AKADÉMIAI KIADÓ

3D printed carbon-fiber filament density effects on mechanical properties

Samah Falah Hasan[1*], Fahad Mohanad Kadhim[2] and Yasser Muhammed[1]

[1] Department of Aeronautical Technical Engineering, Al Farahidi University, Baghdad, Iraq

[2] Department of Prosthitic and Orthotics Engineering, University of Al-Nahrain, Baghdad, Iraq

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ABSTRACT

This study aims to select the suitable density of the material according to the mechanical properties needed by the 3D-printing application in which it will be used. 3D-printed carbon fiber filaments with different printing densities have been tensile, and a fatigue test was experimented with to find the mechanical properties. Furthermore, the modulus of elasticity, yield stress, and ultimate tensile strength of the material was determined by analyzing the stress-strain curves. The result shows that the parts printed with a high infill density give better mechanical properties, more time to build the object, more strength, and heavier weight than those printed with low infill density.

KEYWORDS

prosthetic, pylon, carbon-fiber, ANSYS, simulation

1. INTRODUCTION

The process of converting a digital file into a three-dimensional solid object is known as 3D printing or additive manufacturing. Additive processes are used to produce a 3D-printed object. An object is created in an additive process by layering material until the entire object is created [1]. The 3D printing technique was used for various reasons; involves obtaining an exact dimensional product despite the complexity of the inside structure, low manufacturing cost, high quality, and a more straightforward manufacturing method than other commonly used manufacturing techniques [2]. 3D printing is a quick manufacturing technology that allows for the printing of various materials using an extra process in which successive layers of materials are printed down in various configurations [3]. This technology eliminates the need to design, print, and glue together separate model parts; this revolutionary method for creating 3D models with inkjet technology helps to save time and cost. Another manufacturing technology commonly used to generate models, prototypes, and parts are Fused Deposition Modeling (FDM). It is one of the ways to get 3D printing. FDM works on an "additive" principle, which means that material is laid down in layers; Parts can be made with materials that come out of a coil, like plastic or metal wire [4]. The basic 3D printing process consists of these procedures: at first, using 3D Computer Aided Design (CAD) to create the model's design, then exporting the three-dimensional model as an (OBJ) or (STL) file, then converting the (STL) or (OBJ) file to a G-code file, and finally prototyping the part with a three-dimensional printer and finishing the printed part [5]. 3D printing is used in aerospace and architectural applications (e.g., creating complex lightweight and structural models) [6, 7], art fields [8, 9], and medical applications (e.g., printing tissues and organs) [10, 11], as well as prosthetics and orthotics parts [12, 13]. In this study, the idea of research will be applied in the field of prosthetic parts, specifically the pylon part. The prostheses are generally used to replace missing parts due to illness, injury (trauma), or missing since birth

*Corresponding author.
E-mail: eng.samahfalah90@gmail.com, Sama.Falah@alfarahidiuc.edu.iq

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(congenital), etc., [14–17]. Figure 1, illustrates that the prosthesis comprises several essential components: sockets, shank, ankles, and feet.

In this study, the pylon will be manufactured from carbon fiber with different densities to know the patient's weight that the pylon can bear for each density it is made of.

2. MATERIAL USED

The specimens and the pylon prosthesis used in this study were printed with carbon fiber filaments. The carbon fiber filaments had a diameter of 1.75 mm and were printed at 200–220 °C. This material was chosen because it is stronger, sturdier, dimensionally more stable, and lightweight and has appropriate mechanical properties for this application.

3. EXPERIMENTAL WORK

Different densities are used to print specimens. The 3D printer infill controls the density and the spacing between the printed lines inside the internal object structure, which expresses the ratio of the printed thermoplastic volume to the volume of air [18]. The infill density is expressed as a percentage; zero percent equals no infill, while one hundred percent equals a rigid print. There are many different percentages in between, and the changing value can have a wide range of applications. To change the mass of print, certain too clear utilization is required. A high infill density produces a solid part of the print with a higher weight than a printed part with a low infill density. In addition to the effect of the infill density on the weight of the printed part, it can affect the strength and buoyancy of the printed part. Variable density parts offer performance, weight, and strength advantages. It also minimizes the time and cost of construction. The CREALITY CR10 3D printer was used to print the carbon fiber specimens with a variable printing density (40, 60, 80, and 100%).

