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ORIGINAL RESEARCH PAPER

Design of adjustable prosthetic pylon for children amputees: Numerical analysis case study

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ABSTRACT

The pylon is an essential part of lower limb prosthetics. It is usually made of titanium, aluminum, and steel. However, it is expensive and difficult to be available in developing countries, especially for children who suffer from amputation. Moreover, they constantly need new pylon pieces during close periods due to the growth and increase in the child's length. *Purpose:* This study aims to design an adjustable pylon that can change in length to suit the increase in the length of the healthy leg of the child without the need for a new pylon and reduce the economic cost. *Design/methodology/approach:* In this study, an adjustable pylon model was designed using the CAD software (Solid work) and work to manufacture the pylon from low-cost materials (carbon fiber filament) capable of bearing the amputee's weight, and manufacturing printed parts by using additive manufacturing technical (CREALITY CR20 3D printer). *Findings:* The results showed that the pylon is successful in design and strength as it bears the patient's weight without any failure or buckling, and the proof that the maximum amount of stress generated is 27.8 MPa, which is far from the value of the yield stress. *Originality/value:* The design of the adjustable pylon prototype offers good strength and ability to bear the patient weight, reducing the cost and time of manufacturing.

KEYWORDS

pylon, prosthetic, amputee, analysis, 3-D printer

1. INTRODUCTION

Amputation refers to the surgical removal of a limb (arm or leg) or another bodily part as a treatment for an illness or injury, such as diabetes or cancer [1, 2]. A prosthetic is a device to replace a natural body part lost due to injury, illness, or a congenital disability (congenital disorder). Prosthetics aim to restore normal bodily function by functioning as artificial replacements for a lost body component [3]. The main components of the lower limb prosthetic consist of the socket, pylon, joints, and foot [4]. The details of the lower limb prosthetic can be shown in Fig. 1.

This study focuses on enhancing the design and manufacture of a pylon. In this field, there are some researchers as Luca Gabriele De Vivo Nicoloso et al., whose study presents the design and fabrication of a 3D printed transtibial prosthesis, complete with socket, pylon, foot, and monocoque construction [5]. Athmar T. N. et al. research was done to determine

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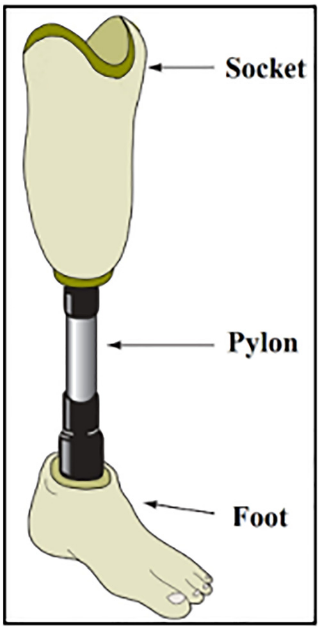

Fig. 1. The main parts of the below-knee prosthetic of amputees

how to select the best design for a 3D printing prosthetic pylon [6]. Ameer A. Kadhim et al. worked on manufacturing an ABS prosthetic shank with Adapters by 3D Printer [7]. Samah F. H. et al. worked to select the appropriate density of the material in accordance with the mechanical prosperities required by the 3D-printing application in which it will be employed in the manufacture of the prosthetic pylon [8]. The research of Hayder Zaher Abdalikhwa et al. aims to show the hung improvements and developments of new suggested composite materials, to change the prosthetic pylon by boosting the user's comfort and extending the life of the prosthetic pylon [9]. Zainab H. Zaier and Kadhim K. Resan worked on manufacturing prosthetic shanks from porous functionally graded materials (ABS filament materials) by additive fabricating technique [10]. Ammar M. and Mahmud R. Ismail designed an elastically curved shank of below knee prosthesis to reduce patient effort and consumption of metabolic energy [11]. Raihan Kenji Rizqillah searches for the best material selection of below-knee leg prosthetics and finds the PLA carbon fiber is the best material for pylon of below knee in respect to weight, cost performance, and strength [12]. Schmitz worked to quantify the fatigue properties of three-dimensional printed carbon fiber has been used to create lower limb prosthetics [13].

Muhsin J.J. et al. developed three prosthetic pylons, each designed and manufactured using different composite material layers (6, 9, and 12) [14]. Jawad K. Oleiwi investigated the tensile and buckling properties of PMMA-reinforced jute fibers for prosthetic pylons [15]. Muhammad S. et al. [16] designed a low-cost, easily manufacturing prosthetic that can simulate the gait cycle of an amputee from carbon fiber filament material, as it has high strength and good resistance to variation of temperature, so it can be used in extreme climates in different countries. Fariborz Tavangarian et al. [17] studied pylon of lower limb prosthetic, which was manufactured using an additive fabricating technique. ABS materials were used as the filament materials of pylons for 3D printing. The 3D printed specimens have good compression requirements. This result confirms that additive fabricating can easily and efficiently create shanks without using conventional methods. At the same time, this study aims to design a pylon that can change in length to be suitable for the growth of the length of the healthy limb without the need to use a new pylon.

