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**Araştırma Makalesi / Research Article**

# 3D printed models of the digital skeleton of the horse

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ABSTRACT:

Veterinary anatomy education has become a field where theoretical knowledge has dominated considerably in general. Due to the limited amount of educational material and the presence of different kinds of animals, practical education remains in the background. The study is to point out the three-dimensional (3D) printing models of the digital skeleton of the horse with all advantages and disadvantages such as anatomical accuracy, accessibility, and cost in veterinary anatomy. The proximal, middle, and distal phalanx of four horses were used. Bone samples were scanned using a multidetector computed tomography device. These images were processed with various software to rendering the 3D bone digital models. After the segmentation process was made, a fused deposition modelling printer and the polylactic acid filament were used to obtain 3D printing models. The proximal, middle, and distal phalanx were successfully printed. All samples were determined to preserve anatomical structures in high detail for veterinary anatomy education. The processes of 3D printing technology are considered to be advantageous in terms of cost, workload, and time. The process presented in this study can be applied widely to produce various bone models for veterinary anatomy education.

## *At Parmak İskeletinin 3B Baskı ile Modellenmesi*

ÖZET:

Veteriner anatomi eğitimi, genel olarak teorik bilginin önemli ölçüde hakim olduğu bir alan haline gelmiştir. Sınırlı miktarda eğitim materyali ve farklı hayvan türlerinin varlığı nedeniyle, pratik eğitim arka planda kalmaktadır. Bu çalışma, veteriner anatomide anatomik doğruluk, erişilebilirlik ve maliyet gibi tüm avantaj ve dezavantajlar yönünden atın parmak iskeletinin üç boyutlu (3B) baskı modellerine işaret etmektir. Dört ata ait parmak iskeletini oluşturan kemikler multidedektörlü bilgisayarlı tomografi cihazı kullanılarak tarandı. Bu görüntüler, üç boyutlu parmak kemik modellerini oluşturmak için çeşitli yazılımlarla işlendi. Segmentasyon işlemi yapıldıktan sonra, üç boyutlu baskı modelleri elde etmek için bir Katmanlı Üretim Teknolojisi yazıcı ve polilaktik asit filamenti kullanıldı. Proksimal, orta ve distal phalanx'lar başarıyla baskılandı. Tüm örneklerin, veteriner anatomi eğitimi için anatomik yapıları yüksek ayrıntıda koruduğu belirlendi. üç boyutlu baskı teknolojisinin süreçleri maliyet, iş yükü ve zaman açısından avantajlı olarak değerlendirilmektedir. Bu çalışmada sunulan süreç, veteriner anatomi eğitimi için çeşitli kemik modelleri üretmek için yaygın olarak uygulanabilecektir.

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## 1. Introduction

It requires a practical educational approach to relay theoretical information in anatomy education. A high number of students, decreasing the practice lesson hours, cadaver donations, and hazardous chemicals are the biggest problems faced by veterinary faculties during practice education all over the world (2, 6). In the last few decades, the use of three-dimensional (3D) visualization and 3D printing models has increased enormously with the development of medical imaging techniques in education (6). 3D printing models are used in anatomy education, which has an important place in modern medicine (1, 2). Anatomical model production is still one of the main application areas for additive manufacturing (10). There is also a trend that educators, operators, or researchers produce their models to use for their own purposes. The use of 3D printing models has enabled the physical samples to be produced quickly and cheaply (2).

Horse digits are the most common region of lameness due to the amount of stress on the hoof area. Therefore, teaching the structures on these bones and the properties of these structures are essential for veterinary osteology. In addition, hoof anatomy should be learned in order to prevent and treat complications that may occur during surgical operations (2). The traditional teaching methods of bones include two-dimensional (2D) atlases, drawings or photographs, and organic materials. 3D virtual images have been used in education in recent years. In spite of this, 3D images cannot be handled. 2D atlas and drawings are limited by students' imaginations. Organic materials have some disadvantages such as donor deficiency, ethical concerns, high storage costs, and long preparation times (15). By means of developing technology, Additive manufacturing is used in innovations such as vascular modeling, surgical simulation, preoperative planning, and anatomical relationship (3). 3D printing models are easier to understand than 2D drawings or figures. In this case, the 3D printing model has become an important educational tool in anatomy, pathology, and surgery education (8, 11, 13, 15).

The aim of this study is to point out the use of 3D printing models of the digital skeleton of the horse with all advantages and disadvantages such as anatomical accuracy, accessibility, and production.