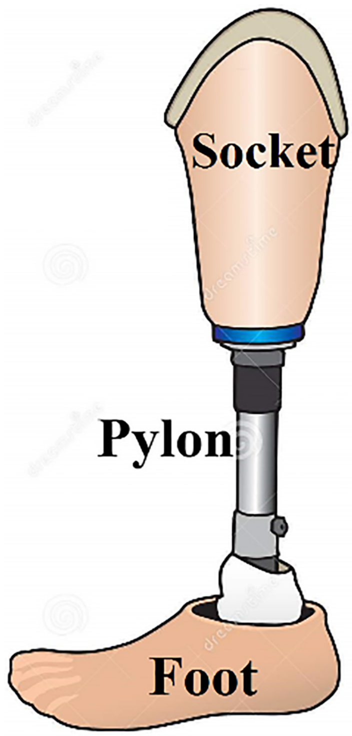

Fig. 1. The main parts of the below-knee prosthetic of amputees (*Source*: Authors' plot)

3.1. Tensile test

The carbon fiber samples are printed with a 3 mm thickness based on the ASTM-D638-V dimensions [19]. The standard dimension of the sample is shown in Fig. 2a. Three carbon fiber samples were printed by the 3D printer devise for each group. Samples were printed for four groups. Each group is printed with a specific density. The carbon fiber specimens were printed with a variable density (40, 60, 80, and 100%). The tensile test was achieved using the Testometric device.

3.2. Fatigue test

The specimen was drawn using 3D CAD based on the dimensions of the fatigue device test. The specimens were printed using a 3D printer device to produce six samples for each density group. The fatigue machine (HI-TEICH) was used to perform the fatigue test. The specifications of the fatigue specimen are demonstrated in Fig. 2b.

3.3. Prosthetic pylon model

In this study, the idea of changing the density of materials used in 3D printing and its effect on their mechanical properties will be applied to the prosthetic pylon. By using the finite element method, the mechanical behavior of the prosthetic pylon was studied when various patient weights were applied. Four carbon fiber prosthetic pylon models were simulated numerically with 40, 60, 80, and 100% densities.

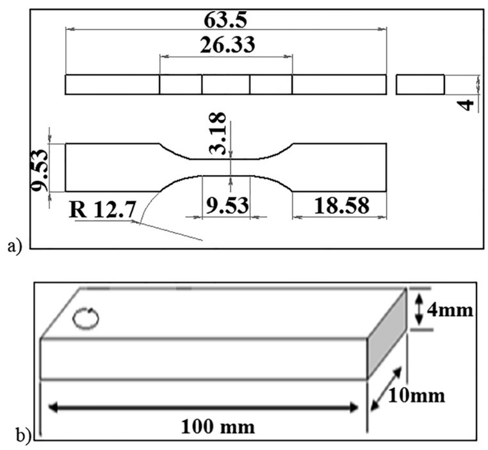

Fig. 2. a) The dimension of the printed specimen according to ASTM-D638-V; b) the dimension of the printed fatigue specimen

3.4. Numerical analysis of prosthetic pylon

Analyzing the pylon requires building a geometric model to apply the boundary conditions and obtain the results. Boundary conditions used to evaluate mechanical behavior in the pylon are represented in the form of generating stresses and deformations in the parts of the model. The boundary conditions include applying the patient's weight wearing the prosthesis in the form of a load on the upper end of the pylon and fixing it on the other end, as it is shown in Fig. 3. This study applied different patients' weights to each pylon model, which is assumed to be printed from carbon fiber with 40, 60, 80, 100% densities. When a person walks, whether healthy or an amputee, he goes through two main phases of the gait cycle: stance and swing. In the stance phase, both feet contact the ground, and the person's weight is distributed on both extremities. In the swing phase, the person supporting one extremity and the other is off the ground and swinging forward. In this phase, the person's total weight is applied to the supporting extremity. For example, if the person's weight is 60 kg, the force applied to the supporting extremity is 60·9.81 N. The patient's weight will be selected during the swing phase because the pylon exposing to the highest applied force value at this walking stage. Several weights are assumed for amputee patients of different ages. The weights of the case study considered 30, 60, 75, and 90 kg, which is equivalent to the following forces 294.3, 588.6, 735.75, 882.9 N. Several weights have been suggested to simulate the pylon because the study assumed that the pylon is printed from several densities. In the simulation process, the relationship between the printing density of each model with its ability to bear the assumed weights will be studied.