2. MATERIALS AND METHODS

The experimental producer of this study is summarized as follows: Design of the pylon using CAD software. Then, the carbon fiber filament material was chosen to be suggested in manufacturing of the designed pylon. Then the proposed material was printed using the 3D printer as samples for the tensile and fatigue test.

The ground reaction force values were calculated by laboratory tests that were previously conducted on children suffering from lower limb amputations. The ground reaction force data were used to apply the boundary conditions in the analysis and engineering simulation of the designed pylon test.

2.1. Pylon design

The pylon is designed from two overlapping parts of different diameters. The upper part is a hollow shaft with an outer diameter of 30 mm and a thickness of 3 mm. The top of the lower part contains a lock connecting the pylon's two parts at the appropriate length. The inner diameter of the lock and the lower part of the pylon is 30 mm, and its thickness is 3 mm. The lock consists of an open cylinder connected to two rectangular lips attached to two screws. The lock is controlled by tightening and loosening the screws. When the screw is tightened, the diameter of the lock is reduced, and the two parts of the pylon are connected at the appropriate length. When the screw is loosened, the lock diameter increases and allows sliding of the two parts of the pylon to move to the required length. Figure 2 shows the design and parts of the pylon in the case of lengthening and shortening.

2.2. Material selection

Carbon fiber filament material was selected to manufacture pylon because it is low-cost, has good mechanical properties, and is suitable for prosthetic and orthotic parts. Also, this material was chosen because it can be used in the 3D printer technic to manufacture parts, in contrast to the selection of metal materials that require expensive techniques such as CNC machines and lathes to manufacture pylon. The parameters of the filament are 1.75 mm in diameter with a specific weight = 1.5 g m^{-1}, and the printing temperature was 250–265 °C.

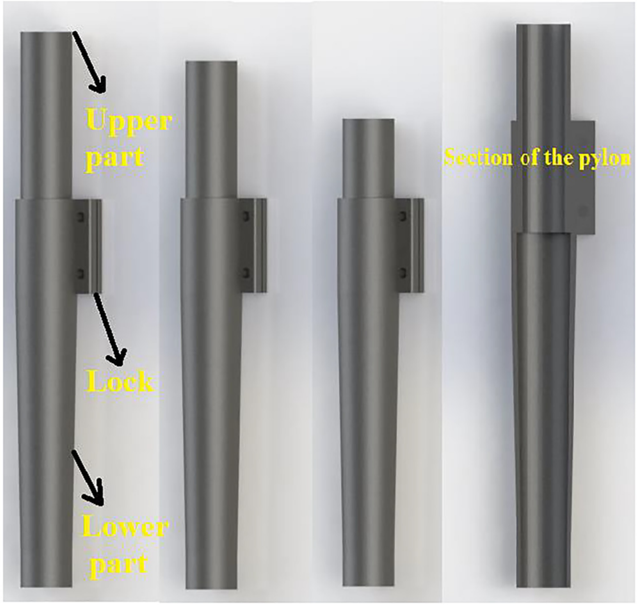

Fig. 2. The design of the pylon model

2.3. 3-D printer device

An additive manufacturing technology was chosen because it is low-cost, easy to use, and quick to accomplish compared to other technologies. Due to its rapid prototyping, print on

