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AOA Critical Issues in Education

The Use of 3D Printing as an Educational Tool in Orthopaedics

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Background: Three-dimensional (3D) printing has proven to be effective in orthopaedic surgery, improving both surgical planning and outcomes. Despite its increasing use in surgical programs, reviews evaluating its educational impact are sparse. Therefore, the aim of this review was to provide educators with evidence-based findings on 3D printing's potential in training junior surgeons, as well as discuss its benefits in enhancing patient communication.

Methods: A comprehensive search using PubMed and Web of Science databases was performed to identify articles related to orthopaedics, 3D printing, and education. After removing duplicates, 2,160 articles were screened, 152 underwent full-text review, and 50 met inclusion criteria. Articles discussed the impact of 3D-printed models on comprehension or surgical performance. Data on publication details, sample size, teaching focus, learning outcomes, costs, and conclusions were extracted. Learning effects in the control (didactic) and experimental (3DP) groups were compared.

Results: In fracture management training, studies demonstrated significantly improved fracture classification accuracy, surgical performance, and interobserver classification agreement with 3D models compared with didactic learning and traditional imaging modalities. These benefits were particularly evident in cases of complex fractures and junior trainees. In arthroscopy, 3D-printed simulators improved procedural accuracy and were more cost-effective than virtual reality simulators and cadaveric laboratory results. Three-dimensionally printed simulators were also assessed for skills related to spine surgery, in which trainees demonstrated clear learning curve improvements for pedicle screw placement and osteotomy techniques, as well as a better understanding of vital paraspinal structures. The application of 3D printing in patient education was equally promising, as it facilitated the process of informed consent, ultimately promoting shared decision making.

Conclusion: The use of 3D-printed models offers effective and customizable methods for developing essential surgical skills. Future research should focus on larger, more diverse study populations and should include long-term follow-up to better assess the impact of 3D printing on education and patient outcomes.

Introduction

Three-dimensional (3D) printing has introduced innovative applications in the medical field, providing valuable tools across various specialties. Originally developed in the 1980s, 3D printing involves creating 3D objects by layering materials based on digital models[1]. In medicine, this tool enables the

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production of customized implants, prosthetics, and anatomical models. This approach has been shown to significantly improve patient outcomes, reduce surgical risks, and optimize procedural efficiency[2-4].

Three-dimensional printing has emerged as an effective tool in orthopaedics, particularly in surgical interventions[4,5]. Traditionally, surgeons relied on two-dimensional imaging techniques such as radiographs, computed tomography (CT) scans, and magnetic resonance imagings (MRIs) to plan surgeries. While these methods provide valuable information, they may not fully convey the spatial relationships required for complex procedures[6]. Three-dimensional printing addresses this limitation by converting these images into models that accurately replicate the patient's anatomy, allowing for preoperative planning. This has been shown to improve the accuracy of surgical procedures and minimize the potential for intraoperative complications by reducing operative time, intraoperative blood loss, and radiation exposure[5,7-10]. Another application of 3D printing includes the creation of patient-specific instrumentation (PSI), including customized navigation templates, surgical guides, surgical instruments, and even orthopaedic braces[11]. Using PSI offers more comfort compared with standard options, and these customized solutions have also been shown to improve surgical precision and reduce the time required in the OR[12].

Beyond its clinical applications, 3D printing serves as an invaluable educational tool for medical students, orthopaedic surgery residents, and patients[13-15]. For students and residents, it offers a hands-on learning experience, enabling them to interact with accurate replicas of human anatomy, avoiding the challenges of cadaver-based training or live surgery. This tactile engagement enhances their understanding of complex structures and pathologies, bridging the gap between theoretical knowledge and practical skills. Many medical institutions have integrated 3D printing into their educational and training programs for orthopaedic surgery residents, with applications such as fracture reduction training and arthroscopy simulations[16,17]. However, a synthesis of the published data to assess the efficacy of 3D printing as an educational tool has not been conducted. For patients, 3D-printed models may provide a visual representation of their medical condition and the proposed surgical procedures, fostering better communication and informed decision making. Thus, the purpose of this review was to inform educators and medical professionals about the potential 3D printing can offer based on the current published evidence.

