depth and 10 mm hole depth. Now translate it with two instances in the vertical direction and then mirror the whole side on the other side

2.1.2 Modelling of Mobile Bearing

The middle part in the joint is the bearing which helps the tibial and talus parts to fit accordingly in their slots. Sketch a rectangle of 34x10 mm and extrude it for 13 mm with mirror extend. Also fillet the corners and edges. Plot a circle D55 mm from the point (-18,0) in Y-Z plane and trim, then apply groove option and cut the portion falling under it. Sketch a part and apply groove which provides the talus part to freely displace or rotate at certain angle. The filleting of the complete body is done with automatic filleting definition with 1 mm radius.

2.1.3 Modeling Of Talus Part

The talus is the inferior part of the ankle joint when seen in the sagittal plane. Sketch the profile same as that of the mobile bearing section to make it align perfectly on the bearing. Employ shaft command and mention the first and second angle limits as 40 degrees and also the sketch profile with thickness 3mm also draw a circle and extrude for carry loads which yet again should be mirrored to produce a two way support. Position the holes 9.4 mm from the bottom edge with M3 thread type and depth of thread 5 mm and hole depth of 18 mm. Mirror the hole to the other end and also to the two other impressions. All the holes must be filleted with radius 0.5 mm. All the parts are thus modeled and assembled such that the parts are aligned properly the multi view of the assembled part is as shown in Figure

2.2 Analysis in ANSYS

Analysis part is carried in ANSYS Workbench to understand and thus proceed for the physical test. The geometry is imported. Use the "Static Structural using Mechanical APDL Solver" and drag towards the imported geometry and the materials are first added in the library. Then the project is updated which enables to apply the materials in the Mechanical solver. The tibial part and talus part are given Titanium alloy and the mobile bearing is of polyethylene. The reference temperature is 22°C by body and with stiffness behaviour as flexible. The meshing is carried out in which the nodes and elements are 29947 and 16707 respectively. The body grains are given coarse with minimum edge length of 0.004154 mm. The mass of 100 kg is enacted on the surface of the part body or the tibial part which is the standard highest average value of the human body. A pressure of 1.58 Mpa is experienced on the surface. The hook on the tibial part and the circular base of the talus part are given fixed support. After giving constraints the solution is generated. The solution must be given a specific required type of the solution to be generated. Equivalent (von-Mises) stress is selected and evaluated for results where the maximum stress was recorded as 8.7529 MPa and minimum stress as 0.0042421 MPa.

2.3 3D Printing of The Ankle Joint

The designed model obtained with the CATIA software was converted into STL format. Then ankle joint was printed on AHA 3D proto centre 999 printer using PLA plastic. The three parts were individually printed with fill densities of 50% for the tibial and talus parts and 80% for the mobile bearing. The time consumed for the printing process is around

2.4 Physical Testing of Prosthetic Ankle Joint

The 3D printed prototype was fixed on the UTM and the compression test was performed as shown in Figure 3.26.

The following was values of the applied load and the corresponding deformation were obtained and tabulated in Table 1.1

Table 1.1 Compression test observations

Force Applied (KN)	Deformation (mm)
12.5	0
13	1
13.75	2
13.75	3
14	4
15	5



Figure 3.26 Testing of prototype on UTM

The forces are calculated for titanium material by using standard conversions. The densities of PLA and titanium alloy are 1250 kg/m³ and 4506 kg/m³ respectively. The conversion factor used is the ratio of force applied on PLA specimen to the division of density of titanium alloy to that of density of PLA. Hence the forces acting on titanium alloy and the deformation is as obtained in Table 1.2

Table 1.2 Forces and Deformation of Titanium alloy

Forces Applied (KN)	Deformation (mm)
45.06	0
46.86	1
49.56	2
49.56	3
50.46	4
54.79	5