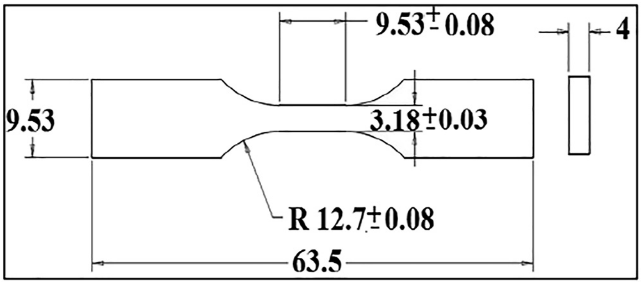

Fig. 3. The dimension of the tensile specimen

Fig. 4. The tensile specimen was printed from a carbon fiber filament

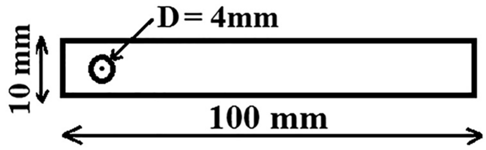

Fig. 5. The dimension of the fatigue test specimen

Fig. 6. The printed fatigue specimen from a carbon fiber filament

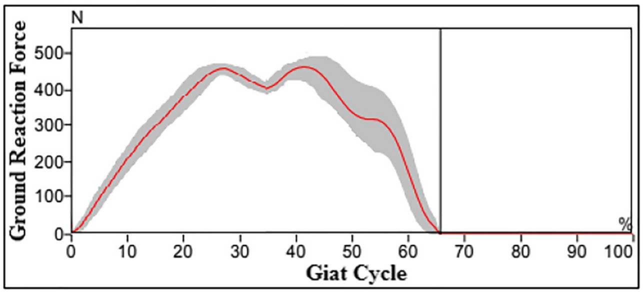

Fig. 7. The ground reaction force for an amputee child weighed 42 kg

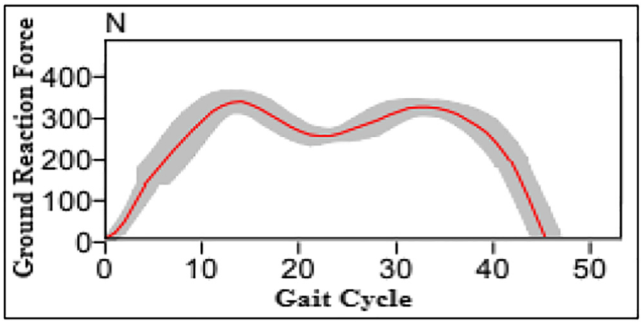

Fig. 8. The ground reaction force for an amputee child weighed 35 kg

demand, sturdy and lightweight parts, fast design and production, minimizing waste, cost-effectiveness, and accessibility, 3D printing allows for the design and printing of more complicated structures than conventional manufacturing processes. In this study a CREALITY CR20 3D printer was used.

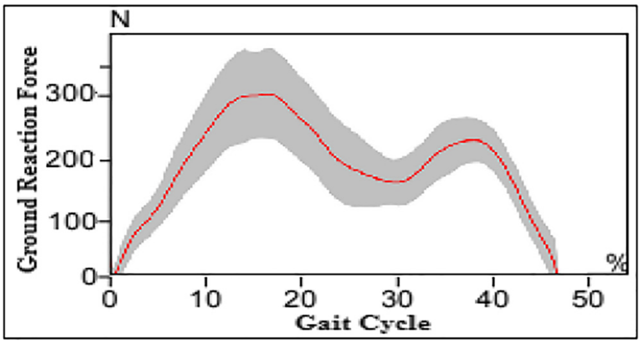

Fig. 9. The ground reaction force for an amputee child weighed 29 kg

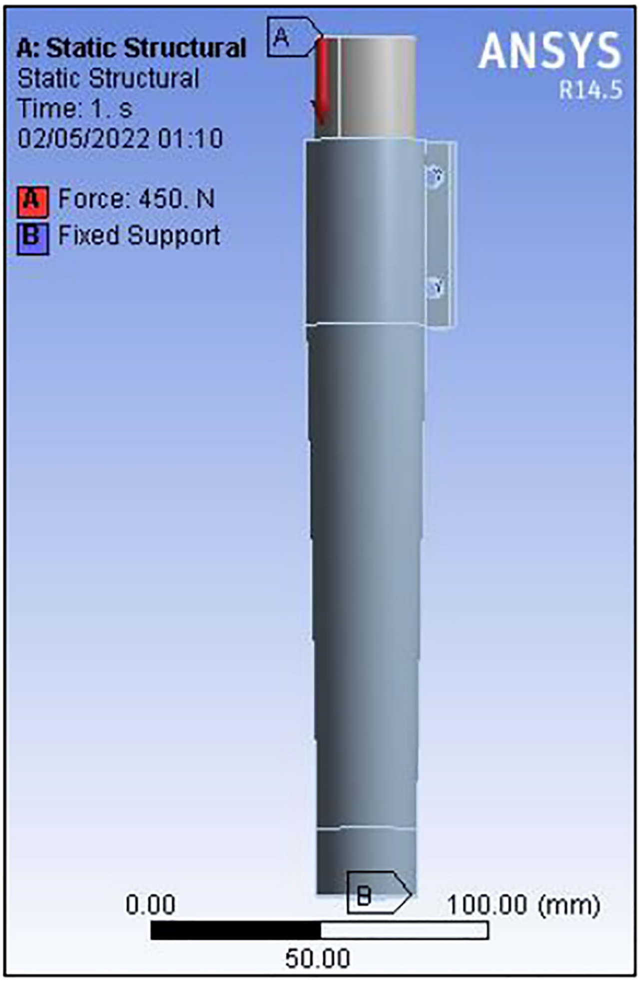

Fig. 10. The boundary conditions are applied to the adjustable pylon

2.4. Material test

The material was tested to determine its mechanical properties and use mechanical properties as inputs to the numerical analysis process. First, the material was tested using the tensometer tensile device, where three samples were printed using the CREALITY CR20 3D printer with a density of 100% according to the dimensions of ASTM 638D [18]. The details of the specimen dimension of the tensile test are shown in Fig. 3, while the printed specimens of the tensile test are shown in Fig. 4. Also, a fatigue test was done, where the samples were printed with a density of 100% according to the device dimensions, as shown in Fig. 5. A machine (HI-TEICH) was used to test fatigue [19]. The printed fatigue specimen are shown in Fig. 6.

