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ORIGINAL RESEARCH PAPER

Optimal design and manufacturing of 3D printable prosthesis pylon

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ABSTRACT

The aim of this study is to design a pylon with an engineering structure that gives it support and strength and manufacture a pylon characterized by low cost, lightweight, and bearing the patient's weight. This study designed two pylon models and fabricated by additive manufacturing techniques. The polylactic acid polymer is used as the filament for the 3D printing of pylons. A force plate and tensile test with finite element method simulation ANSYS software were applied to the pylons to evaluate their performance. The results showed that 3D printed pylon with Y-section has enough strength under stress and good safety factor, and the ability to bear a high patient load without buckling and exceed the requirements to become instead of the metallic prosthetic pylons.

KEYWORDS

pylon, Y-section, cylindrical, shank, prosthesis, 3D printer, polylactic acid polymer

1. INTRODUCTION

The lower limb prosthetic device is used to compensate for the amputation of a patient's body part. It assists the patient in maintaining appropriate mobility during daily activities [1–3]. The socket, pylon, and artificial foot are the main components of the lower limb prosthesis, as it is shown in Fig. 1. The pylon, also known as the shank, is a long shaft that serves as a frame structure for transferring biomechanical forces from the socket to the foot [4].

Lower limb tubes, also known as pylons, are prosthetic components that bear the patient's weight while walking and performing other daily activities, i.e., in lower limb amputations, when attached to a socket, they serve as a support structure in place of the tibia and fibula bones [5]. According to the market and literature studies, prosthetic tubes are typically made of metallic materials like titanium and stainless steel [6]. In comparison to plastic tubes, the mass of these tubes is usually high. Several studies deal with the study of pylon specifically. Glenn K. Klute et al. worked [7] to understand the effects of Vertical Shock-Absorbing Pylons (VSAP) on amputee gait, and researchers studied the mechanical properties of the pylons. M. Pitkin [8] tested the flexural strength of two pylons: composite pylons with a solid titanium core and drilled holes and porous sintered titanium pylons. The result showed that the composite pylons are better than porous titanium pylons in flexural strength and stiffness. K. L. Coleman et al. [9] studied the effects of pylon flexibility in trans-tibial prostheses on Ground Reaction Forces (GRFs) during walking and stepping down. Shasmin, bamboo was used to develop a low-cost pylon by replacing traditional pylon materials like titanium, stainless steel, and aluminum with bamboo. The mechanical properties of this pylon, like (flexural strength, compression, and tensile), the result showed that the bamboo pylon had adequate strength and modulus, with the former being stronger than the aluminum pylon [10]. Diego M. Junqueira, et al. [11] works on designing, manufacturing, and evaluating the

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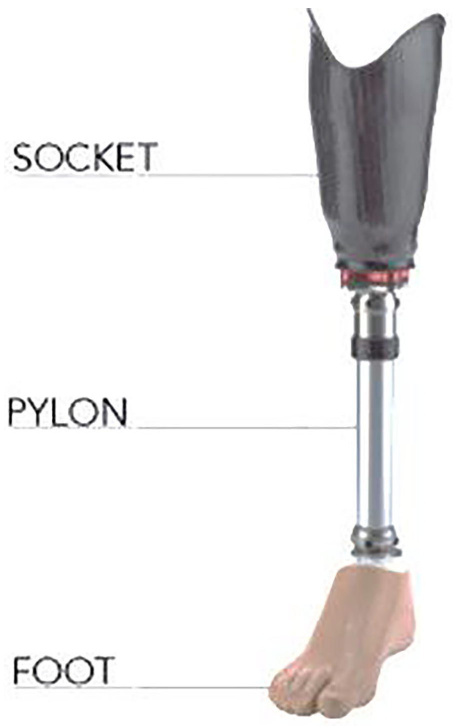


Fig. 1. Components of lower limb prosthetic

viability of a new composite pylon concept with a lattice structure and an inner layer. The aim of the study is to find the best design for a pylon made of a lightweight and low-cost material that can bear the weights of patients.

