Alpha Journal of Engineering and Applied Sciences
(2023) 1/ 1: 1 – 9
Alfa Mühendislik ve Uygulamalı Bilimler Dergisi
(2023) 1/1: 1 – 9

Research Article

Received	Accepted	Published
24/09/2023	19/12/2023	31/12/2023

Design of an Artificial Femur Scaffold for Bone Tissue Engineering

Yusuf SAĞLAM [a], Harun GÖKÇE [b, *], Neslihan TOP [b], İsmail ŞAHİN [b]

[a] Department of Industrial Design Engineering, Graduate School of Natural and Applied Sciences, Gazi University, Ankara, Türkiye
[b] Department of Industrial Design Engineering, Faculty of Technology, Gazi University, Ankara, Türkiye
*Corresponding author's e-mail address: harungokce@yahoo.ca

Abstract
With the technological developments in bone tissue engineering, direct production of bone scaffolds by additive manufacturing methods has become possible. This has led to the design of bone scaffolds in more complex structures and various interventions on pore sizes. This study involves the design of a new and unique cellular unit suitable for additive manufacturing methods for the femur and its integration into the bone scaffold. The lattice structure of the unit cell design has been converted into a solid model in a CAD environment first as a wireframe and then by sweeping in a circular cross-section. The bone model has been obtained from the CT data of the femur bone has been transferred to the *nTopology* software. Finally, cellular unit elements have been applied to the bone geometry. A finite element model has been prepared to measure the strength of the resulting scaffold. In this way, the behavior of the lattice structures against the loads on the bone has been determined.

Keywords: *Artificial bone scaffold, bone tissue engineering, femur bone, additive manufacturing*

Kemik Doku Mühendisliği İçin Yapay Femur İskelesi Tasarımı

Özet
Teknolojik alanda yaşanan gelişmelerin kemik doku mühendisliği alanında sağladığı imkanlar ile kemik iskelelerinin eklemeli imalat yöntemi ile doğrudan üretimi mümkün kılınmıştır. Bu durum kemik iskelesinin daha karmaşık yapılarda tasarlanabilmesini, gözenek boyutları üzerinde çeşitli müdahalelerin gerçekleştirilebilmesine yol açmıştır. Bu çalışmada femur kemiği şaft bölgesi kırıklarında kullanılmak üzere eklemeli imalat yöntemine uygun yeni ve özgün bir hücresel birim tasarımı ile kemik iskelesi oluşturulmuştur. Birim hücre tasarımı kafes yapısı CAD ortamında önce tel kafes olarak, ardından dairesel kesitte süpürülerek katı modele dönüştürülmüştür. Femur kemiği CT verisinden kesit alınarak elde edilen kemik modeli *nTopology* ortamına aktarılmıştır. Son olarak hücresel birim elemanları kemik geometrisine uygulanmıştır. Elde edilen iskelenin dayanımını ölçmek adına sonlu elemanlar modeli hazırlanmıştır. Femur kemiğine karşılık gelen mekanik yüklerin tespiti sonrası analiz işlemleri gerçekleştirilmiştir.

Anahtar kelimeler: *Yapay kemik iskelesi, kemik doku mühendisliği, femur kemiği, eklemeli imalat*

1. Introduction

The additive manufacturing (AM) method has gained significant attention and witnessed significant developments in product development processes in recent years. This method has been widely used in many industries, including automotive, aerospace, healthcare, architecture, fashion, and toys. Notably, this method can more easily and cost-effectively meet customer demands that generate high costs with existing production processes. The increasing requirements for lightweight, high-strength, rapidly manufacturable, functional, and ergonomic products have made AM an ideal condition. Additionally, AM offers significant potential in areas such as rapid prototyping, mass production, customized manufacturing, and sustainable production, and it is predicted to play an even more critical role in the field of manufacturing technologies in the future. With its capabilities, it has advantages over traditional manufacturing methods. Today, it stands out, especially for its ability to quickly transform Computer-Aided Design (CAD) into physical products and facilitate the production of complex structures [1-2].