4. RESULTS AND DISCUSSIONS

Figure 4 shows the stress-strain curve of carbon-fiber filament specimens at a variable printing density (100, 80, 60, and 40%), respectively. The result shows the mechanical properties increased with increasing the density of the printed specimen due to increasing the weight to strength ratio. Figures 5–8 show the fatigue curve of carbon-fiber filament specimens at a variable printing density (100, 80, 60, and 40%), respectively. The tensile and fatigue test values of printed specimens at a variable density can be summarized in Table 1. The result shows the stress endurance increased with increasing the printed specimen's density because the specimen with low density has porosity inside the structure. These porosities work as a crack, which is propagation and causes sudden failure during applied cyclic load.

When the loads are applied to the different pylon's densities, the Von-Misses will generate. The value of Von-

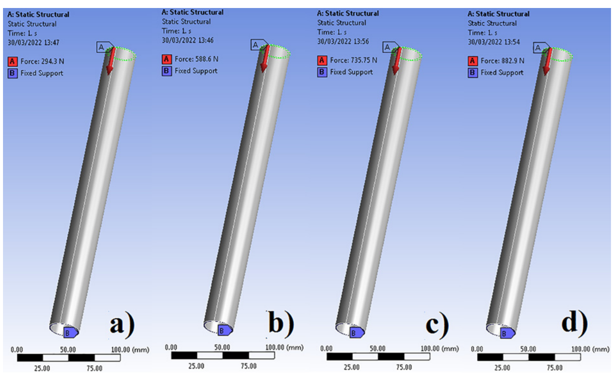

Fig. 3. The boundary condition applied on a prosthetic pylon with a load, a) 294.3 N, b) 588.6 N, c)735.75 N, d)882.9 N

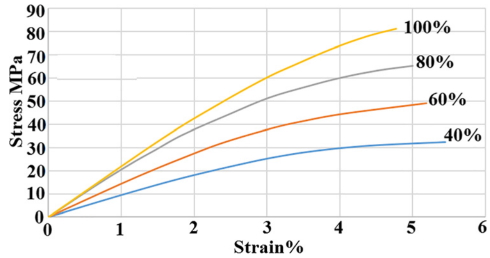

Fig. 4. The stress-strain diagram of carbon fiber filament at different specimens densities

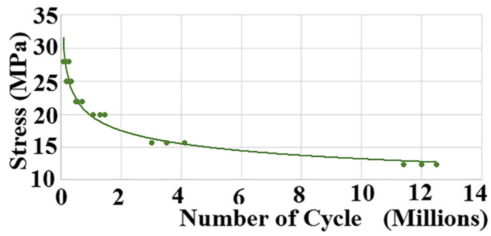

Fig. 5. The stress-number of cycle relation curve of a specimen with a density of 40%, $y = 213.43x^{-0.172}$, $R^2 = 0.9637$

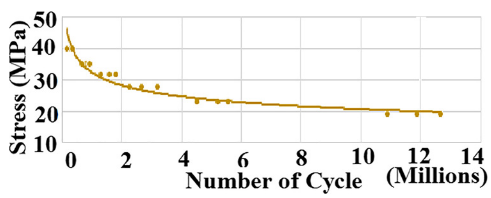

Fig. 6. The stress-number of cycle relation curve of a specimen with a density of 60%, $y = 2.474x^{0.164}$, $R^2 = 0.9429$