2.. MATHEMATICAL ANALYSIS OF THE PYLON AND HUMAN WALKING MODELING

The ground reaction force is equal in magnitude and opposite in direction to the body's force on the supporting surface through the foot [1]. Therefore, when the equilibrium equation is applied, as it is shown in Fig. 2, the following are the motion equations in the X and Y directions:

$$F_X = M_t \cdot \ddot{X}_C, \tag{1}$$

$$F_Y = M_t {*} \left(g + \ddot{y}_C\right). \tag{2}$$

With vertical axes, the angle of inclined is:

$$\theta = 2\,\tan\left(\frac{-K_1 \pm \sqrt{K_1^2 + K_2^2 - K_3^2}}{K_3 - K_2}\right). \tag{3}$$

The position of the moment about center of mass of human can be determined by using the following formula:

$$y_C = b_i \cdot \cos\theta, \tag{4}$$

$$x_C = b_i \cdot \sin\theta. \tag{5}$$

The ankle moment evaluated with Eq. (6)

$$M_{XY} = F_N N - F_M M + F_h h - mga, \tag{6}$$

where

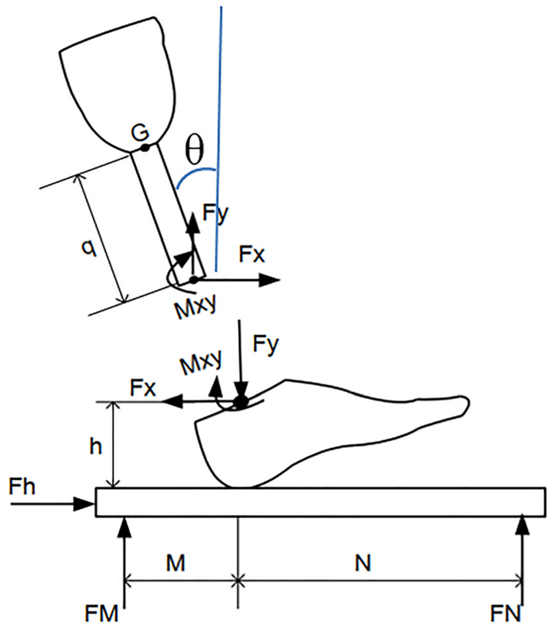


Fig. 2. Forces and moments on a below-knee prosthetic

$$K_1 = \left(\left(M_t + m\right)IN - M_t^2 b_i^2\right)g - I\left(F_N + F_M\right), \tag{7}$$

$$K_2 = F_h I, \tag{8}$$

$$K_3 = M_t\; b_i\left(F_N N - F_M M + F_h h\right). \tag{9}$$

F_N and F_M are perpendicular ground reaction forces; and F_h is the horizontal components of ground reaction force. The force plate device is used to measure these forces,

$$\sigma_G = \frac{\pm F_y \cos\theta - F_X \sin\theta}{A} \pm \frac{\left[\left(F_y \cos\theta + F_X \sin\theta\right)q - M_{xy}\right]\left(\frac{d_0}{2}\right)}{I}. \tag{10}$$

The vertical and horizontal components of the ground reaction forces are applied. These components cause a moment at the ankle joint region and forces at the heel strike and toe-off phase of the gait cycle. The pylon's lower end has three stresses: bending and compression stress generated, and the compression stress generated at the mid-stance phase.

At swing phase the $\sigma_G = \sigma_{\max} = 0$. At stance phase (heel strike):

$$\sigma_G = \sigma_{\max} = \frac{F_y \cos\theta - F_X \sin\theta}{\frac{\pi\,(d_o^2 - d_i^2)}{4}} \pm \frac{\left[\left(F_y \sin\theta + F_X \cos\theta\right)q - M_{xy}\right]\left(\frac{d_0}{2}\right)}{\frac{(d_o^4 - d_i^4)}{64}}. \tag{11}$$

3. EXPERIMENTAL WORK

3.1. Material used

Polylactic acid was selected as the most suitable material for the manufacture of pylons because it has good mechanical properties appropriate for this application and is lightweight [12–14]. The technology used to manufacture the pylon is

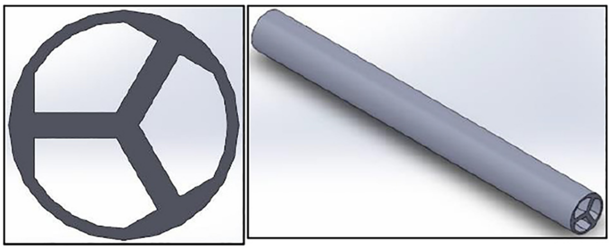
Additive Manufacturing (AM) systems by the 3D printer device, which can be easily implemented in domestic or small-scale manufacturing environments as a low-cost and simple manufacturing technology [15, 16].