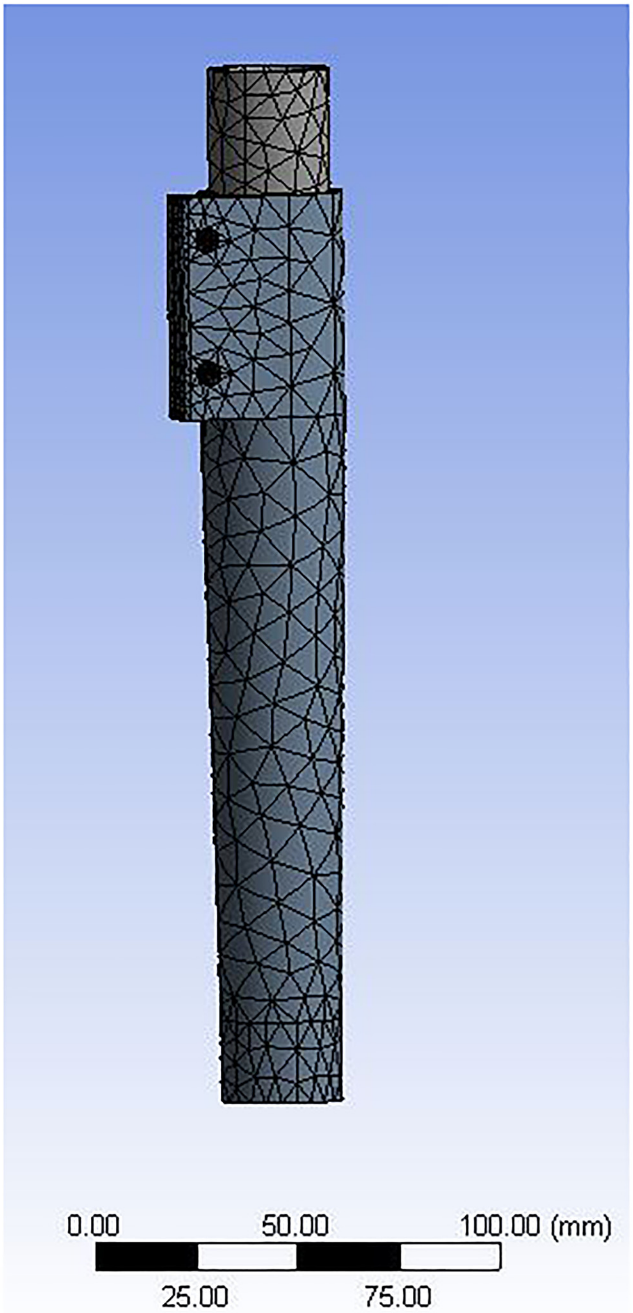

Fig. 11. The mesh the adjustable pylon model

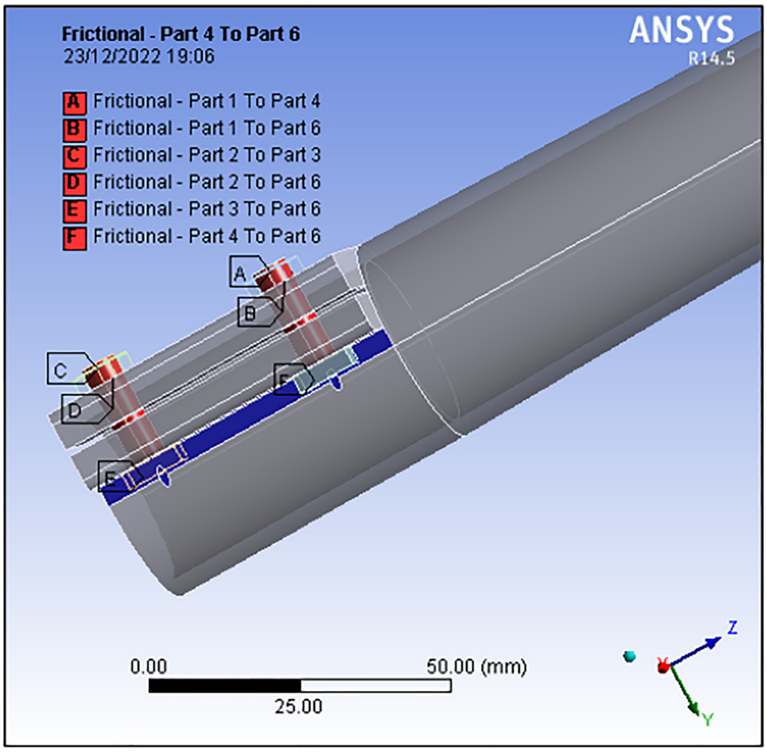

Fig. 12. The boundary condition of friction for contact region, the value of coefficient friction 0.35