## 2. Material and Methods

Four-foot cadavers of Thoroughbred racehorses were used for this study. Each foot was separately scanned with the continuous axial volumetric acquisition by a multidetector computer tomography scanner (SOMATOM Scope, Siemens). Acquisition settings were kV: 110, X-ray tube current: 57 mA, exposure: 71 mAs, exposure time: 1000 ms, slice thickness: 5 mm, resolution: 512 x 512 pixels. Images of each specimen data are stored in Digital Image and Communication in Medicine (DICOM) format and then all images are imported into 3D Slicer software (Version 4.11.2, r29402, USA). Regions of interest are extracted based on each segment of data with thresholding and manual setting, which are then used to render the 3D model samples in stereolithography (STL) format. A threshold value was selected that would create as a complete structure of the phalangeal bone as possible. The segmentation was applied manually, all parameters used for smoothing functions were standardized (5). The 3D models were then exported to Meshmixer (Version 3.5.474, San Rafael CA Autodesk inc.) for the recreation of the models. Ultimaker Cura (Version 4.8.0, USA) was used for the slicing of final STL images and to produce physical 3D printing models with the Fused Deposition Modelling (FDM) printer (Anycubic I3 Mega, Shenzhen technology, China) and polylactic acid (PLA)-grade thermoplastic filament. The FDM printer created the 3D model layer by layer and the layer thickness was 0.2 mm. At the end of the printing, post-processing was necessary to remove the supporting structures with fine cutting pliers. The anatomical terms used in the descriptions of the figures are from the Nomina Anatomica Veterinaria (12).

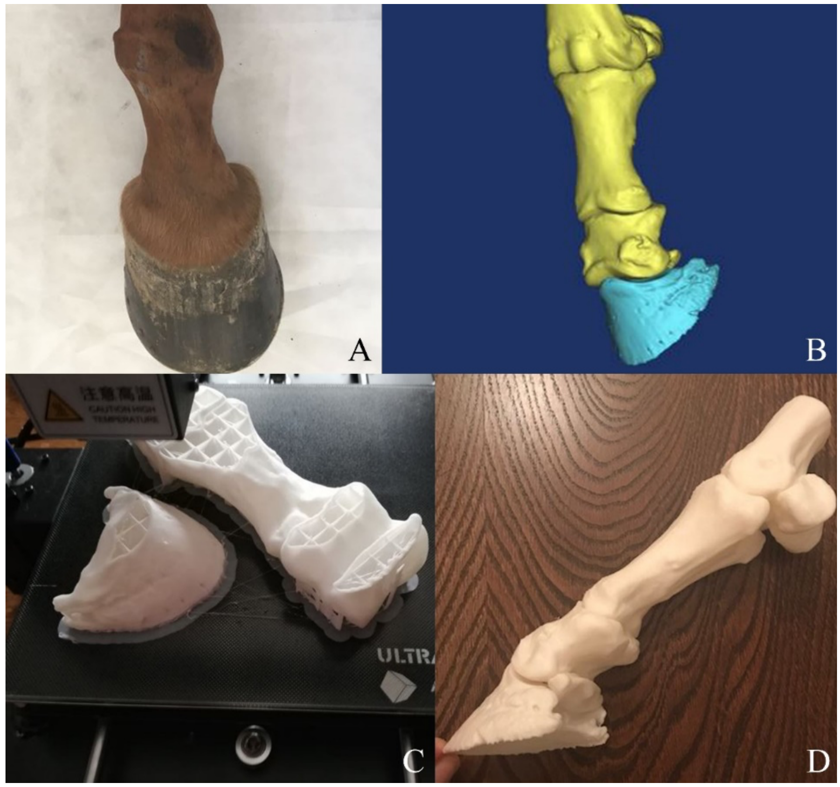


**Figure 1: (A)** Specimen used for visualization by computed tomography, **(B)** 3D segmentation model of the digital skeleton of the horse, **(C)** The printing stage of the digital skeleton of the horse by FDM 3D printer and **(D)** 3D printing bone models.

***Şekil 1: (A)*** *Bilgisayarlı tomografi ile görselleştirmek için kullanılan örnek,* ***(B)*** *Atın parmak iskeletinin 3B segmentasyon modeli,* ***(C)*** *Atın parmak iskeletinin FDM 3B yazıcı ile baskı aşaması ve* ***(D)*** *3B baskı kemik modelleri.*

## 3. Results

The proximal phalanx, middle phalanx, distal phalanx, proximal sesamoid bones, and navicular bone that form the digital skeleton were successfully printed in this study. The digital skeleton models printed with FDM printer technology were shown in Figure 1 and Figure 2. The bone replicas were durable and odorless. They were lightweight and easy to manipulate (drillable and fusible). It took approximately 180 minutes to print one proximal phalanx, 70 minutes to print one middle phalanx, 80 minutes to print all sesamoid bones and 220 minutes to print one distal phalanx. All of these parts took approximately to print 13 hours on one stage. Although it was seen that these models can be printed in different sizes, we reproduced all the 3D printing models in 1:1 size (Figure 3). The details of the surfaces of the printing models were evaluated as a high-level accuracy for anatomy as an education model. All projections, holes, and notches were evident on the anatomical surfaces (Figure 2C-f). All bony processes were well-differentiated, including the openings, notches, and attachment surfaces for the joints and soft tissues were present especially in the distal phalanx.

