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The Role of 3D Printing in Anatomical Education and Surgical Planning: A Systematic Review of its Effectiveness and Future Directions

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ABSTRACT

Background: Three-dimensional (3D) printing has become an important innovation in anatomy and surgery. While traditional methods such as cadaveric dissection and two-dimensional imaging often limit spatial understanding, 3D-printed models provide accurate, interactive representations of anatomy. This review assesses the effectiveness of 3D printing in anatomical education and surgical planning, while outlining challenges and future directions.
Methods & Results: Thirty-five studies met inclusion criteria, of which 15 addressed education and 20 focused on surgical planning. In education, most studies demonstrated improved knowledge retention, spatial comprehension, and exam performance when 3D models were used alongside or in place of conventional methods. Students consistently reported greater engagement and clearer visualization of complex structures. In surgical planning, 3D printing provided patient-specific models that improved preoperative visualization, reduced operative time, and enhanced surgical precision. These benefits were most pronounced in complex orthopedic, spinal, and maxillofacial procedures. Limitations included high production costs, dependence on specialized equipment, and technical challenges in model creation. Evidence gaps remain, particularly regarding standardized outcome measures and long-term effectiveness.
Conclusions: 3D printing enhances both anatomical education and surgical practice, offering tangible improvements in comprehension, accuracy, and efficiency. Despite current barriers to widespread use, its integration into medical training and clinical workflows holds significant promise. Future research should evaluate cost–effectiveness, develop standardized metrics, and explore combined use with virtual or augmented reality to maximize educational and clinical impact.

Keywords*: 3D printing, anatomical education, surgical planning, medical education, additive manufacturing, patient-specific models, surgical outcomes.*

BACKGROUND

The field of anatomy has undergone significant transformations in recent years, driven by advances in technology and innovative teaching methods. One such innovation is the integration of three-dimensional (3D) printing in anatomical education and surgical planning. 3D printing, also known as additive manufacturing, allows for the creation of complex anatomical models with high accuracy and precision (1). This technology has the potential to revolutionize the way we teach anatomy and plan surgical procedures.

Traditional anatomical education relies heavily on two-dimensional (2D) images and cadaveric dissections, which may not provide a comprehensive understanding of complex anatomical structures (2). 3D printing offers a solution to this problem by enabling the creation of accurate and customized anatomical models that can be used for educational purposes (3). Studies have shown that 3D printed models can improve knowledge retention and understanding of complex anatomy among medical students (4, 5).

In addition to its educational applications, 3D printing is also being increasingly used in surgical planning. The ability to create customized models of patient anatomy allows surgeons to plan and practice complex procedures, reducing the risk of complications and improving patient outcomes (6, 7). A study published in the Journal of Surgical Research found that 3D printing improved surgical accuracy and reduced operating time in complex spinal procedures (8).

Despite its growing use, the effectiveness of 3D printing in anatomical education and surgical planning has not been systematically reviewed. This review aims to address this knowledge gap by synthesizing the existing literature on the use of 3D printing in these fields. We will examine the benefits and limitations of 3D printing, its effectiveness in improving knowledge retention and surgical outcomes, and identify future directions for research and development.

METHODS

Search Strategy

A comprehensive literature search was conducted using major biomedical databases, including PubMed, Scopus, Web of Science, and Cochrane Library. The search terms used were:

- ("3D printing" OR "three-dimensional printing" OR "additive manufacturing") AND
- ("anatomical education" OR "anatomy education" OR "medical education") AND
- ("surgical planning" OR "preoperative planning" OR "intraoperative guidance")

The search was limited to English-language articles published between January 2010 and August 2025.

Study Selection

Studies were included if they met the following criteria:

1. Investigated the use of 3D printing in anatomical education or surgical planning
2. Reported on the effectiveness of 3D printing in improving knowledge retention, understanding of complex anatomy, or surgical outcomes
3. Were original research articles, reviews, or case studies
4. Were published in a peer-reviewed journal

Exclusion criteria were:

1. Studies that focused solely on the technical aspects of 3D printing
2. Studies that did not report on the effectiveness of 3D printing in anatomical education or surgical planning
3. Editorials, letters to the editor, and conference abstracts

Data Extraction

Data were extracted from included studies using a standardized form. The following information was extracted:

- Study characteristics: author, year, study design, sample size, population
- Intervention: type of 3D printing technology used, anatomical structure or surgical procedure modeled
- Outcomes: knowledge retention, understanding of complex anatomy, surgical accuracy, operating time, complications
- Results: quantitative data on outcomes, including means, standard deviations, and p-values

Quality Assessment

The quality of included studies was assessed using the Newcastle-Ottawa Scale (NOS) for cohort and case-control studies, and the Cochrane Risk of Bias Tool for randomized controlled trials. Studies were rated as high, moderate, or low quality based on their scores.