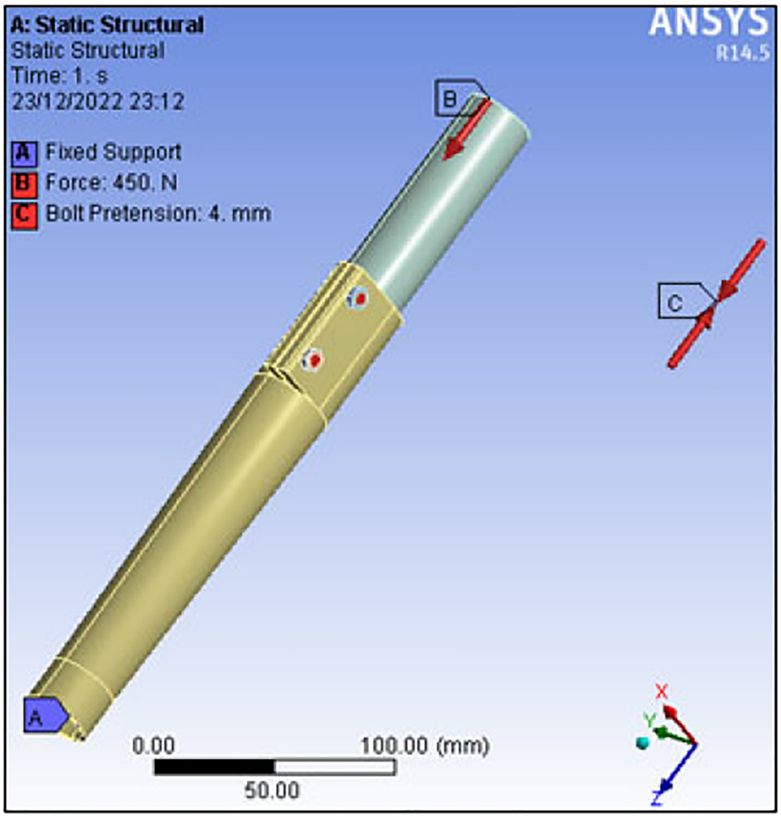

Fig. 13. The boundary condition for applied weight of patient at upper tip of the pylon and fixed at lower tip with bolt pretension for two bolt

2.5. Ground reaction force (GRF)

GRF is the value of the reaction force of the ground on the human body while walking. GRF data is divided into three components, two horizontal and one vertical. A vertical force is directed upwards towards the body through the leg. The vertical force is the same force that passes through the prosthesis, and it is the same that will be applied to the pylon during the numerical analysis process. With the help of the Medical Rehabilitation Laboratory at Al-Nahrain University, several data were quoted to measure the ground reaction force of the children suffering from amputation above the knee using the prosthesis.

Data were extracted for three children with amputated, one of whom weighed 35 kg and had an above-knee amputation of his right leg. Another child weighed 42 kg, and the third child weighed 29 kg and had an above-knee amputation of his right leg. Data for the child who weighed 42 kg was selected to apply the maximum load on the pylon during the numerical analysis. The ground reaction diagrams of children's amputations with a weight of (42, 35, 29) are shown in Figs 7–9.

2.6. Finite element analysis method (FEM)

The design of the adjustable pylon model was tested by the Finite element method as a case study to know the ability of the pylon to bear the weight of the amputee child, the stresses generated, and the deformations that occur due to applying the patient's weight. The simulation process on the pylon requires the application of the boundary conditions on the pylon model. The boundary conditions include applying the weight of the amputation child, which is equivalent to the amount of ground reaction, on the upper top of the pylon while the pylon is fixed from its lower end. The applied boundary conditions can be shown in Fig. 10. Mesh convergence tests were done previously to determine the best mesh size. A mesh size of 1.5 mm was chosen for this model based on the convergence analysis. The nodes number are 6,455, and the elements are equal to 3,157. The meshing is done with the tetrahedrons method, as shown in Fig. 11. The effect of friction was not taken into account between the two parts of the pylon, because the bonding process between the two parts occurred as a result of tightening the screws. As for the numerical analysis of the screws, they can be found in Figs 12 and 13.

3. RESULTS AND DISCUSSIONS

The mechanical tests showed that carbon fiber has excellent properties that can be employed to manufacture prosthetic parts. The tensile test results can be observed in the stress-strain diagram shown in Fig. 14 where the yield

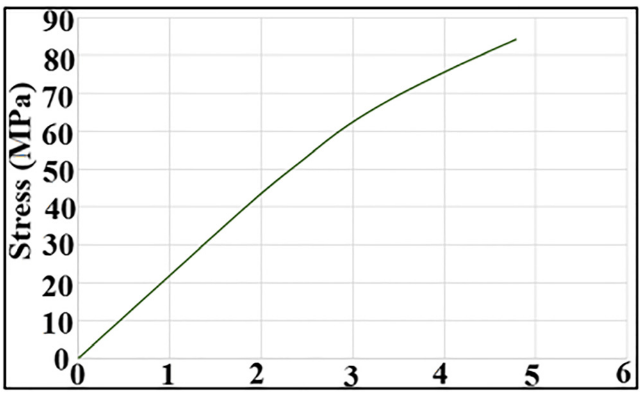

Fig. 14. The Stress-Strain diagram of the printed carbon fiber filaments specimen