Methods

Search Strategy

Data were downloaded from PubMed and Web of Science databases on February 20, 2024. Literature was searched using text words and MeSH terms including orthopaedics, 3D-printing, and education. Boolean operators (or, and) and asterisks for truncation were used to optimize the search results. Search results from all databases were uploaded to Covidence, and duplicates were automatically removed. The number of publications obtained for screening was 2,160 (Fig. 1). Articles were initially screened independently by 2 reviewers based on title and abstracts. The remaining 152 articles were screened based on the full text. Disagreements were discussed between the 2 reviewers to reach a consensus, and conflicts were resolved by the senior author, a pediatric orthopaedic surgeon.

Eligibility Criteria

This systematic review focuses on the use of 3D printing as an educational tool. Inclusion criteria required that studies (1) used 3D printing as the primary training intervention, (2) focused on anatomy or surgical procedures relevant to orthopaedics, (3) measured a learning effect (comprehension or technical skill) or surveyed participants on their experience, and (4) focused on educating medical students, residents, attending physicians, or patients. All available publication years were included. Studies were excluded if (1) 3D printing was not used; (2) the article was irrelevant to orthopaedics; (3) the study was a review, editorial, technique article, methods paper, conference proceeding or incomplete (e.g. only abstracts available); and (4) the outcomes focused solely on surgical outcomes rather than learning outcomes. Based on these criteria, 50 articles were included (Fig. 1).

Data Extraction

Included studies were compiled in a database, and the following information was extracted: study title, author list, year of publication, sample size, the type of surgical procedure or anatomy being taught, the given learning outcome being assessed, cost of the 3D model, and final conclusions by authors. For all studies, data for both control (didactic learning) and experimental (3D-printing) groups were compared and summarized.

Results

Classification and Reduction of Fractures

Three-dimensional printing offers a promising alternative by providing highly customizable models that can replicate a wide range of fracture patterns and bone densities. These models provide residents with the opportunity to practice reduction techniques and fixation strategies on anatomically accurate replicas without the constraints of time, risk, or ethical concerns.

Several studies have demonstrated the effectiveness of using 3D printing for training residents in the identification and classification of acetabular fractures (Table I)[16,18,19]. Currently, radiographs and CT are the two-dimensional imaging modalities used to interpret these fractures. However, the complex 3D geometry of these fractures can make it difficult for residents to develop proficiency in the identification and classification of acetabular fractures. Goyal et al. compared lectures with and without 3D-printed models and found that residents who were taught with 3D-printed models improved significantly more in classifying acetabular fractures than the group that was taught with only a lecture (Table I)[16]. Huang et al. and Lim et al. compared 3D-printed models with other educational tools, such as virtual reality (VR), CT, radiographs, and physical models[18,19]. Residents were evaluated through different objective tests such as identifying anatomical landmarks, identifying fracture patterns, and deducing the traumatic mechanism. In the study by Huang et al., groups trained with 3D-printed models showed a clear advantage