3.2. Pylons design and fabrication

The pylon is designed as a hollow cylinder whose walls are connected from the inside by the *Y* section, as it is shown in Fig. 3a. This design is compared with the traditional design (cylindrical section). The pylon is designed with this geometrical structure to obtain sufficient durability and prevent mechanical failure. The pylon's dimensions are 30 mm in outer diameter and 250 mm in length. The pylon is designed with an engineering structure that takes into account the material used in its manufacture and the application in which it can be used. The designed pylon was drawn using the SolidWorks program and made using a 3D printer device. The designed pylon can be shown in Fig. 3b.

3.3. Tensile test

For manufacturing the pylon, it is necessary to identify and test the materials used in its manufacture. In this test, polylactic acid will be examined to find out its mechanical properties. The samples were printed to test the materials using a 3D printer. Standard dimensions were adopted for ASTM-D638-V [17] with a thickness of 3 mm. The samples used in the tensile test can be illustrated in Fig. 4.



a) b)

Fig. 3. a)The cross-section of the designed pylon, b) the overall shape of the designed pylon

Fig. 4. The polylactic acid test specimens

3.4. Fatigue test

It is essential to test the fatigue of the materials selected to manufacture the pylon to know the fatigue stress limits for each material. The 3D printer printed the fatigue test samples according to the dimensions of the fatigue device (HI-TEICH) [18]. The dimensions of each sample have a length of 100 mm, a width of 10 mm, and a thickness of 4 mm, as it is shown in Fig. 5.

3.5. Force plate test

Any person, when walking, generates a reaction force on the legs called the ground reaction force. It is composed of two main horizontal and one vertical component. These forces are found by having a subject walking across a force plate in the form of a walkway [19]. The test was done on the patient wearing the prosthesis and walking on the force plate, as it is shown in Fig. 6. The test in this study aims to measure the forces that pass through the pylon during a patient walk.

3.6. Manufacturing process

A 3D printer device was used to manufacture the prosthetic pylon. The model was made using polylactic acid. This technique was chosen for the manufacture of pylon because it is low-cost and fast in the manufacture of the model and produces characterized by accurate dimensions. The model with white color refers to the pylon made of plastic, as it is shown in Fig. 7.

3.7. Results of mechanical test

The tensile test results showed the mechanical properties of polylactic acid filament are yield stress $\sigma_{yeild} = 49$ MPa, ultimate stress $\sigma_{Ult} = 36$ MPa, and modulus of elasticity

