Research Article

The Mechanical Comparison of Artificial Bone and 3D Printed Bone Segments

Yapay Kemik ile 3D Baskılı Kemik Segmentlerinin Mekanik Karşılaştırılması

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Abstract: Bone is considered as an anisotropic structure due to the differences in the mechanical properties of cortical and spongiosal parts of the long bones. Researchers are attracted to bone related diseases and fractures in the mechanical studies and this leads them to seek alternative models. Artificial bones, especially Sawbones, have been preferred for biomechanical studies for decades. The reason for this, is the fact that artificial bones have density approximate to that of human bone. On the other hand, 3D printing has been used to create bone models for many studies in recent years. In this study, we compare the mechanical properties of artificial bone segments and 3D printed bone segments. Cross sectional dimensions of anatomical femur were examined with Computed Tomography (CT) and a solid model was created using this data. Fused Deposit Manufacturing (FDM) technique and PLA filament were used for producing the specimens. Two different groups of bone segments produced by using a 3D printer with cortical thicknesses of 1.2 mm and 2.8 mm, respectively and a height of 10 mm. These groups were compared with sawbones that are cut in 10 mm heights. A biomechanical compression test was performed in three groups at a speed of 2 mm / min at 1000 N. As a result, maximum force average for sawbone, 1.2 mm and 2.8 mm thicknesses was 1000 N. Meanwhile, maximum displacement average for sawbone, 1.2 mm and 2.8 mm thicknesses were 0.203 mm, 0.183 mm and 0.191 mm, in the same order as above. In conclusion, 3D printed bone models were found to be a good alternative for biomechanical analysis due to its similar force and displacement ratios.

Keywords: 3D printed bone model, cortical bone, cancellous bone, compression test, biomechanics

Özet: Kemik dokusu, özellikle uzun kemiklerin kortikal ve spongiyöz kısımlarının mekanik açıdan farklılıklar göstermesi nedeniyle anizotropik bir yapı olarak kabul edilir. Araştırmacılar, mekanik çalışmalar açısından bakıldığında kemikle ilgili hastalıklar ve kemik kırıklarıyla yakından ilgilenmekte ve bu da onları alternatif modeller aramaya yönlendirmektedir. Uzun yıllardır yapılan biyomekanik çalışmalarda özellikle kemik dokusuna yoğunluk açısından benzediği kabul edilen yapay kemikler (sawbone) yaygın olarak tercih edilmektedir. Öte yandan son yıllarda 3D yazıcı tabanlı teknolojilerden faydalanılarak üretilen yapay kemik modelleri kullanılarak gerçekleştirilen birçok biyomekanik çalışma da bulunmaktadır. Bu çalışmadaki amacımız da yapay kemik (sawbone) ve 3D yazıcı ile üretilmiş olan kemik kesitlerinin mekanik özelliklerine göre karşılaştırılmasıdır.
Bilgisayarlı Tomografi (CT) ile anatomik femurun boyutları incelenmiş ve alınan bu verilerle bir katı model oluşturulmuştur. Fused Deposit Manufacturing (FDM) tekniği ve PLA filament kullanılarak numuneler üretilmiştir. 3 boyutlu yazıcı kullanılarak iki grup kemik kesiti 1,2 mm ve 2,8 mm kortikal kalınlıklarında 10 mm yüksekliğinde üretilmiştir. Bu numuneler 10 mm yükseklikte kesilen sawbone ile kıyaslanmıştır. Biyomekanik kompresyon testi ile mekanik basma dayanımları 1000 N'de 2 mm / dk hızda üç grup için de gerçekleştirilmiştir.
Sonuç olarak, maksimum kuvvet sawbone, 1,2 mm ve 2,8 mm kalınlıkta örnekler için 1000 N iken maksimum deplasman ortalaması ise sırasıyla 0,203 mm, 0,183 mm ve 0,191 mm idi. Sonuç olarak, benzer kuvvet ve yer değiştirme oranları nedeniyle, 3D baskılı kemik modellerinin biyomekanik analiz için yapay kemiklere iyi bir alternatif olduğu görülmüştür.