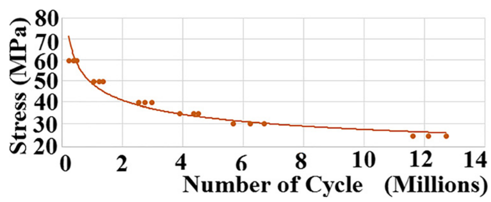

Fig. 7. The stress-number curve of a specimen with a density of 80%, $y = 2.1916x^{0.256}$, $R^2 = 0.9514$

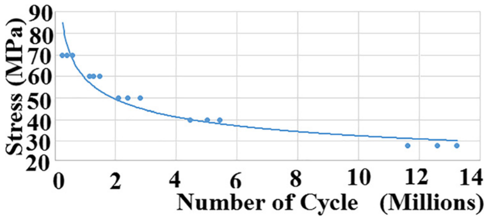

Fig. 8. The stress-number curve of a specimen with a density of 100%, $y = 9.7212x^{0.252}$, $R^2 = 0.9298$

Table 1. The mechanical properties of carbon fiber filament at different specimen's densities

Density	Yield stress	Ultimate stress	Modules of elasticity	Endurance stress (MPa)	Weight
40%	23	32.43	0.93	12.5	4.85
60%	33.5	49.14	1.38	20	5.93
80%	43.1	65.35	1.82	24	8.21
100%	53.25	81.57	2.14	30	9.1

Misses stress remains constant at different densities for the same load; for example, the Von-Misses stress is equal to 15.62 MPa for applied 294.3 N for the pylon with a density 40, 60, 80, and 100%. Von-Misses stress value equals to 15.62, 24.99, 37.48, 45.29 MPa for applied load equal to 294.3, 588.6, 735.75, 882.9) N, respectively, as it is shown in Fig. 9.

The load applied on the pylon works as a compression force. The pylon will undergo deformation when exposed to the compression load. The pylon with a density of 40% deformed with a 0.53, 1.077, 1.34, and 1.61 mm for a load of 294.3 N, respectively as it is shown in cases a), b), c), and d) in Fig. 10, while the pylon with a density 60% deformed with a 0.36, 0.72, 0.9, 1.08 mm or a load 588.6 N, respectively as it is shown in cases a), b), c), d) in Fig. 11, and the pylon with a density 80% deformed with a 0.275, 0.55, 0.688, 0.826 mm for a load 735.75 N, respectively as it is shown in cases a), b), c), d) in Fig. 12. Finally the pylon with a density 100% deformed with a 0.24, 0.46, 0.58, 0.7 mm for a load 882.9 N, respectively as it is shown in cases a), b), c), d) in Fig. 13. The results

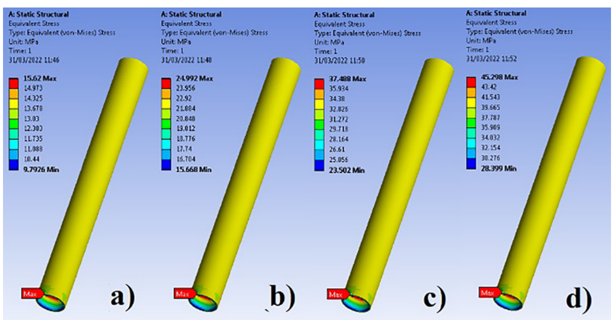

Fig. 9. The Von-Messis stresses analysis of prosthetic pylon with a load, a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

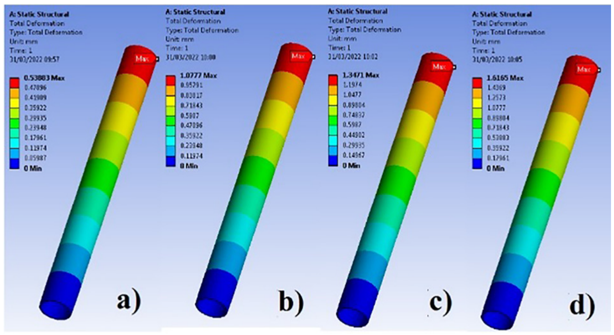

Fig. 10. Deformation analysis for the pylon assumed printed with 40% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