In traditional manufacturing, the production of parts is often a complex process. The output of a part typically involves a series of operations such as cutting, drilling, shaping, and assembly of the material. Production processes with these methods are often time-consuming and require more labor to implement a design. Moreover, implementing changes in the invention can also be time-consuming. The AM method simplifies this process significantly. The design is created as a digital model in a computer environment and is then transformed into a physical object by sending it to a device like a 3D printer. This allows for the conversion of a design into prototype production or mass production to be accomplished much more quickly [3]. Complex geometries, organic shapes, and nested structures that could be limited and costly due to conventional manufacturing methods can be produced at lower costs with AM processes.

The increase in design iterations during the product development process means that improvement activities continue until the final design is achieved. The iterative design approach makes it possible to achieve better design results and optimize the product's performance. The use of AM in the defense and aviation industry proves these advantages. Porous internal structures and optimized geometries produced using this method reduce the weight of platforms aiming for high payload capacity and increase fuel efficiency. One of the most researched topics in recent years due to its advantages in this field is Design for Additive Manufacturing (DfAM). Neslihan et al. utilized DfAM capabilities to construct an artificial bone scaffold. In their study, they designed three different cellular units, namely scutoid, regular dodecahedron, and biomimetic, which were used in redesigning the L4 bone based on CT data, and their strength was examined based on the loads applied to the bone [4]. Yavuz, in his study on lattice designs, expressed that the most suitable geometry for bone development is the gyroid, which is a surface-based geometry. He designed a fixation implant for the humerus bone with a gyroid lattice structure and obtained stresses on the implant and bone under load through Finite Element Analysis (FEA). This allowed for the analysis of the reliability of the lattice structure [5].

There is extensive literature on the use of lattice structures in various disciplines. In a study aimed at reducing the weight of suspension arms used in the front wheels of vehicles, three different lattice structures were employed. Aslan's work was conducted under static load conditions as a reference point for lattice structures. The differences between lattice structures were elucidated using FEA methods [6]. Wang et al. proposed a new structural design methodology for optimizing graded lattice structures. The study indicated that the targeted strategy significantly reduced computational time for solving homogeneous equations and enhanced design efficiency [7]. In this study, Şükrü compared the structural behaviors of solid and porous polymer foam structures produced using AM through mechanical testing. He demonstrated the success of thermoplastic polyurethane filaments in achieving impact-absorbing behavior for microcellular polymeric structures [8]. Egan et al. developed a computational approach to evaluate the characteristics of eight different lattice structures for bone tissue engineering applications. These characteristics include porosity, pore size, surface-to-volume ratio, elastic modulus, shear modulus, and permeability. The lattice topologies were created by patterning beam-based unit cells, and design parameters for beam diameter and unit cell length were determined. FEA was performed for each topology, quantitatively determining how elastic modulus and shear modulus changed with porosity and how permeability varied with the square of the surface-to-volume ratio [9]. In his study, Yeşiloğlu aimed to compare the mechanical properties of parts made from PLA material with different infill geometries and densities. Unit geometries with octet, gyroid, and cross lattice structures were modeled with dimensions of 5 x 5 x 5 mm. Experimental samples were produced at relative densities of 50%, 30%, and 20%. Tensile, compression, and impact tests were conducted to investigate the mechanical behavior of these parts and determine the most suitable unit cell structure in terms of compared mechanical properties [10].

In this study, an artificial femur bone with a lattice geometry was designed. The hexagonal unit cell model designed in 3D in a CAD environment was replicated by sweeping on the circular axis. FEA was applied to the obtained circular geometry to determine its structural behavior against the loads applied to the femur bone. The circularly replicated hexagonal lattice geometry was trimmed from the surface model of the femur bone outer geometry to form the femur bone inner structure. The results obtained show that the lattice structures will be suitable for use in artificial bone scaffolding.

2. Experimental Procedure

In the initial stage of the study, the 3D circular design of the hexagonal lattice structure, which was determined as the lattice model, was prepared in a CAD environment. Subsequently, the structural strength of the lattice under static load was obtained using the FEA method. Finally, information was provided for the AM processes. The process steps are introduced below in sequence.