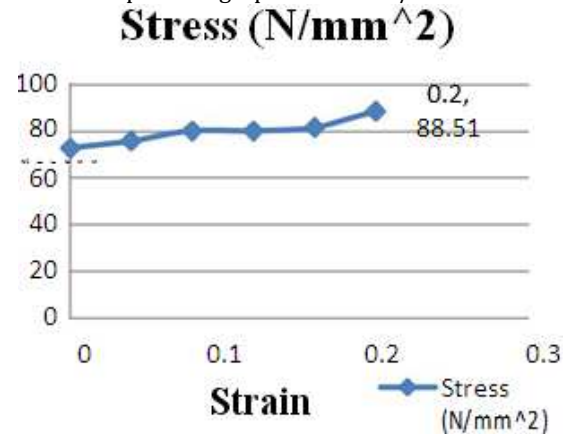
The corresponding stress is calculated to project the graph and observe the Yield, Working and Ultimate stress. As stress is the ratio of force applied per unit area, the physical test involved the surface area of tibial surface as 669 mm². The strain related to deformation is calculated and the stress and strain values for the titanium alloy is tabulated as in Table 1.3

Table 1.3 Stress and strain values for titanium alloy prototype

Stress (N/mm ²)	Strain
72.79	0
75.7	0.04
80.06	0.08
80.06	0.12
81.51	0.16
88.51	0.20

The graph is plotted between the stress and strain as seen in Graph 3.1

Graph 3.1 A graph of Stress V/s Strain



3. RESULTS

The testing was carried out analytically and also physically on ANSYS and Universal Testing Machine respectively. The compression test carried on both the types. The results are noted and analyzed which are as follows.

3.1 Analytical Test Results

The results obtained for compression on a prosthetic talocrural joint are in terms of stress. Equivalent (von-Mises) stress is chosen and evaluated for results where the maximum stress was recorded as 8.7529 MPa and minimum stress as 0.0042421 MPa which can be seen in Figure 4.1

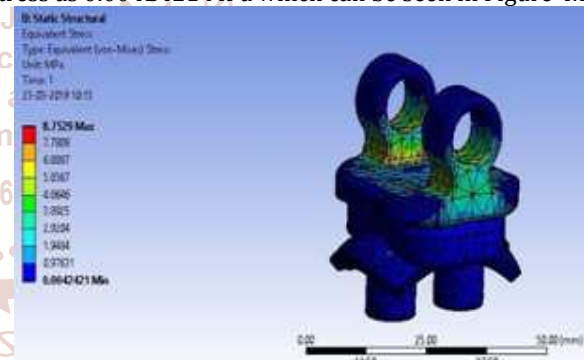


Figure 1.1 A result of Equivalent (von-Mises) stress

3.2 Physical Test Results of Prosthetic Ankle Joint

The Universal Testing Machine (UTM) was used for conducting compression test on the body. The load was increased gradually and the changes in dimensions are noted.



Figure 1.2 3D Printed Prototype before testing.

The maximum load applied is 15 KN where fracture was observed. The load is applied till the failure is observed. Initially the deformation was not observed till load reached 12.5 KN. Thereafter the steady deformation is observed. The yield point is to be found at a load of 13.75 KN at which the deformation increased from 2 mm to 3 mm. The load further added to reach fracture at 15 KN where deformation is observed to be 5 mm.



Figure 1.3 The prototype after testing

After certain calculations we could observe the stress at the deformation for the titanium prosthetic joint as 72.79 MPa which is the working stress. Whereas the stress experienced near fracture point was observed as 88.43 MPa.

4. DISCUSSION

Total Ankle replacement with additive manufacturing involved has got a lot many benefits for ankle prosthesis. The prosthetic talocrural joint as observed in both analytical and physical testing shows that the design was safe for human weights as the Ultimate stress was less than that of the stress obtained when tested physically on Ultimate Testing Machine. As the analytical test values Equivalent (von-Mises) stress is obtained as maximum stress 8.7529 MPa and minimum stress as 0.0042421 MPa. Whereas the allowable stress obtained in the physical testing was 72.79 MPa.

Thus the design is safe for 100 kg weight of human body under the static position.

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