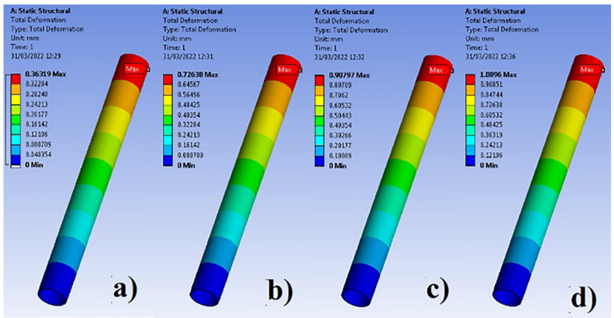

Fig. 11. Deformation analysis for the pylon assumed printed with 60% density with a load a) 294.3 N, b) 588.6 N, c)735.75 N, d) 882.9 N

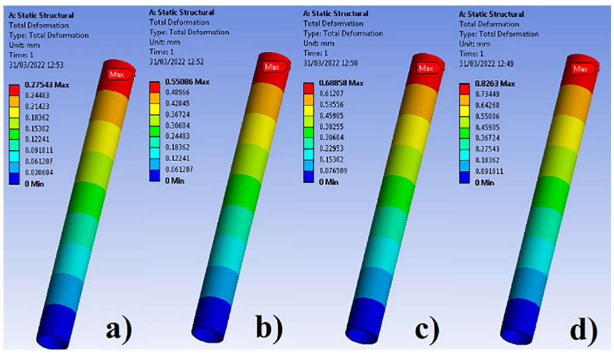

Fig. 12. Deformation analysis for the pylon assumed printed with 80% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

show the value of deformation decreased with increasing the density of the pylon due to the decrease in the porosity inside the structure and the pylon becoming a more rigid texture.

Also the result shows the safety factor value when applied the 294.3,88.6,35.75, 82.9 N equal to 6.6, 1.3, 0.66, 0.41, respectively for a pylon with a density of 40% as it is shown in cases a), b), c), d) in Fig. 14, equal to 10.11, 5, 1, 0.37 for a pylon with a density 60% as it is shown in cases

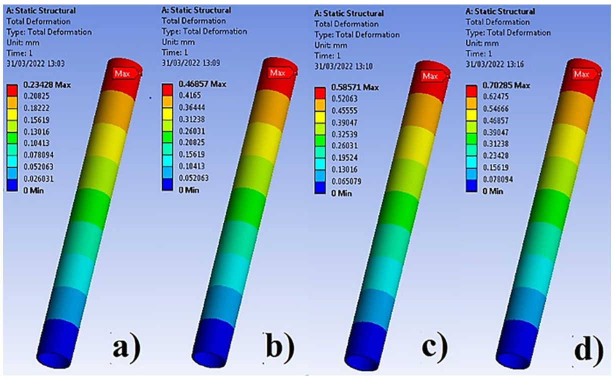

Fig. 13. Deformation analysis for the pylon assumed printed with 100% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

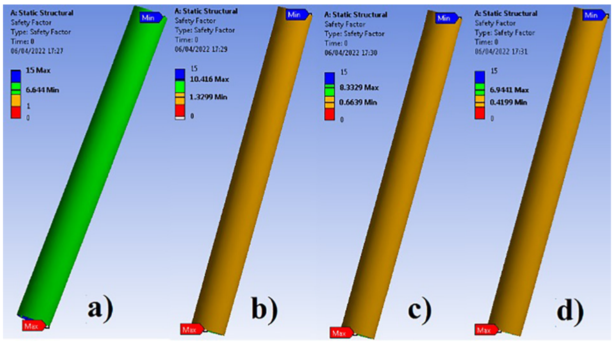

Fig. 14. Safety factor analysis for the pylon assumed printed with 40% density with a load a) 294.3 N, b) 588.6 N, c)735.75 N, d) 882.9 N

a), b), c), d) in Fig. 15. Also equal to 12.7, 6.38, 5.1, 4.25, respectively of a pylon with a density 80% as it is shown in cases a), b), c), d) in Fig. 16, while equal to 14, 7.4, 5.95, 4.96, respectively of a pylon with a density 100% as it is shown in cases a), b), c), d) in Fig. 17. The fatigue safety factor will be safe in design if the safety factor is equal to or higher than 1.25 [20]. From previous results, note the pylon with high density is safer to withstand the high weight.