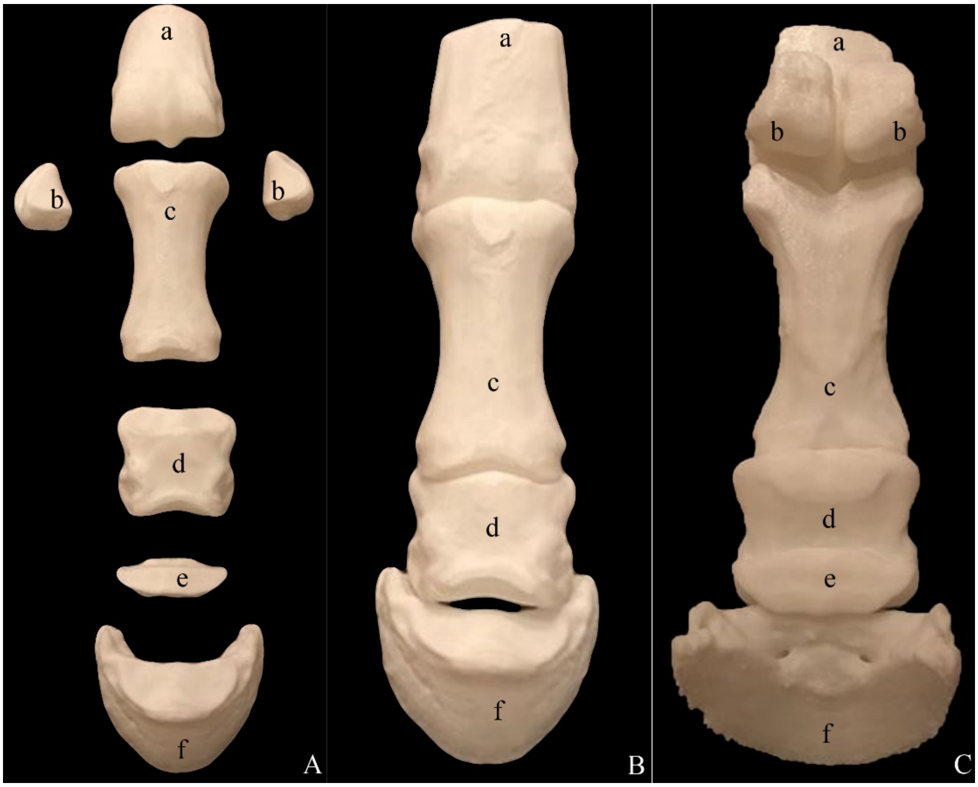


**Figure 2: (A and B)** Dorsal aspect and **(C)** palmar aspect of 3D printing model of the digital skeleton of the horse. **(a)** metacarpal bone, **(b)** proximal sesamoid bones, **(c)** proximal phalanx, **(d)** middle phalanx, **(e)** distal sesamoid bone (navicular bone) and **(f)** distal phalanx.

***Şekil 2:*** *Atın parmak iskeletinin 3B baskı modelinin dorsal yönü* ***(A ve B)*** *ve palmar yönü* ***(C)****.* ***(a)*** *os metacarpale III,* ***(b)*** *ossa sesamoidea proximale,* ***(c)*** *phalanx proximalis,* ***(d)*** *phalanx media,* ***(e)*** *os sesamoideum distale ve* ***(f)*** *phalanx distalis.*

## 4. Discussion and Conclusion

The use of cadavers for anatomy education has been used for four hundred years and it has the most important place in anatomy education (4). However, 3D printing models have made great progress in medicine due to the disadvantages of the use of cadavers. Anatomy education, surgical planning, morphometric measurements, implant production, and guide development are some areas of 3D printing technology instead of a cadaver specimen. In this way, models, regardless of their purposes, can be printed cheaply and any number of times (1, 2, 14, 17). In this study, 3D printing models were obtained for the purpose of anatomy education which is one of our main subjects, with less cost and less energy loss compared to the cadaver preparation and storage conditions. It was observed that educational methods supported by three-dimensional reconstruction increase students' year-end exam success. In addition, it ensured that the information they learned remained in mind for a long time. It was also recognized that three-dimensional reconstruction images increase the curiosity and attention of the students due to approaches such as their cross-sectional images can be examined, viewed from different angles by rotating, and anatomical structures can be hollow. It was stated that all these qualities had benefits in anatomy education (16). Due to this technology, three-dimensional images can be easily created from existing two-dimensional image series. Thus, it can provide an understanding of the desired anatomical structure (7). All 3D printing models of the digital skeleton of the horses have been presented to the students in anatomy practical lessons with high anatomical sensitivity. It was emphasized by the students that it is advantageous due to its opportunity, number, and variety. Three-dimensional printing models produced in the desired size, shape, and structure are thought to close the gap in theoretical knowledge.