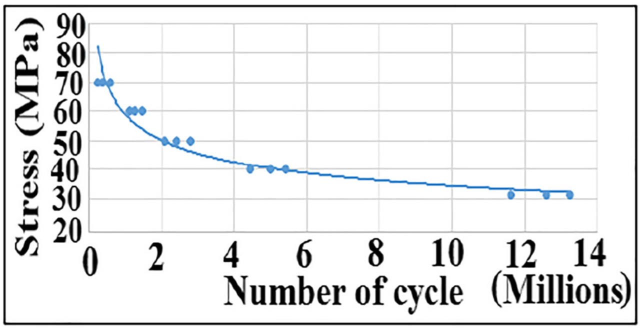

Fig. 15. The S-N curve of the printed carbon fiber filaments spermine

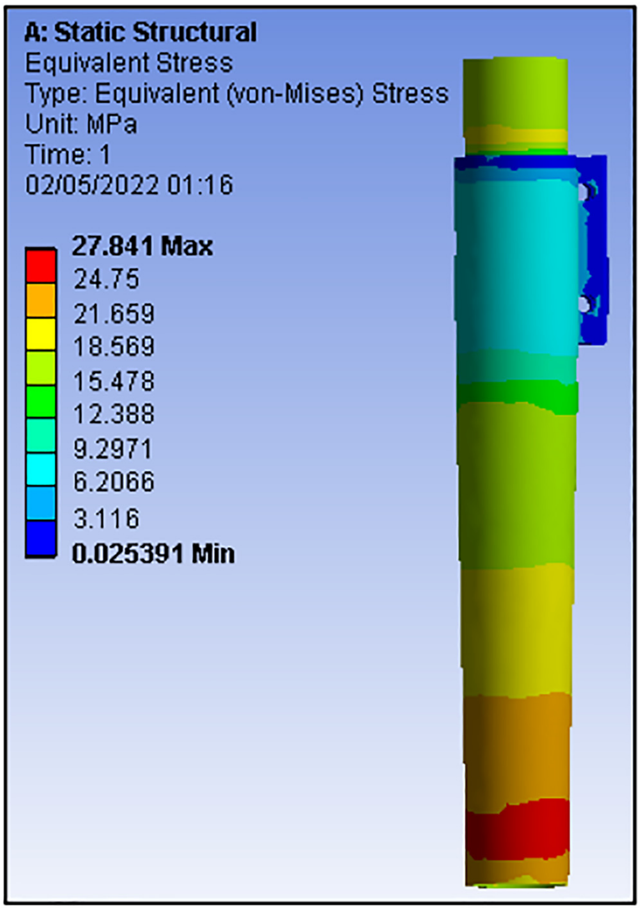

Fig. 16. The simulated adjustable pylon's Von Mises stress

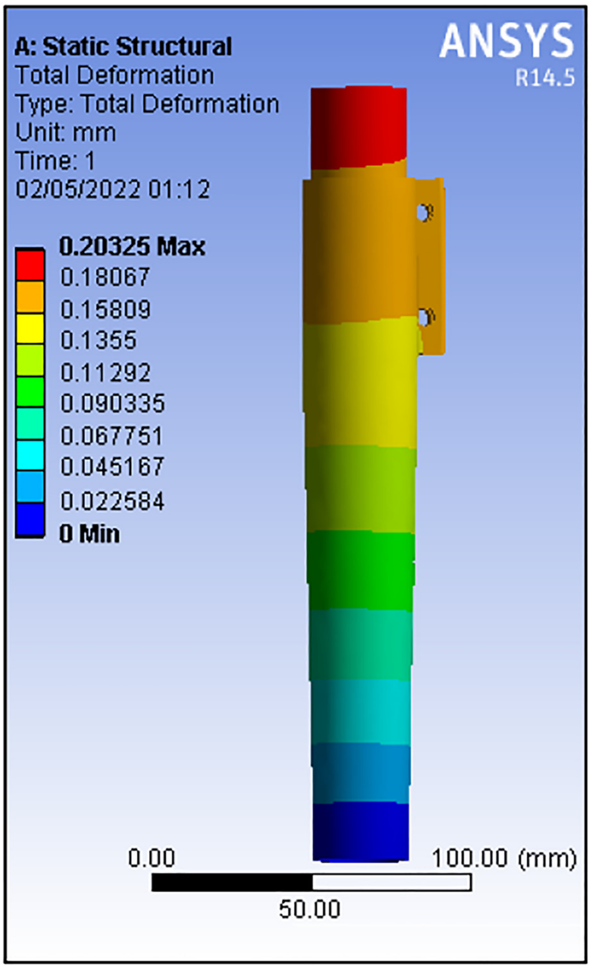

Fig. 17. Deformation values for pylon model analysis

stress = 53.25 MPa, Ultimate stress = 81.57 MPa, and modulus of elasticity = 2.14 GPa. Also, the fatigue test results in the (stress-number of cycles) curve are shown in Fig. 15. At the 1.32E + 07 cycle number, the carbon fiber's stress endurance equals 31 MPa. The results of the mechanical test agree with the results of previous or other works [5, 6, 8, 12].