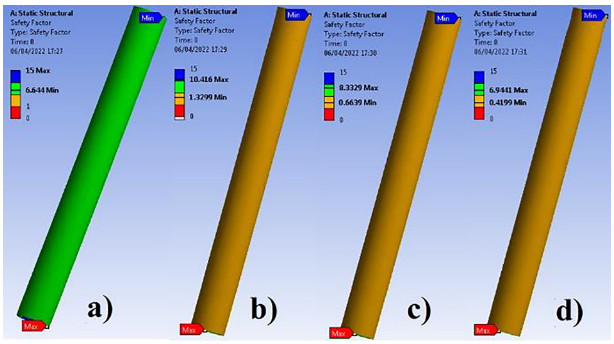

Fig. 15. Safety factor analysis for the pylon assumed printed with 60% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

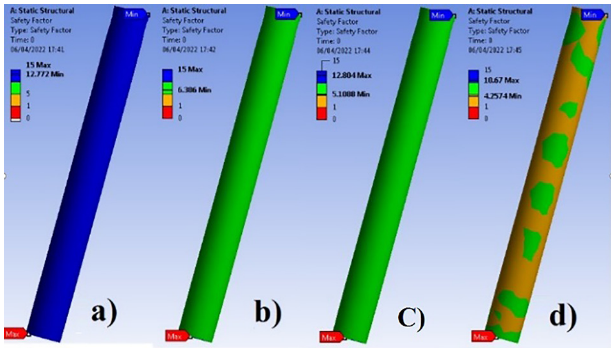

Fig. 16. Safety factor analysis for the pylon assumed printed with 80% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

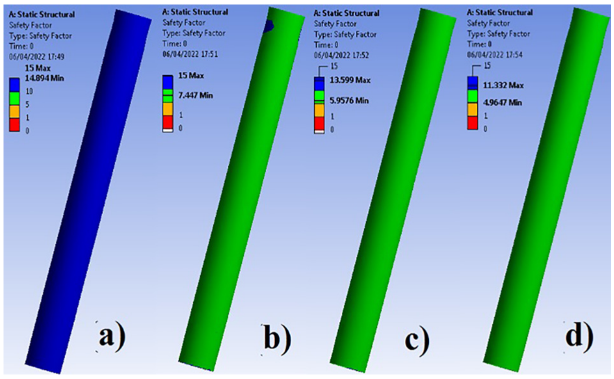

Fig. 17. Safety factor analysis for the pylon assumed printed with 100% density with a load a) 294.3 N, b) 588.6 N, c) 735.75 N, d) 882.9 N

5. CONCLUSIONS

- The mechanical properties of carbon fiber filaments increase with the increasing density of filaments printed using a 3D printer;
- The pylon printed from high-density carbon filament can bear a higher amputated weight than the pylon printed from low-density carbon filament;
- The deformation value of a pylon printed from a higher density filament is less than the deformation value of a pylon printed from a lower density filament;
- The pylon printed from high-density carbon filament is safer when using high amputee weight than the pylon printed from low-density carbon filament;
- From the obtained results concluded that the density of carbon fiber printed filaments was determined according to the application used and the load applied to the printed part;
- Determines the density of carbon fiber filaments required for printing to reduce the time needed for printing and the amount of filaments used for printing.

REFERENCES

[1] J. Q. Al-Maliki and A. J. Q. Al-Maliki, “The processes and technologies of 3D printing,” *Int. J. Adv. Comput. Sci. Technol.*, vol. 4, no. 10, pp. 161–165, 2015.

[2] M. S. Al-Din Tahir and F. M. Kadhim, “Design and manufacturing of new low (weight and cost) 3D printed pylon prosthesis for amputee”, *IOP Conf. Series: Mater. Sci. Eng.*, vol. 1094, 2021, Paper no. 012144.