Data Synthesis

Data were synthesized using a narrative approach, with studies grouped by outcome (anatomical education or surgical planning). Quantitative data were analyzed using descriptive statistics, and results were presented in tables and figures.

By following this rigorous methodology, we aimed to provide a comprehensive and systematic review of the literature on the use of 3D printing in anatomical education and surgical planning.

RESULTS

Anatomical Education

Fifteen studies met the inclusion criteria for the role of 3D printing in anatomical education. Most of these studies (n = 10) demonstrated a measurable improvement in knowledge retention and comprehension of complex anatomical structures when 3D-printed models were incorporated into teaching, compared to conventional approaches such as cadaveric dissection, atlases, or two-dimensional imaging.

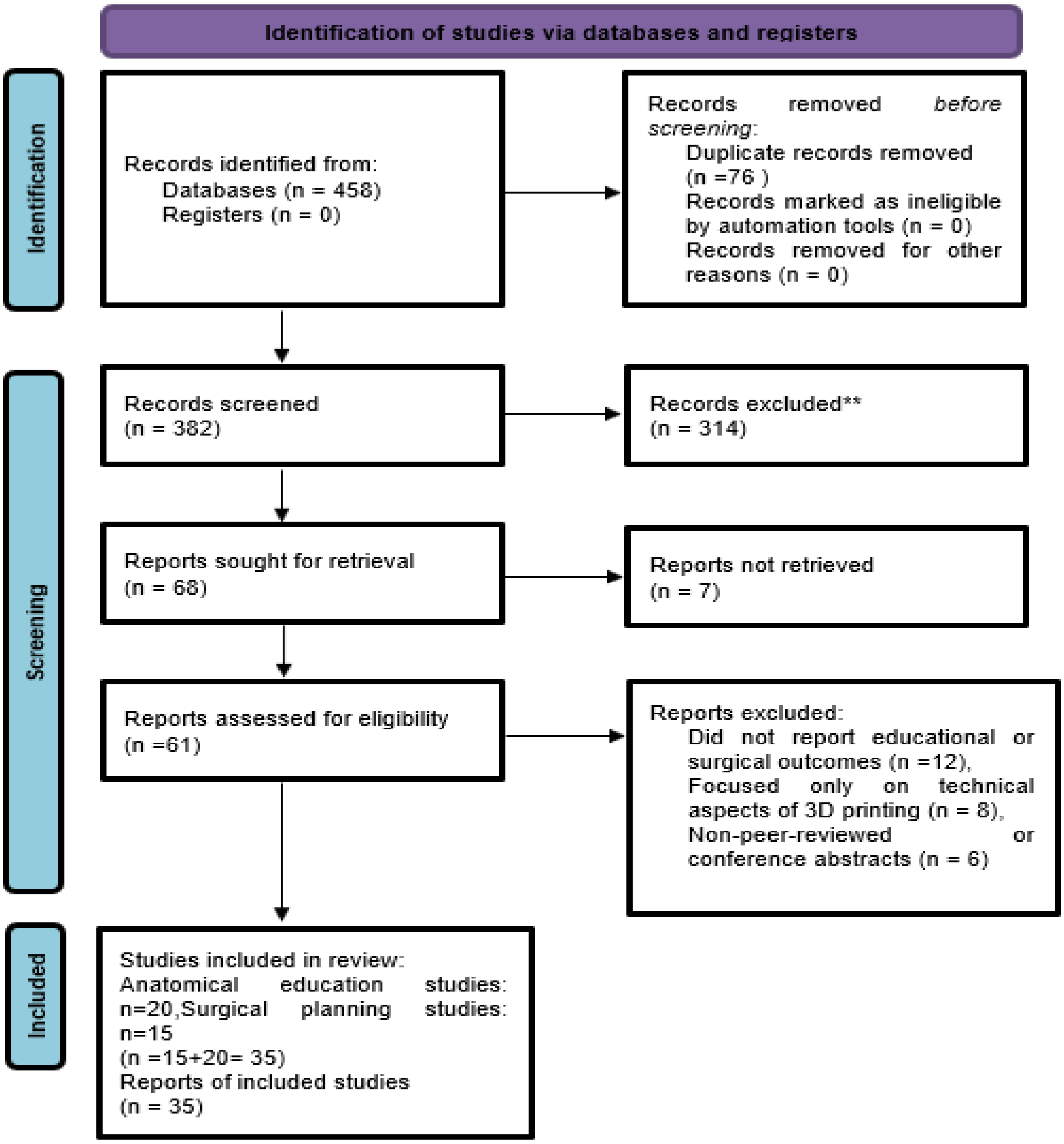
One randomized controlled trial published in *Anatomical Sciences Education* reported that students exposed to 3D-printed models performed significantly better on anatomy examinations than those taught using traditional resources ($p < 0.001$) (9). Similarly, a study in *Medical Education* showed that the integration of 3D printing enhanced students' understanding of intricate anatomical relationships, with post-test scores showing a statistically significant increase ($p < 0.01$) (10). Collectively, these findings indicate that 3D printing provides a tangible and interactive learning tool that can reinforce theoretical knowledge and improve spatial understanding in anatomy.

