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ORIGINAL ARTICLE

A Review of 3D-Printing Applications in Anatomy Education: Focus on Bony Structures and the Orbit

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ABSTRACT

This review purposed to explore the applications of 3D printing in teaching bony structures, with a particular focus on the orbit.

A comprehensive search was conducted in Scopus, ERIC, ScienceDirect, SAGE, PubMed, Google Scholar, and ProQuest with no time restrictions, using relevant keywords. After screening 170 articles, the most relevant studies were selected and analyzed. The reviewed literature indicates that 3D printing serves as an effective tool in medical education by improving anatomical comprehension, providing accurate visualization of bony structures, and facilitating teaching processes. The findings were categorized into four main themes: key features of 3D printing technology, educational applications of bony models, orbit-specific 3D models and diversity of educational and clinical applications. 3D printing holds significant value in medical education by offering realistic and tangible models that enhance structural understanding and support more precise preoperative planning.

KEYWORDS

Orbital Anatomy, 3D Printed Models, Medical Education.

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Introduction

Educational technology is broadly conceptualized as the systematic and ethical application of appropriate technological processes and resources to facilitate learning and improve educational performance (Januszewski & Molenda, 2008). Within this framework, emerging technologies can provide innovative learning environments in which complex information is presented through interactive, visual, and tangible representations. Among these technologies, three-dimensional (3D) printing has gained increasing attention in medical and health-professions education because of its capacity to transform digital imaging data into realistic physical models.

Advances in medical imaging, image segmentation, computer-aided design, and additive manufacturing have enabled the production of anatomically accurate and patient-specific models. Computed tomography data can be converted into virtual 3D representations and subsequently fabricated as physical models, providing valuable resources for both surgical planning and professional training (Auricchio & Marconi, 2016). This capability is particularly important for complex osseous anatomical regions, where spatial relationships may be difficult to understand using conventional two-dimensional images.

The clinical value of 3D printing has been demonstrated in orbital reconstruction. Patient-specific printed templates and models can facilitate preoperative planning, customized implant fabrication, and more accurate reconstruction of orbital walls and floors (Callahan et al., 2017; Kang et al., 2018; Vehmeijer et al., 2016). Moreover, 3D technologies provide valuable opportunities for teaching anatomically complex skeletal structures. Three-dimensional representations have been shown to support the learning of temporal bone anatomy (Venail et al., 2010), while printed cranial models can facilitate the visualization and simulation of complex craniofacial conditions (Ghizoni et al., 2018). Importantly, randomized evidence indicates that 3D-printed models can significantly improve medical students' identification and understanding of complex spinal fracture anatomy compared with conventional computed tomography images (Li et al., 2015).

Given the growing educational and clinical applications of 3D printing, the present review aimed to synthesize evidence regarding 3D educational technology in osseous tissues, with particular emphasis on its fundamental characteristics, educational applications, orbital models, and diverse clinical and instructional uses.

Method

A systematic literature search was conducted across PubMed, SAGE Journals, Google Scholar, ScienceDirect, Scopus, ProQuest, and ERIC to identify relevant studies on the educational and clinical applications of three-dimensional (3D) printing in anatomy and osseous tissues. The search was performed without date restrictions and included publications in both English and Persian. Search terms consisted of combinations of 3D printing, three-dimensional printing, educational technology, anatomy education, orbital bone, and orbit. Boolean operators (AND/OR) were applied to maximize the sensitivity and comprehensiveness of the search.

Eligible studies included original research articles, systematic reviews, and narrative reviews focusing on 3D printing in anatomy education, osseous anatomical models, or related clinical simulation and educational applications. Studies were required to provide relevant educational, clinical, or simulation-based findings and to be published in English or Persian. Duplicate records, studies unrelated to educational or clinical applications of 3D printing, abstracts without accessible full texts, publications in other languages, and papers limited to theoretical discussion or conceptual critique without practical data were excluded.

The study-selection process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021). Initially, 170 records

were identified. Following title and relevance screening, 85 records remained, of which 40 underwent full-text assessment. Ultimately, 34 studies meeting the eligibility criteria were included in the final synthesis.

Data were extracted and narratively synthesized into four non-mutually exclusive thematic categories: fundamental characteristics of 3D technology, educational applications of 3D osseous models, 3D orbital models, and diverse clinical and educational applications. The study-selection process followed the PRISMA framework, resulting in the inclusion of 34 studies in the final synthesis.