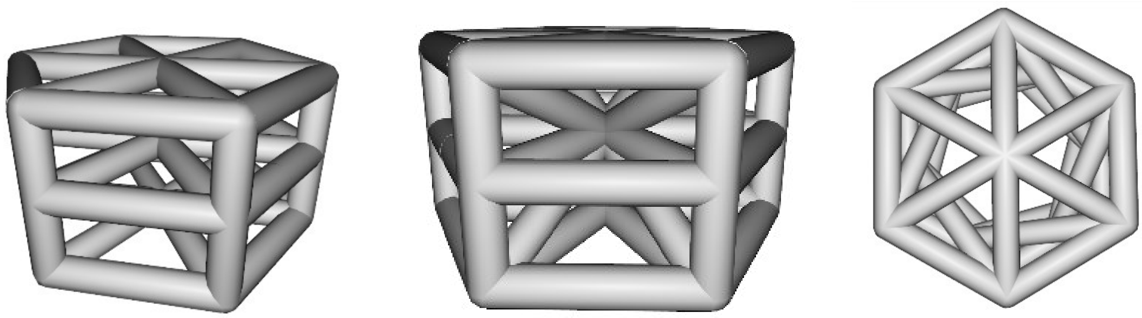


Figure 1. 3D model of hexagon strut-based lattice geometry

The process of creating the lattice geometry was successfully implemented using wireframe and solid modeling approaches. In particular, modeling lattice structures with strut elements as wireframes significantly accelerates the design process. While surface-type lattice structures are modeled using surface modeling approaches, strut-type structures are constructed with wireframe geometry, followed by solid modeling of the unit cell. Below, the design process of the hexagonal lattice structure is detailed (Figure 1).

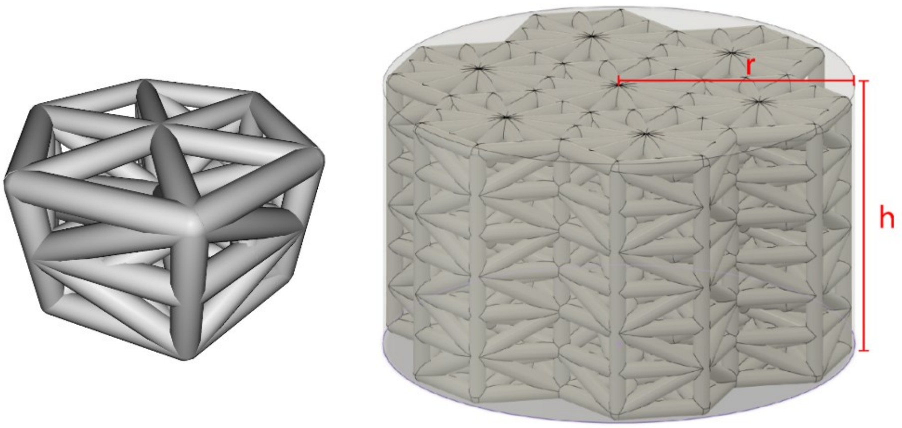


Figure 2. Circular pattern hexagonal lattice model

The elements for constructing unit cells were modeled as wireframes, as shown in Figure 1. With reference to the nozzle diameter used in the 3D printer, a 0.4mm circular cross-section wireframe was swept over the lattice structure, resulting in 3D unit solid geometries. To achieve a 20mm circular formation of unit elements, they needed to be replicated in the same proportion. Figure 2 provides replicated geometries within a cylinder structure. The variation in lattice structures' geometries leads to differences in the pattern methods when duplicated as cylinders.

For the hexagonal unit cell model, 5-unit cells were patterned along the X, Y, and Z axes in a manner that they would contact each other at flat edges (Figure 3). Mock-up models were used to determine the most suitable replication method for the cell models. Replicating complex and asymmetric polyhedral lattice structures can pose challenges. Therefore, evaluating ideal replication approaches is appropriate. In this study, the cells were prepared from paper mock-ups, and replication methods were identified. Below are mock-ups prepared for three different lattice models (Figure 3).