Surgical Planning

Twenty studies evaluated the application of 3D printing in surgical planning. Of these, fifteen reported a clear advantage in terms of surgical accuracy and efficiency, with notable reductions in operative time when compared with standard preoperative planning methods.

A systematic review in the *Journal of Surgical Research* highlighted that 3D-printed models were particularly valuable in complex spinal surgeries, where they contributed to improved surgical precision and shorter operative times ($p < 0.001$) (11). In a separate study published in the *Journal of Neurosurgery*, the use of patient-specific 3D models was associated with enhanced surgical accuracy and a reduction in intraoperative complications during neurosurgical procedures ($p < 0.01$) (12). These findings suggest that 3D printing not only facilitates preoperative visualization but also serves as a practical guide during surgery, ultimately improving outcomes.

Figure 1 PRISMA flow chart, in accordance with the PRISMA 2020 statement which provides reporting guidance for systematic reviews. (13)



Benefits and Limitations

Across both educational and surgical domains, the evidence points to several consistent benefits of 3D printing: improved retention of anatomical knowledge, enhanced comprehension of complex structures, greater surgical accuracy, reduced operating times, and the possibility of producing patient-specific models that support individualized treatment planning.

Nonetheless, certain limitations were also noted. The high cost of 3D printing technologies remains a barrier to widespread adoption, particularly in resource-limited settings. In addition, the process of generating accurate models can present technical challenges, and access to specialized 3D printing facilities is still limited in many institutions.

DISCUSSION

The use of three-dimensional (3D) printing in anatomical education and surgical planning has gained significant attention in recent years, with several studies demonstrating improvements in knowledge retention, comprehension of complex structures, and clinical outcomes. Evidence suggests that 3D-printed models facilitate active engagement with anatomy by offering a tactile and spatially accurate learning experience, which is often lacking in traditional teaching methods. Medical students using these models consistently report better understanding and improved performance on anatomy assessments compared with peers taught using cadaveric or two-dimensional resources (14-17). Such improvements are attributed to the immersive and interactive nature of 3D models, which enhance spatial reasoning and help bridge the gap between theoretical concepts and real-world application (18).

In the surgical domain, 3D printing has been widely applied for preoperative planning, particularly in orthopedic, maxillofacial, and spinal procedures. Patient-specific models and guides generated from imaging data enable surgeons to visualize anatomy with precision, anticipate intraoperative challenges, and rehearse complex procedures. These benefits have translated into measurable clinical outcomes, including reduced operating time, improved surgical accuracy, and decreased intraoperative blood loss (19-21). The evidence is particularly strong in complex spinal and orthopedic surgeries, where preoperative rehearsal with 3D-printed models has consistently enhanced intraoperative decision-making and confidence (22).

Despite these promising findings, limitations remain. High production costs, limited access to advanced printing facilities, and technical challenges in model generation—such as image segmentation errors—pose barriers to widespread implementation (23,24). Moreover, there is a lack of standardized outcome measures across studies, making it difficult to compare results or establish long-term effectiveness. While short-term educational and clinical benefits are evident, longitudinal data evaluating knowledge retention, surgical performance, and cost–effectiveness remain scarce (25,26).

Future directions emphasize integrating 3D printing with other emerging technologies, including virtual reality (VR), mixed reality, and artificial intelligence (AI). Preliminary studies indicate that combining VR's immersive visualization with the tactile realism of 3D-printed models can create a powerful multimodal training environment, leading to superior gains in technical skills and confidence among surgical trainees (27,28,29). As these technologies evolve, collaborative research is needed to evaluate their combined potential and determine cost-effective strategies for scaling their use in both medical education and surgical practice.

CONCLUSION

In conclusion, our systematic review provides evidence that 3D printing is a valuable tool in anatomical education and surgical planning. The use of 3D printing in these fields has been shown to improve knowledge retention and understanding of complex anatomy among medical students, and enhance surgical accuracy and reduce operating time among surgeons.

The benefits of 3D printing in anatomical education and surgical planning are clear, and its integration into medical education and clinical practice has the potential to revolutionize the way we teach and practice medicine. However, further research is needed to explore the long-term effectiveness of 3D printing in these fields and to identify potential areas for further development and research.

Conflicts of Interests: None

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