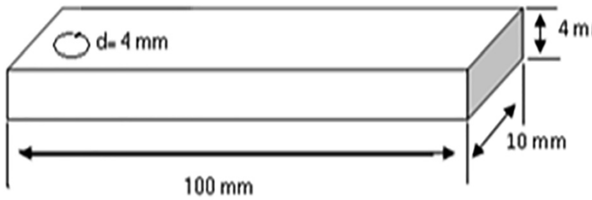


Fig. 5. Dimension of fatigue sample

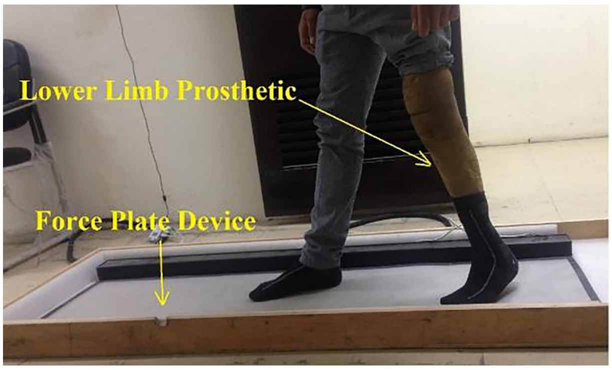


Fig. 6. Patient wearing lower limb prosthetic walk on force plate device

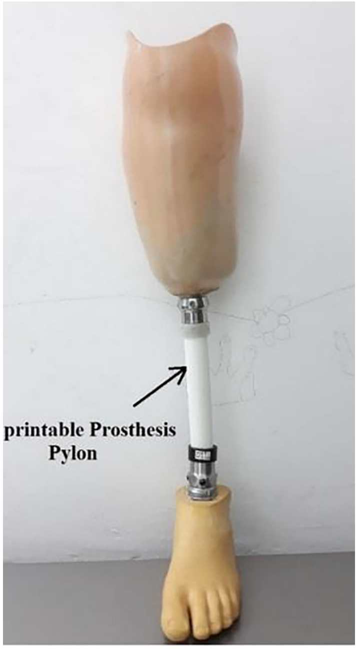


Fig. 7. The printable pylon attached to the knee prosthetic

E = 1.28 MPa. The curve of stress-strain can be seen in Fig. 8. As it is illustrated in Fig. 9, the fatigue test results showed stress and the number of polylactic acid filament cycles relationship. The stress endurance of the polylactic acid filament is equal to 23 MPa.

The force plate test results show the maximum ground reaction force equal to 800 N, which is applied to simulate the pylon model using the finite element method. The force diagram is shown in Fig. 10.

4. FINITE ELEMENT ANALYSIS

For getting the pylon's optimum design, an engineering simulation of the pylon is made related to the pylon's load and the material mechanical properties. The boundary conditions must be applied for the simulation process: fix the pylon from one end and apply the load representing the patient's weight from the other end. The boundary condition of the two pylon models is shown in Fig. 11.

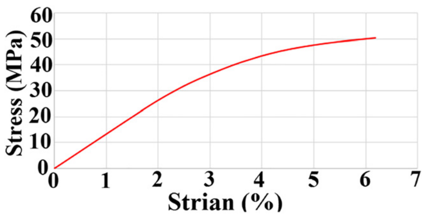


Fig. 8. Stress-strain curve of polylactic acid

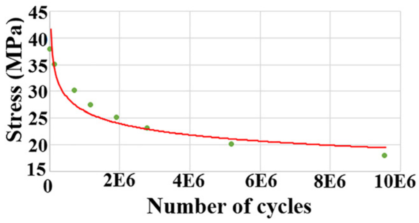


Fig. 9. The stress-number of cycle curve for polylactic acid

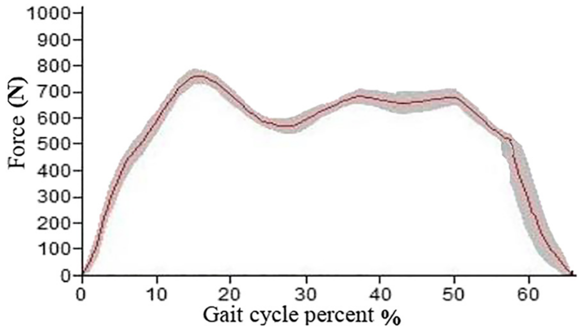


Fig. 10. Ground reaction force diagram for amputation leg

4.1. Pylon models stress analysis

The stresses are generated in the pylon due to the patient's weight being applied to it while walking. The maximum Von Mises stress equals 3.16 MPa for the pylon with the *Y*-section model and 6.8 MPa for the cylindrical pylon model, as it is shown in Fig. 12. Both models have a big gap between the maximum generated Von Mises stress and the yield stress of polylactic acid filament, which the pylon manufactured from it. The yield strength meaning is the stress value of the material can bear without any permanent deformation [20, 21]. The results mean the pylon models can bear the generated stresses without failure.

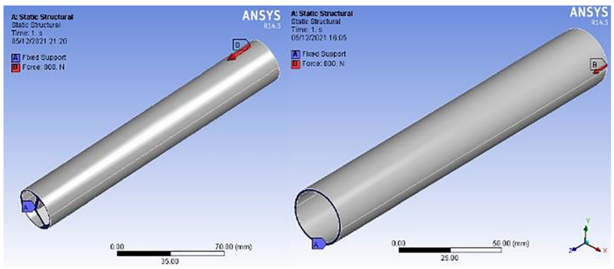


Fig. 11. The boundary conditions applied to both pylon designs

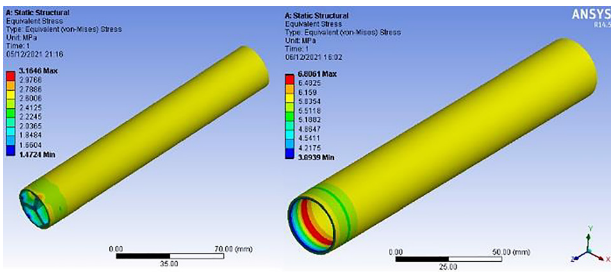


Fig. 12. The Von Mises stress of the two models of the pylon

4.2. Deformation analysis of pylon models

The deformation analysis gave us knowledge of the values and location of the total deformation of the pylon. The maximum deformation value equals 0.419 mm for the pylon with the *Y*-section model and 0.928 mm for the cylindrical pylon model, as it is shown in Fig. 13. Both models have acceptable values of deformation due to applied patient weight.