The simulated pylon was weighted numerically, where its weight was equal to 110 g. The cost of carbon fiber filament of 110 g does not exceed 4$ for manufacturing the prosthetic pylon. The finite element analysis of simulated a geometrical pylon model shows the following results:

Von Mises stress analysis: As the patient dresses the lower limb prosthesis, the patient's weight will be applied as a compression force to the adjustable pylon, which is equivalent to the ground reaction force. Consequently, the load applied to the pylon will generate stresses in various region, as depicted in Fig. 16. The results show that the pylon has maximum Von Mises stress of 27.84 MPa. There is a significant difference between the Von Mises stress and yield stress values of carbon fiber filament material. The result means that the selected pylon model and material have passed in design.

The deformation analysis detected the total deformation of the adjustable pylon's values and location. The pylon's maximum deformation value is 0.2 mm, as shown in Fig. 17.

The results show that the Von Mises stress at the screws and nut has maximum value equal to 15.702 MPa as shown in Fig. 18. The bolt and nut material is steel-4310.

FEM software was used to analyze the pylon models and calculate the fatigue safety factor. The simulated pylon's safety factor is passed during design. It is worth noting that the safety factor value varies by region, depending on the

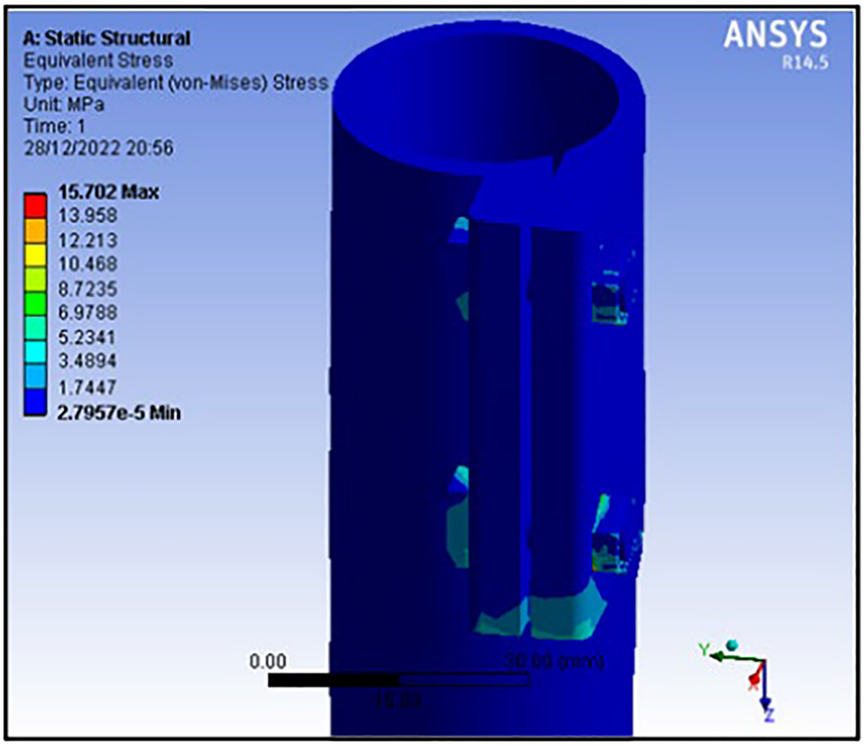

Fig. 18. Von Mises stress at the screws and nut

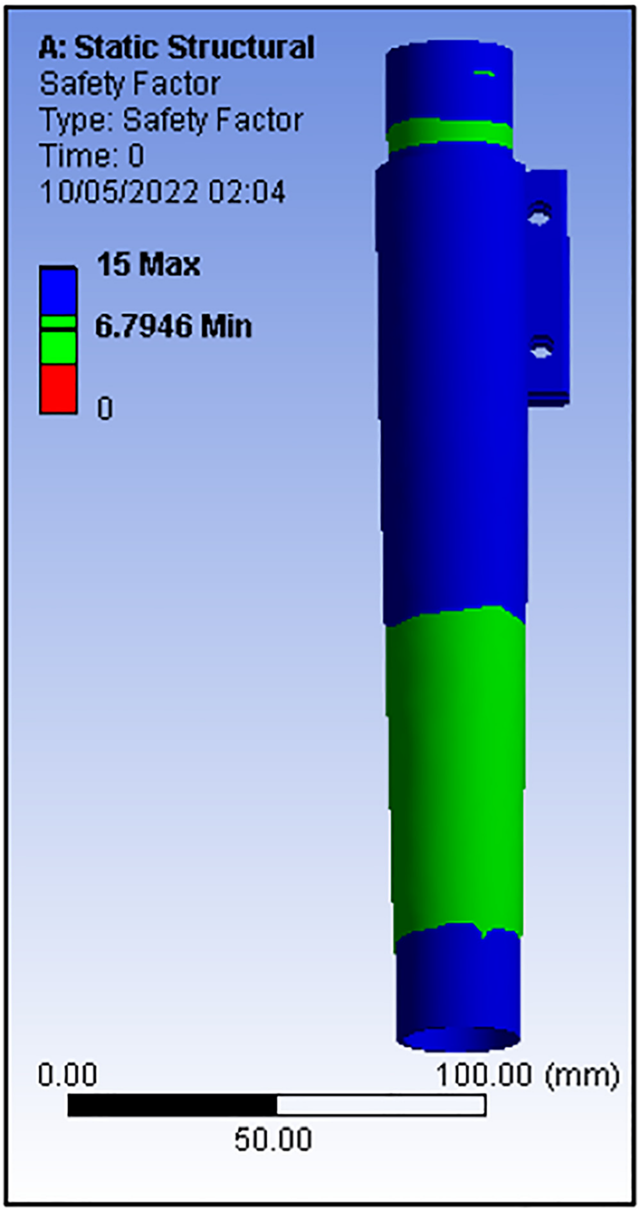

Fig. 19. The safety factor values for the simulated adjustable prosthetic pylon

stress distribution and endurance stress. Figure 19 shows that the safety factor is greater than (1.25). If the fatigue safety factor is equal to or greater than (1.25), the design will be safe [20].