Anahtar Kelimeler: 3D baskılı kemik modeli, kortikal kemik, süngerimsi kemik, kompresyon testi, biyomekanik

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1.Introduction

Bone is a structure that supports and enables body to move. It is the strongest tissue as it has both organic and inorganic components. While the calcium mineral is responsible in the tissue hardness, the collagen is responsible in elasticity [1]. Depending on the amount of minerals in bone tissue formation, the degree of brittleness varies. The bone is a nonlinear and viscoelastic material, which concludes in a different compressive strength in cortical and cancellous bone. Cortical bone is denser and has a higher Young's modulus of elasticity (around 20 GPa) than cancellous bone (around 1 GPa). Cortical bone is also more resistant to bending and torsion. In other words, it is an anisotropic tissue depending on the direction of loading [2].

Furthermore, artificial bones (sawbones) are commonly used instead of cadaveric specimens due to their availability and low variance. They provide a cleaner, less contaminated working space, and also shows a uniform structure [3]. Artificial bones are usually preferred in biomechanical studies since their densities are similar with natural bone. Therefore, diseases such as bone tumors, osteoporosis and low bone density, fractures,etc. can be mimicked with the usage of artificial bones. In the recent years, researchers began to test the treatments on 3D printed bone models with filaments such as Polylacticacid (PLA), Polyether ether ketone (PEEK), Acrylonitrile butadiene styrene (ABS), etc. In this study, we produced a femoral segment model by using PLA filament which is easily available and a biocompatible material. Moreover, it has a melting point of 200°C which provides an ease in 3D printing [4].

There have been many studies on the use of 3D printers in recent years. For instance, Bohl et al. were examined the biomechanical performance of a three-dimensional (3D)-printed vertebra on pedicle screw insertional torque (IT), axial pullout (APO), and stiffness (ST) testing. They concluded that, 3D printed vertebral body models could reliably produce a model that mimics bone of a specific bone mineral density [5].

In another study, Bohl et al. investigated the fluoroscopic performance and fidelity to human tissue of a new synthetic spine model. Vertebral bodies (VBs) were 3D printed with variable shell thicknesses and internal densities, and fluoroscopic images were taken to measure cortical thickness and gray-scale density. They accomplished, 3D-printed VBs and segmental spine models accurately mimic human tissue with respect to their anatomical appearance [6].

Additionally, Hu et al. produced a customized graft for repairing large mandibular defects using topological optimization and 3D printing technology. It was aimed to characterize the mechanical behavior of 3D printed anisotropic scaffolds as bone analogs by fused deposition modeling (FDM). The results showed a great potential for topological optimization and 3D printing technology of artificial porous graft manufacturing [7].

In this study, we aimed to compare the artificial bone and 3D printed femoral bone segments according to their mechanical properties. CT images were used in solid model standardization and three groups were investigated in the recent study. We recommend an alternative model instead of artificial bones for biomechanical studies.

2.Materials and Methods

3D Modeling of Bone and Specimen Preparation

Cross sectional dimensions of an anatomical femur was examined with the Computed Tomography (CT) from a healthy woman aged 35. Mean of cortical thickness was determined as 1.2 mm / 2.8 mm from the longitudinal sections. By using the Fused Deposit Manufacturing (FDM) technique and PLA filament, specimens were produced with the filling ratio of 40% within two different cortical thickness groups. Solidworks software was used to create a solid model from femur cross-sections. The cortical thicknesses were taken as 1.2 mm and 2.8 mm to investigate the anatomical convenience of bone models (Figure 1-a,b). The 3D printed bone segments of each group were produced in 10 mm height in six replicates.

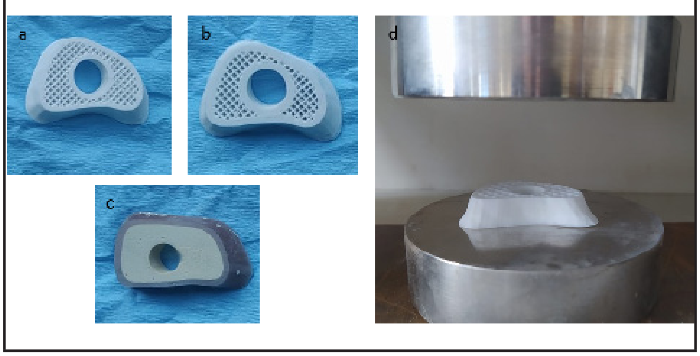

Figure 1: Samples (a) 1.2 mm cortex, (b) 2.8 mm cortex, (c) sawbone and (d) biomechanical test setup.