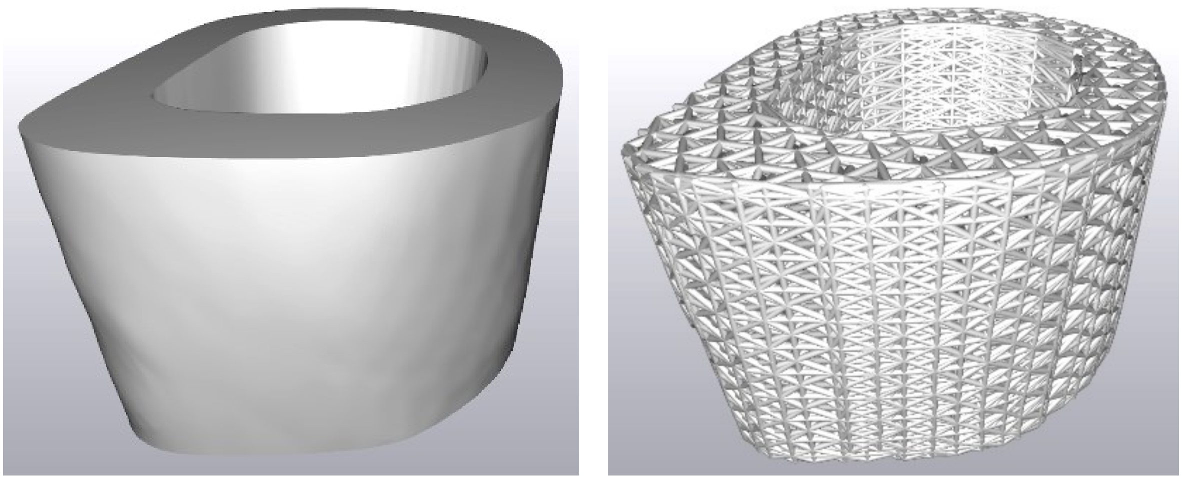


Figure 3. Hexagonal lattice model in the femur bone structure

3. Lattice Model Structural Analysis

The Ansys Workbench software was used for the static analysis of the designed hexagonal lattice geometry. Initially, rigid plates with a thickness of 2 mm were placed on the bottom and top of the replicated cell models. FEA is an approach that involves breaking down the geometry into a finite number of elements to obtain information about the geometry by solving a finite number of equations instead of an infinite number. Table 1 provides information about the number of elements and element size for the solution grid of the 3D model used in the analysis.

Table 1. Lattice geometry number of mesh, number of nodes and mesh size

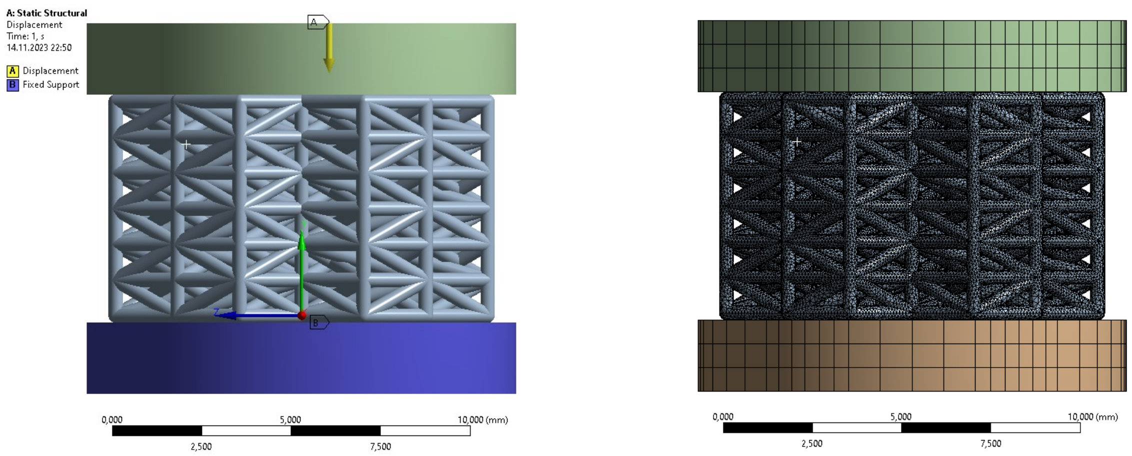
Geometry D: 20mm	Number of Nodes	Number of Meshes
Hexagonal Lattice Model	419914	23340