4.3. Safety factor

The analysis of the pylon models was achieved to compute the Fatigue Safety Factor (FSF) of fatigue. The FSF for both pylon models is successful in design. The safety factor value varies from region to region depending on the distribution of stresses generated and the endurance stress. The values of safety factors are more than 1.25 for both pylon models, as it is clarified in Fig. 14. If the fatigue safety factor equals or exceeds 1.25, the design will be safe [22].

4.4. Buckling analysis

Buckling occurs when a structural component deforms suddenly under load, like a column bowing when affected by a compression load. If a structure is subjected to a gradually increasing load when the load reaches a critical level, a structure may suddenly change shape; this case is called a buckled [23, 24]. The buckling analysis shows the critical load bears before bowing or buckling prosthetic pylon is 160 kg for the *Y*-section model and 96 kg for prosthetic pylon with a cylindrical section, as it is shown in Fig. 15. The result shows the pylon with a *Y*-section design can resist buckling more than the pylon with a cylindrical section design. The pylon design with a *Y*-section is better performance than the pylon design with a cylindrical section with about 43.75%.

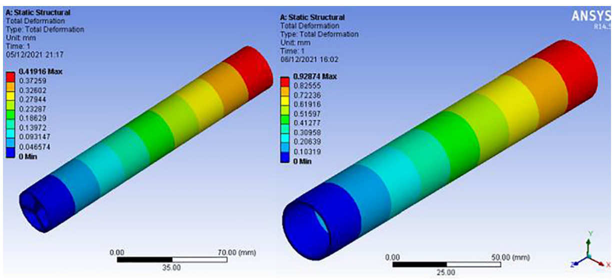


Fig. 13. The deformation analysis of two pylon models

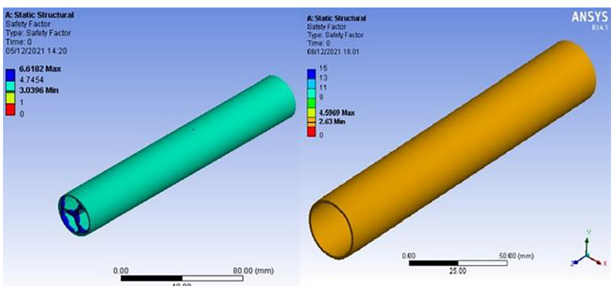


Fig. 14. The safety factor values for both pylon models

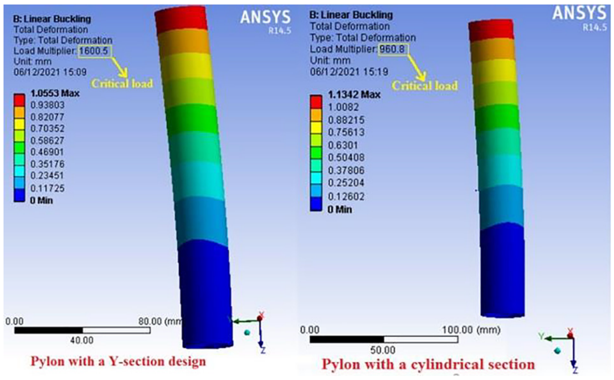


Fig. 15. The buckling analysis with the critical load for two models of the pylon

5. CONCLUSION

- Both models of pylons passed in design;
- The pylon with a *Y*-section design is available for a patient weight of less than 160 kg;
- The pylon with a cylindrical section is available for a patient weight of less than 96 kg;
- The pylon with *Y*-section is better in design and safer than a pylon with a cylindrical section due to having more safety factors, higher bearing generated stress, and low deformation when applied load and requires a load of more than 1600 N to buckle;
- Both pylon designs are low cost, lightweight, and have good mechanical properties due to polylactic acid material use.

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