**Figure 3: (A)** Dorsal aspect of the specimen and **(B)** 3D printing model of the digital skeleton of the horse. **(a)** metacarpal bone, **(b)** proximal sesamoid bones, **(c)** proximal phalanx, **(d)** middle phalanx, **(e)** distal sesamoid bone (navicular bone) and **(f)** distal phalanx.

***Şekil 3:*** *Atın parmak iskelet örneğinin **(A)** ve 3B baskı modelinin **(B)** dorsal yönü. **(a)** os metacarpale III, **(b)** ossa sesamoidea proximale; **(c)** phalanx proximalis; **(d)** phalanx media; **(e)** os sesamoideum distale and **(f)** phalanx distalis.*

Image processing and model generating are the most important steps for 3D printing. Data sets of images obtained by using imaging techniques, as an example of computed tomography or magnetic resonance imaging, are used to produce 3D printing models. Segmentation is an error-prone step because it depends on the user. Especially in manual processes, determining the boundaries of the structure in the sections and creating a 3D object requires attention (2, 17). Such technical problems increase the importance of the user. Anatomist perspective and knowledge also gain importance here. The better to know the anatomy of the actual structure, the better the quality of the printed model will be. In this study, all anatomical segmentation, image processing, and model creation were carried out by anatomists.

Sallent et al. (14) stated that the measurements taken from three-dimensional printed models are quite accurate when compared to cadaver samples. It has been stated that three-dimensional images and measurements made on images are safe to use in clinical applications (9). They stated that three-dimensional imaging and printing technology can be used in surgeons' pre-operative planning or the production of patient-specific guides and implants. In this study, the 3D printing bone replicas were anatomically accurate and identical to the organic skeleton specimens. These models can be a convenient alternative for macerated organic bones. These printing prototypes can be used for understanding the morphology and the relationship of hoof bones in anatomy, diagnostic imaging, surgery, and podiatry education. These models will facilitate the continued development of veterinary education. All the models that we produced with our methodology presented a high detail and applicability.

In some studies, printing bone material was generated by a 3D light scanner. These scanners create models by scanning the surface of the specimen. These kinds of 3D printing models are printed hollow. Researchers can fill inside of the model by themselves (8, 11, 13). The scanning was not applied superficially in this study. The entire bone structures of the cross-sectional images are selected in the segmentation phase and printed by 3D printers. Because of this reason, it is thought that the 3D printing models produced in this study, are more realistic for practical education in anatomy. It is thought that orthopedic modeling or models created for fractures, fissures, or similar situations will provide more realistic results.

Bones can be easily duplicated by 3D printing because they are hard tissue and monochromatic. ABS and PLA are the most common plastics available for 3D printing (14). In this study, the models were printed without any error parallel to the previous study. The conversion from DICOM to STL format has been identified as one main step for accuracy. STL is also described as the most accurate technology (14). Therefore, the DICOM files were used to generate 3D reconstruction images, and STL format was applied to create 3D printing models in this study.

In conclusion, this study reveals that 3D digital modeling and 3D printing technology can be easily applied in anatomy education. These developed models can be easily produced and used for this purpose. Due to the appropriate production costs, the stock deficiencies of educational institutions can be eliminated. The acquisition of 3D printing models does not only create physical models but also provides two-dimensional serial section images of this specimen and 3D digital images that can be modified and examined from desired angles. Against all these advantages, the production processes must be prepared correctly for a single time. The study reveals the potential of these models that can be produced repeatedly with 3D printing technology with low cost and high efficiency.

**Conflict of Interest**

The author declared no conflict of interest.

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**Authors' Contributions**

Idea / concept: Çağdaş OTO
Experiment design: Caner BAKICI
Supervision / Consultancy: Çağdaş OTO
Data collecting: Caner BAKICI, Orçun GÜVENER
Data analysis and interpretation: Caner BAKICI, Orçun GÜVENER
Literature search: Caner BAKICI, Çağdaş OTO
Writing the article: Caner BAKICI
Critical review: Çağdaş OTO

**Ethical Approval**

The ethics committee report of this study was obtained from Ankara University, Local Ethics Committee of Animal Experiments (Decision number: 2021-1-2).

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