Table 2. ABS mechanical properties for FEA studies

Material	Young Modules (MPa)	Poisson Ratio (v)
ABS Plastic	2240	0.38

The material chosen for the FEA of the geometries was Acrylonitrile Butadiene Styrene (ABS) plastic. ABS plastic is resistant to acids and bases and has good electrical insulation. ABS plastic material is a polymer obtained by polymerization of styrene acrylonitrile in polybutadiene. The substance ratios of 20% acrylonitrile, 20% butadiene, 60% styrene form the characteristics of the material. Styrene gives the plastic shine and a good surface. It can be used in the temperature range of -20 and 60 degrees. Its most important features are that it is not harmful to the environment and is used in products with durable bodies. Table 2 shows the modulus of elasticity and Poisson's ratio of ABS used in the structural analysis.

The modulus of elasticity refers to the linear elastic behavior of the material, meaning that as the amount of stress increases in direct proportion, the amount of deformation that occurs increases. Different materials can have different moduli of elasticity. For example, rigid materials such as steel may have a high modulus of elasticity, while flexible materials such as rubber may have a low modulus of elasticity.



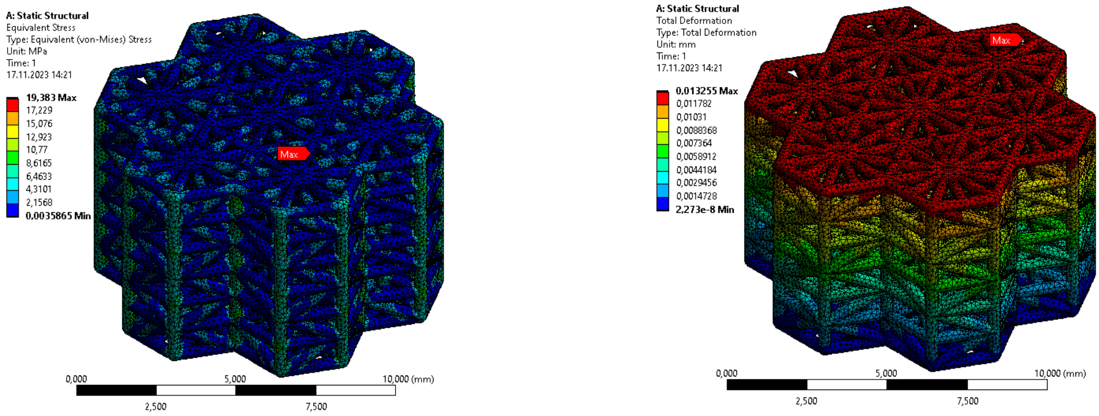
(a) (b)

Figure 4. a) 3D FEA model b) FEM boundary conditions

Poisson's ratio is a material property that describes the elastic behavior of a material. Poisson's ratio shows how much a material compresses or stretches in the transverse direction while being stretched longitudinally. Poisson's ratio can vary between negative values. Negative values mean that the material tends to compress in the transverse direction when stretched longitudinally, while positive values mean that the material tends to expand in the transverse direction when stretched. For example, for most metallic materials, Poisson's ratio has a positive value, meaning that it expands in the transverse direction when stretched longitudinally. Poisson's ratio is important in fields such as materials engineering and structural analysis. Understanding the elastic behavior of materials is important for the correct analysis of designs and structures. Poisson's ratio can be obtained from sources such as material tests or material property tables.