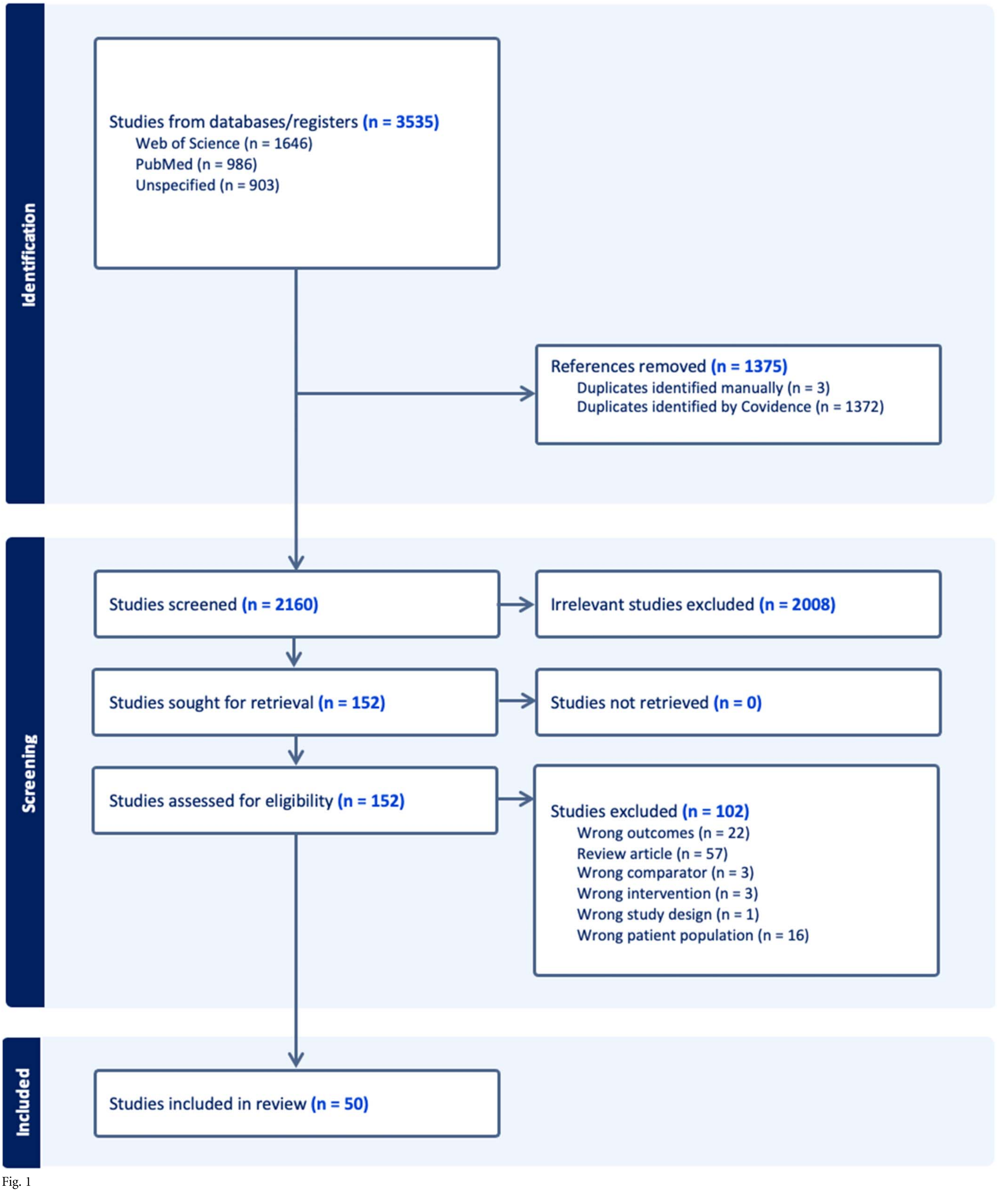

Fig. 1
Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram.

TABLE I Summary of Findings Comparing the Use of 3D Printing with Didactic Learning for Fracture Classification

Study	Location of Fractures	Sample Size (# of Trainees)	Significant Improvement in Fracture Classification When Using 3D Printing
Goyal et al.[16]	Acetabulum	16	$p < 0.05$
Huang et al.[18]	Acetabulum	141	$p = 0.003$, $p = 0.010$
Lim et al.[19]	Acetabulum	41	$p < 0.001$
Masada et al.[20]	Scapula., humerus, radius, pelvis, tibia/fibula	12	$p < 0.01$
Montgomery et al.[21]	Calcaneus	21	$p < 0.01$

over VR and physical model groups when it came to correctly identifying major fracture lines and classifying the fracture. The rate of correct classifications was 51.1%, 27.7%, and 27.7% in the 3DP, VR, and physical model groups, respectively[18]. Lim et al.'s study demonstrated significant improvement in fracture identification using 3D models compared with radiographs[19].

Although residents evidently display higher levels of diagnostic accuracy and faster times with increasing years of residency training, 1 study highlighted the effect 3D-printed models had on trainee diagnosis accuracy, perceived accuracy, and confidence in fracture understanding[21]. Interestingly, the use of 3D models significantly improved perceived accuracy and confidence of understanding regarding fracture patterns in junior levels, far more than in seniors[21].

Another study compared the efficiency and outcomes of fixation surgeries by residents with and without 3D models. They used the Ottawa Surgical Competency Operating Room Evaluation (O-Score) to evaluate the residents, which assesses factors such as preprocedure plan, case preparation, knowledge, technical performance, and communication. They found that residents significantly improved their O-scores between the first and second surgery when they trained with 3D models, an improvement that was not observed in the control group[20]. The 3D model group also had significantly greater improvements in OR time, fluoroscopy time, and patient-reported physical function[20].