[3] D. M. Patel, “Effects of infill patterns on time, surface roughness and tensile strength in 3D printing”, *Int. J. Eng. Develop. Res.*, vol. 5, no. 3, pp. 566–569, 2017.

[4] V. Srisairam and C. D. M. Kumar, “Rapid prototyping – additive/ solid free form manufacturing in automobile engineering,” *Int. J. Eng. Develop. Res.*, vol. 3, no. 4, pp. 799–802, 2015.

[5] S. Yang, Y. Tang, and Y. F. Zhao, “A new part consolidation method to embrace the design freedom of additive manufacturing,” *J. Manuf. Process*, vol. 20, Part 3, pp. 444–449, 2015.

[6] E. Kroll and D. Artzi, “Enhancing aerospace engineering students’ learning with 3D printing wind-tunnel models”, *Rapid Prototyp. J.*, vol. 17, no. 5, pp. 393–402, 2011.

[7] K. V. Wong and A. Hernandez, “A review of additive manufacturing,” *Int. Sch. Res. Notices*, vol. 2012, 2012, Pape no. 208760.

[8] D. B. Short, “Use of 3D printing by museums: Educational exhibits, artifact education, and artifact restoration,” *3D Print. Addit. Manuf.* vol. 2, no. 4, pp. 209–215, 2015.

[9] P. Walters and K. Davies, “3D printing for artists: Research and creative practice,” *Rapport*, vol. 1, pp. 12–15, 2010.

[10] S. V. Murphy and A. Atala, “3D bioprinting of tissues and organs,” *Nat. Biotechnol.*, vol. 32, no. 8, pp. 773–785, 2014.

[11] H. Chen, X. Yang, L. Chen, L. Y. Wang, and Y. Sun, “Application of FDM three-dimensional printing technology in the digital manufacture of custom edentulous mandible trays,” *Sci. Rep.*, vol. 6, 2016, Paper no. 19207.

[12] F. Tavangarian, C. Proano, and C. Zolko,”Performance of low-cost 3D printed pylon in lower limb prosthetic device,” in *148th Annual Meeting and Exhibition of The Minerals, Metals and Materials Society*, San Antonio, United States, Mar. 10–14, 2019, pp. 1207–1215.

[13] B. Rochlitz and D. Pammer, “Design and analysis of 3D printable foot prosthesis,” *Period. Polytech. Mech. Eng.*, vol. 61, no. 4, pp. 282–287, 2017.

[14] F. M. Kadhim, M. S. Al-Din Tahir, and A. T. Naiyf, “The effect of vibrations on the mechanical properties of laminations,” *Pollack Period.*, vol. 17, no. 1, pp. 62–65, 2022.

[15] S. F. Awad and F. M. Kadhim, “Compare EMG signals by using Myo-Ware muscle sensor and Myo-Trace device for measuring the electrical activity of the muscles”, in *AIP Conf. Proc.*, vol. 2386, no. 1, 2022, Paper no. 040009.

[16] S. F. Awad, F. M. Kadhim, W. S. Aboud, and M. S. Al-Din Tahi, “Strain and deformation measurement for prosthetic parts using the Arduino microcontroller and strain gauges instruments”, *Int. J. Mech. Eng.*, vol. 7, no. 1, Part 1, pp. 1–7, 2022.

[17] F. M. Kadhim, E. Z. Gheni, A. T. Naiyf, and M. S. Al-Din Tahir, “Optimal material selection based on finite element method for manufacturing hip implant,” *Pollack Period.*, vol. 17, no. 3, pp. 60–64, 2022.

[18] M. W. Barclift and C. B. Williams, “Examining variability in the mechanical properties of parts manufactured via polyjet direct 3D printing,” Department of Mechanical Engineering, Virginia Tech., Technical report, pp. 876–890, 2012.

[19] *ASTM D638:2000*, Standard test method for tensile properties of plastics, American Society for Testing and Materials International, 2000.

[20] B. A. Miller, R. J. Shipley, R. J. Parrington, and D. P. Dennies, *Failure Analysis and Prevention*. ASM International Handbook, 2002.