4. Finite Element Analysis Results

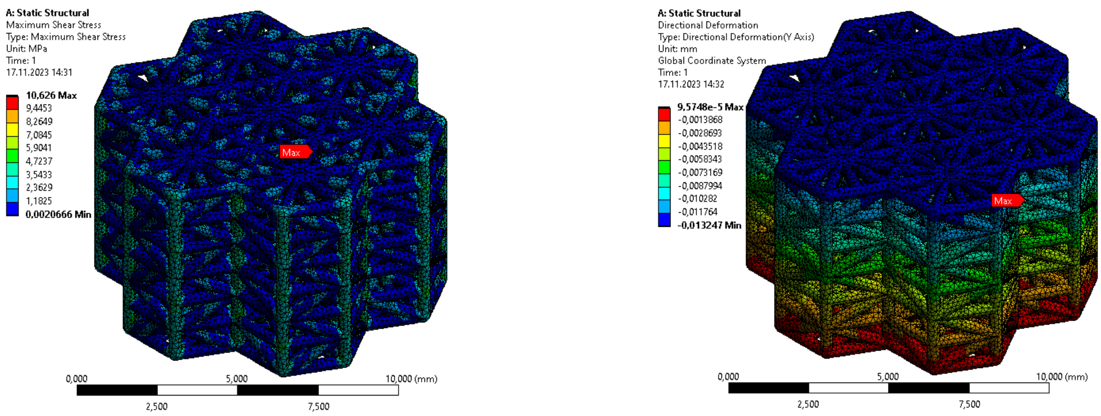
Ansys Workbench software was used to obtain the results of the structural behavior of the designed hexagonal truss model by FEA. In the study, the model is held between plates defined as 5 mm rigid, and the bottom plate is fixed with 0 degrees of freedom in each region. The connection type between the plate and the lattice is defined as "bonded". A similar definition was made for the top plate and lattice geometry contact surfaces and a distributed load of 100N was applied on the top plate. Figure 5 shows the boundary conditions applied in the FEA study.



(a) (b)

Figure 5. a) von Mises stress result b) Maximum displacement result

Von Misses stress is a type of structural analysis performed to determine whether the flexible material undergoes shape change when the stress is equal to its limit. The von Misses stress analysis of the geometry used is shown in Figure 5.



(a) (b)

Figure 6. a) Maximum shear stress result b) Z-Directional deformation result

The Shear Stress Result provides insights into the distribution of shear forces within a structure subjected to applied loads. It illustrates the intensity and direction of shear stresses at different points, aiding in the assessment of potential weak points or areas prone to deformation. On the other hand, the Displacement Result provides information about the displacement or movement of nodes within the analyzed structure under the specified loading conditions. It quantifies the magnitude and direction of deformations, offering a comprehensive understanding of how the structure responds to applied forces (Figure 6).

5. Conclusions

The utilization of AM methods in bone tissue engineering has significantly advanced the production of intricate designs for bone scaffolds. This study successfully demonstrated the feasibility of employing FDM, a specific AM method, to fabricate the melt layer of the bone scaffold with reduced material consumption. The incorporation of circular designs in the selected lattice models showcases the adaptability of AM techniques to complex structures. The structural analysis conducted through finite element modeling provided valuable insights into the strength and resilience of the lattice structures under various loads.

The benefits derived from AM methods, particularly FDM, extend beyond the mere production process. The cost-effectiveness and minimal material usage associated with FDM not only contribute to economic savings but also result in lighter parts, addressing a critical aspect of implantable devices. The ability to manufacture intricate designs without compromising on production time further underscores the efficiency of AM techniques in bone tissue engineering. Moreover, the study introduced a novel cellular unit designed specifically for additive manufacturing, tailored to the femur bone. The conversion of the lattice structure into a solid model using CAD techniques allowed for enhanced control and precision in the manufacturing process. The integration of this cellular unit into the bone scaffold represents a significant step forward in the pursuit of more effective and patient-specific solutions in orthopedic applications.

The findings of this research contribute to the growing body of knowledge in bone tissue engineering, offering a blueprint for the development of robust and lightweight bone scaffolds. As technology continues to evolve, the innovations presented in this study pave the way for further advancements in the field, with potential applications in the design and manufacturing of next-generation orthopedic implants.

Acknowledgements and Funding

This study was carried out within the scope of Gazi University Faculty of Technology Industrial Design Engineering 2021 Undergraduate Graduation Project.

Author Contribution

Yusuf Sağlam: Conceptualization, Methodology, Writing – original draft. Harun Gökçe: Writing – review & editing. Neslihan Top: Conceptualization, Methodology. İsmail Şahin: Conceptualization, Methodology, Supervision.