Interobserver and Intraobserver Agreement of Fracture Classification

Accurate classification of fractures is crucial in determining the appropriate treatment for patients as it can directly affect treatment decisions. Traditional imaging methods may lead to variability in interpretation, particularly for complex fractures and for trainees. Several different fracture types have been assessed in the literature (Table II). Cocco et al. demonstrated that 3D-printed models of proximal humerus fractures significantly increased interobserver agreement for classification and treatment planning in shoulder surgeons (Table II)[22]. This group was able to reproduce reliable prototypes from CT images for approximately $30 USD, taking 90 minutes each[22]. Similar results have been observed for distal radius fractures[23].

Notably, some studies reported different levels of improvement depending on the experience level of participants. While numerous studies demonstrated increased interobserver agreement for fracture classification with the use of 3D-printed models[25,27,31,32], junior trainees and medical students had the most prominent improvements. Moreover, a study involving fellowship-trained trauma and upper limb surgeons reported no improvement with the use of 3D models[30], and another reported only minimally improved overall interobserver agreement among surgeons with various levels of experience[27].

While the use of these models may increase agreement on fracture classification in some cases, a decrease in interobserver agreement on the surgical approach has also been observed[25]. This suggests that 3D-printed models may bring attention to different aspects of the fracture otherwise not observed in traditional imaging, broadening the possibilities for surgical options. Therefore, the use of 3D-printed models in orthopaedic education and practice has proven to significantly improve interobserver agreement when classifying fractures, particularly among junior residents and medical students[33].

Arthroscopy 3D-Printed Training Simulators

Arthroscopy is a minimally invasive surgical technique that has revolutionized orthopaedic surgery, particularly for joint conditions. It involves the use of an arthroscope to visualize, diagnose, and treat joint issues through small incisions, minimizing trauma compared with open surgery. However, this approach has a steep learning curve due to the need for precise navigation and manipulation within the joint space using indirect visualization through a camera. Historically, this required extensive hands-on practice, often in cadaveric laboratories, or the use of expensive virtual reality simulators, which can cost upward of $20,000 USD[17]. The introduction of 3D-printing technology has provided a cost-effective solution to this issue, as it allows for the creation of simulators for practicing complex procedures such as portal placement, triangulation, and intra-articular navigation[17,31].

Ferràs-Tarragó et al. designed a 3D-printed practice model that costs $12 USD of filament[17]. Their device was made up of a base with interchangeable practice modules, a lid creating a closed workspace, and a 3.5-mm arthroscope inserted at adjustable angles. A mobile screen displays the camera feed, allowing trainees to navigate the joint. Unlike cadaveric models, it is cost-effective and does not require water. Twenty first-year residents received the 3D-printed simulator in order to practice 14 exercises that increased in complexity and were designed to progressively develop the skills required for arthroscopic surgery. The Arthroscopic Surgical Skill Evaluation Tool (ASSET) score

TABLE II Summary of Findings Regarding the Use of 3D-Printed Models in Interobserver Agreement in Fracture Classification

Study	Location of Fractures	# of Raters	# of Fractures Diagnosed	# of Classification Systems	Significant Improvement in Interobserver Agreement Rates When Using 3D-Printed Models
Cocco et al.[22]	Proximal humerus	4	75	2	$p < 0.001$
Dust et al.[24]	Tibial plateau	22	22	3	$p < 0.05$
Keltz et al.[25]	Acetabulum	18	7	1	$p < 0.001$
Osma-Rueda et al.[26]	Tibial plateau	5	20	1	$p < 0.01$
Grincuk et al.[23]	Distal radius	20	15	1	$p > 0.05$
Huitema et al.[27]	Tibial plateau	25	40	3	p = 0.005, 0.03,0.08
Brouwers et al.[28]	Acetabulum	27	40	1	$p < 0.05$
de Klerk et al.[29]	Elbow	15	20	N/A	$p = 0.002$
Langerhuizen et al.[30]	Distal radius	10	20	1	$p > 0.05$

was used to evaluate the residents' performance. The median overall ASSET score was 22 points[17], whereas the literature shows the average ASSET score for PGY1 and PGY2s to be around 15 to 20[32]. While no control group was used to compare the use of 3D models to traditional didactic learning, participants rated the program highly with an overall satisfaction of 9.5 out of 10 and they unanimously recommend the program as preparatory training[17]. To make the device widely accessible, the authors designed it for easy 3D printing using affordable home printers (under $300) and PLA filaments.