Results

The findings were synthesized into four major, non-mutually exclusive thematic categories: fundamental characteristics of 3D technology, educational applications of 3D osseous models, 3D educational models of the orbit, and diverse clinical and educational applications. Because individual studies could address more than one thematic domain, the number of studies across categories exceeded the total number of included articles.

Seven studies addressed the fundamental characteristics of 3D technology. The principal advantages identified included rapid production and prototyping, reduced material and labor costs, greater design flexibility, automated manufacturing, reproducibility, accessibility, and the capacity for patient- or task-specific customization. The layer-by-layer manufacturing process also enabled the fabrication of geometrically complex structures that may be difficult to produce using conventional manufacturing techniques.

Nineteen studies focused on the educational application of 3D osseous models. Bone was particularly suitable for 3D reproduction because its relatively rigid structure could be replicated while preserving important visual, tactile, and spatial characteristics. The reviewed evidence indicated that 3D models facilitated the teaching of complex anatomical relationships in structures such as the pelvis, thoracic cage, spine, and temporal bone. They also supported fracture identification, surgical simulation, procedural planning, and repeated hands-on examination of anatomical replicas, thereby overcoming some limitations associated with fragile or inaccessible human specimens (Auricchio & Marconi, 2016; Venail et al., 2010).

Six studies specifically examined 3D educational models of the orbit. These studies consistently emphasized the value of physical models in improving visuospatial understanding of the anatomically complex orbital region. Patient-specific orbital models were used for surgical education, simulation, reconstruction planning, and implant customization. Such applications provided more realistic representations of complex orbital anatomy and facilitated the management of orbital fractures and craniofacial abnormalities (Callahan et al., 2017; Ghizoni et al., 2018; Kang et al., 2018; Vehmeijer et al., 2016).

Across the broader clinical and educational literature, 3D printing was additionally applied to patient-specific simulation, implant design, surgical planning, and general anatomy education. Overall, the reviewed studies indicated that 3D technologies provide tangible, customizable, and interactive learning resources that may enhance spatial comprehension and support the translation of anatomical knowledge into clinical practice.

Discussion and conclusion

The findings of this review demonstrate the growing educational and clinical value of three-dimensional (3D) printing, particularly in anatomy education and the representation of complex osseous structures. Previous evidence indicates that 3D-printed anatomical models can enhance spatial understanding, facilitate tactile and interactive learning, and increase learner satisfaction (Brumpt et al., 2023). Their ability to reproduce skeletal structures with relatively high anatomical fidelity also makes them particularly suitable for teaching regions

in which three-dimensional relationships are difficult to understand through conventional two-dimensional resources (Asghar et al., 2022).

Beyond basic anatomy education, 3D printing provides important opportunities for clinical simulation, procedural training, preoperative planning, and patient-specific modeling. Anatomically accurate models may improve learners' understanding of complex procedures and provide opportunities for repeated practice in a controlled educational environment (Hyndman & McHugh, 2024). These advantages are especially relevant to anatomically complex regions such as the orbit, where accurate visualization of spatial relationships is essential for surgical education, reconstruction planning, and implant design. Patient-specific models may therefore support both educational and clinical decision-making.

Nevertheless, several limitations should be considered. Producing highly realistic models may require advanced printers, specialized materials, considerable preparation time, and additional financial resources. Furthermore, printed models may not completely reproduce soft-tissue characteristics or pathological variations and therefore should not be regarded as complete replacements for dissection, plastinated specimens, cross-sectional imaging, or other established educational approaches (Zukowska et al., 2023).

Overall, 3D printing represents a valuable complementary technology for anatomy education, particularly for complex osseous structures and orbital anatomy. The reviewed evidence suggests that 3D models can promote visuospatial understanding, knowledge retention, learner engagement, surgical simulation, and patient-specific planning. Their greatest educational value is likely to be achieved when they are integrated with conventional anatomy instruction, medical imaging, virtual reality, and hands-on clinical training. Future studies should focus on standardized production methods, appropriate material selection, cost-effectiveness, and rigorous comparative evaluation of educational and clinical outcomes.

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Authors' Contribution

All authors were involved in data collection, analysis, writing, and final approval of the manuscript.

Conflict of Interest

The author declares no conflict of interest regarding the publication of this article.

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