Buckling analysis: buckling is the sudden deformation of a structural component under load, such as the bowing of a pylon under compression. The pylon is buckling if the value of the applied load is higher than the critical load of buckling; therefore, the pylon in this study is buckling simulated to know if it is buckled or not. The result showed the critical load on the pylon was equal to 2462.9 N. The results indicated the pylon could bear the patient's weight without buckling because the applied load resulting from the patient's weight is less than the critical load at which the pylon buckles. The buckling analysis is illustrated in Fig. 20. The results of numerical analysis are approximate and in agreement with the other works dealing with analyzing the prosthetic pylon [8, 12].

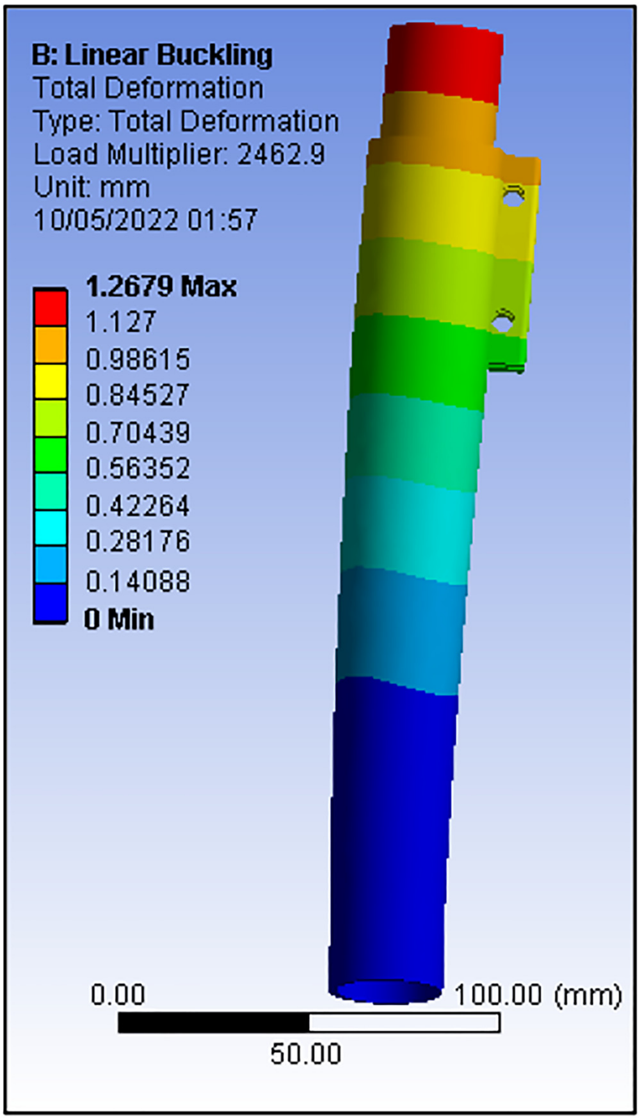

Fig. 20. The buckling analysis for the pylon model

4. CONCLUSIONS

1. The adjustable pylon has a low cost and costs less than the conventional pylon manufactured from metal. The cost of the printed pylon is 4$.
2. The new adjustable pylon design is lightweight, as its weight is 0.11 kg.
3. Due to the low cost, the pylon will be available to amputees with limited income or amputees in poor and developing countries.
4. The adjustable pylon is passed in design and has no mechanical failure when applying the patient's weight.
5. The new pylon design will save the costs incurred to buy a new pylon to compensate for the new length of the pylon due to the increase in the length of the healthy leg of the child.

6. The designed pylon has enough strength to bear the amputee's weight due to the stress generated in the pylon due to the applied ground reaction force having a big gap between the yield force and the safety factor value between (6.7–15).
7. The designed pylon is safe in terms of buckling.

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