References

[1] Top, N., Şahin, İ., Gökçe, H., Gökçe, H., “Computer-aided design and additive manufacturing of bone scaffolds for tissue engineering: state of the art,” Journal of Materials Research, 36 (2021) 3725–3745. Doi: 10.1557/s43578-021-00156-y

[2] Günay, M., Yeşildağ, İ., “GMAW esaslı eklemeli imalat ile üretilen düşük karbonlu çeliğin mekanik özellikleri,” Gazi Journal of Engineering Sciences 7:3 (2021) 175-182. Doi: 10.30855/gmbd.2021.03.01

[3] Sarı, M. İ., Şahin, İ., Gökçe, H., & Öksüz, Ç., “Ring orthosis design and production by rapid prototyping approach,” Journal of Hand Therapy, 33:2 (2020) 170-173. Doi: 10.1016/j.jht.2019.02.003

[4] Top, N., Gökçe, H., “Doku mühendisliğinde bilgisayar destekli yapay kemik iskelesi tasarımı,” Şahin, İ., Eds. Ankara: İKSAD Publishing, 2020.

[5] Yavuz, O., “Eklemeli üretim ile üretilmiş gyroid humerus sabitleme plağının güvenilirlik analizi,” Master's Thesis, Graduate School of Natural and Applied Sciences, Erzurum University, Erzurum, 2022.

[6] Aslan, B., “Yenilikçi tasarım yöntemleri kullanarak eklemeli imalata yönelik optimum ürün geliştirilmesi,” Master's Thesis, Graduate School of Natural and Applied Sciences, Bursa Technical University, Bursa, 2019.

[7] Wang, Y., Zhang, L., Daynes, S., Zhang, H., Feih, S., Wang, M., “Design of Graded Lattice Structure with Optimized Mesostructures for Additive Manufacturing,” Materials & Design, 142 (2018) 114-123. Doi: 10.1016/j.matdes.2018.01.011

[8] Kalaycıoğlu, Ş., “Eklemeli imalat ile üretilen polimerik kafes yapıların mekanik davranışı,” Master's Thesis, Graduate School of Natural and Applied Sciences, Middle East Technical University, Ankara, 2022.

[9] Egan, P.F., Gonella, V.C., Engensperger, M., Ferguson, S. J., Shea, K., “Computationally Designed Lattices with Tuned Properties for Tissue Engineering Using 3D Printing,” PloS one, 12:8 (2017). Doi: 10.1371/journal.pone.0182902

[10] Yeşiloğlu, R., “Eklemeli imalat ile üretilen farklı dolgu geometrisi ve yoğunluğa sahip pla esaslı yapıların mekanik davranışlarının deneysel olarak araştırılması,” PhD Thesis, Graduate School of Natural and Applied Sciences, Karabük University, Karabük, 2022.

About the Authors

 Yusuf Sağlam	Yusuf Sağlam received B.S. degree in Department of Industrial Design Engineering from Gazi University, Turkey in 2021. He continues his master's degree in Department of Industrial Design Engineering of Graduate School of Natural and Applied Sciences from Gazi University. Yusuf Sağlam is currently a mechanical design engineer in the structural and mechanical design division at Titra Technology.
 Harun Gökçe	Harun Gokce received BS and MS degrees in Mechanical Engineering from BEUN in 2005 and 2008, respectively. Then he received PhD degree in Manufacturing Engineering from the Gazi University in 2014. He lectures at the Department of Industrial Design Engineering at Gazi University Faculty of Technology and consultant at the METU Wind Tunnel and Titra Technology.
 Neslihan Top	Neslihan Top received her B.S. degree in Dept. of Industrial Design from Gazi University, Turkey in 2014. She received her M.Sc. and PhD degree in Dept. of Industrial Design Engineering from Gazi University, Turkey in 2019 and 2023 respectively. Neslihan Top is currently a research assistant in the same department. Her research interests are human factor design, computer aided design, design for additive manufacturing and rapid prototyping in tissue engineering applications. Currently, she is also involved in several research projects on product design and development services, curriculum development for rapid prototyping and bone tissue engineering using additive manufacturing.
 İsmail Şahin	İsmail Şahin is a Professor and the Head of Department of Industrial Design Engineering at Gazi University, Ankara, Turkey. He received the PhD. degree from Gazi University, Turkey, in 2008. His research subjects include design for additive manufacturing, rapid prototyping, design optimization and artificial intelligence. He is also project manager of several research projects on Inclusive Entrepreneurship, Product Design, and Development Services, Raising Awareness on effective Waste Management, Active Participation of Civil Society in the Higher Education System and Curriculum Development for Rapid Prototyping in Engineering Education.