Sawbone Specimen Preperation

3th gen femur (Sawbones® Europe AB, Malmö, Sweden) was used for this study. Six specimens of each sawbone were cut from distal femur anatomically by using an oscillating saw (Bosch, Model PMF 220) in 10 mm height sections (Figure 1-c). In addition, specimens were grinded to get a flat surface.

Biomechanical Analysis

The mechanical analysis were performed by using a compressive loading tests (Figure 1-d). The compression analysis data was obtained at 100% humidity and at 24(±1) °C with an electromagnetic actuator device (5 kN AG-X; Shimadzu, Kyoto, Japan). 1000 N axial loading was applied at a speed of 2 mm / min. The force (N) – displacement (mm) values were taken from a TRAPEZIUM X software and processed by GraphPad Prism.

Statistical Analysis

The data were analyzed with the GraphPad Prism software (GraphPad Software, San Diego, CA, USA). The mean and standard deviations were calculated. For statistical analysis, One-way ANOVA was applied and Dunnett's test was used for multiple comparisons. Also, level of significance was set at $p < 0.05$.

3.Results

As it can be seen in Fig 2, there was not a significant difference between the three groups. The average of maximum force for sawbone, 1.2 mm and 2.8 mm thicknesses were 1006.3 N, 1009.5 N and 1010.6 N, respectively. Meanwhile, the average of maximum displacement for sawbone, 1.2 mm and 2.8 mm thicknesses were 0.203 mm, 0.183 mm and 0.191 mm, respectively. When the cortical thickness increases, the mean of maximum force seems to increase. However, the mean of maximum displacement was the highest value in sawbone samples.

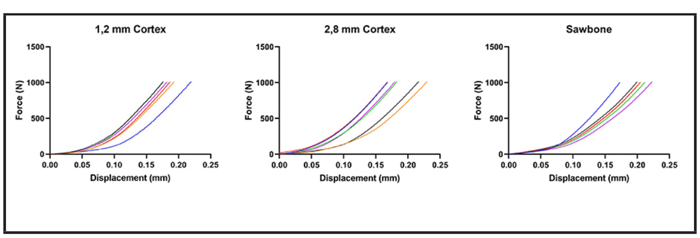

Figure 2: Force (N) and Displacement (mm) of specimens

As a result, when the sawbone's force and displacement values compared to the 3D printed models with the Dunnett's test, there were no significant value ($p>0.05$). The maximum force and displacement p values of 1.2 mm cortex were 0.407 and >0.999. Meanwhile, 2.8 mm cortex p values of force and dislacement were 0.224 and 0.584.

4.Discussion

PLA filament was used to model bone structure in the present study due to the ease of availability. However, this study can be repeated by using other filaments such as PEEK, ABS, etc. Although, the PEEK material is more suitable for bone modelling studies as it is highly biocompatible and has a better biomechanical strength, its printing temperature is approximately 400oC. Thus, it was not preferred since its overprice and challenging in 3D printing [8]. Moreover, ABS is low cost material and it is mostly available. Nonetheless, it was not preferred due to the lower mechanical strength and non-biocompatible structure [9].

The present study was based on the anatomical structure of bone and it has a great importance in biomechanical analysis. However, the limitation of our study was the incompatibility between the present study and the testing procedures of ASTM F1839 standarts [10]. Since the test procedure requires for further tests to calculate shear strength and compressive strength based on the void content determination, foam density and dimensional stability, etc. the present research should be repeated and improved.

5.Conclusion

In conclusion, it might be assumed that 3D printer based modelling studies give a chance to mimic the bone structure in the near future. 3D Printed bone segments has similar compressive strength to polyurethane based artificial bones. By modifiying the cortical thickness and filling density, one might produce a better model to mimic anatomical bone. Therefore, these 3D printed PLA bone segments represent a promising new models for bone in biomechanical analysis.

Conflict of Interest

The authors declare that they have no competing interests.

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