Cai et al. similarly developed a 3D-printed simulator to facilitate the simulation of surgical skills for portal placement, intra-articular identification of anatomical structures, and arthroscope navigation for hip arthroscopy. They invited 29 orthopaedic surgeons and divided them into 3 subgroups based on their training levels. There were significant differences between the 3 subgroups, suggesting that the model performs similarly to real-life scenarios, where more experienced surgeons should perform better. This implies that a reliable hip arthroscopic simulator can be developed to evaluate hip arthroscopic skills[31]. The poststudy survey also showed high satisfaction rates, and surgeons agreed that the simulator was anatomically accurate and provided good haptic feedback on manipulation of the simulator[31]. In both studies, these 3D-printed models allow repetitive practice, improving motor skills and reducing the number of errors, which is especially useful in overcoming the learning curve[17,31].

Spine

Several different 3D-printed spine models and simulators have been described[33–35]. Burkhard et al. describe the development of 3D-printed vertebrae with varying densities (ranging from osteoporotic, soft, normal, and hard) to replicate different bone conditions[36]. The model outperformed conventional Sawbones, as surgeons reported that the printed model was more realistic concerning haptic feedback and accuracy of the simulation[36]. Other more complex models have also been examined, such as the Living Spine Model (LSM) by Bohl et al[37]. This biomimetic model mimics bone quality, contains a synthetic thecal sac, and provides physiological feedback such as bleeding and nerve conduction to create an immersive surgical simulation[37]. Based on surgeons' reports, the study found that the LSM effectively simulates open posterior lumbar surgery and the required workload while performing L3-L5 pedicle screw fixation and L3-L4 laminectomy[37]. These 2 studies establish that 3D-printed models can be developed to effectively replicate various surgical features.

There are a limited number of studies assessing the effectiveness of 3D-printed spine models in teaching surgical skills. The majority of these studies focus on pedicle screw fixation (PSF), as it is 1 of the main skills that spine surgeons must acquire and the gold standard technique for spinal fusion[38]. Accurate placement of pedicle screws is essential for good surgical outcomes, as misplacement can cause inadequate spinal stabilization and nerve damage, and can also be fatal[39–41]. The learning curve plateau for the placement of pedicle screws is reported to start at approximately 40 screws, while the complete learning curve (the stage where a surgeon is considered fully competent) is estimated at 80 screws or 25 cases[42]. Therefore, it is recommended that residents reach this plateau at a minimum during residency, while keeping the patient's safety a priority as well.

A study by Park et al. assessed 2 residents' ability to perform free-hand pedicle screw fixation on 20 3D-printed lumbar spine models[43]. The length of the procedure and number of pedicle screw violations in the 10 first models were compared to the last 10 models. The authors report that the latter half of the models had significantly fewer violations and took significantly less time than the former 10 models, demonstrating a learning curve effect. Notably, higher vertebral levels had a higher percentage of violation compared with lower vertebral levels, possibly due to the decreased width of the higher lumbar vertebrae. The authors infer that narrower pedicles, such as the ones found in young patients with congenital deformities, may have a higher likelihood of screw violations. This highlights the utility of 3D-printed models for training in such specific scenarios, which is not possible with traditional cadaveric training. Another study, conducted by Hong et al., had a slightly higher sample size of 4 residents[38]. Similar to Park et al., the study used CT scans to create a lumbar spine replica (L1-L3) using 3D printing. Residents performed PSF across 3 trials, during which the time of the procedure and screw placement accuracy were recorded. Repeated training over 3 trials led to significant improvement in both procedure time and accuracy (Table III). This significant difference was not observed between the first and second trials, suggesting that a learning curve effect might require multiple practice sessions to achieve measurable improvements. The most recent study on 3D-printing training for PSF was conducted by Carbone et al[33]. Similar to the 2 earlier studies, the findings revealed a learning curve effect with repeated training sessions. Unlike the previous models that focused on bony structures, Carbone et al. used an anthropomorphic model that contained soft tissue components, creating a more realistic training experience. Moreover, these models featured varying levels of anatomical complexity to simulate different clinical scenarios.

In addition to PSF training, the use of 3D-printed models for osteotomy training has also been assessed. For instance, medical students and residents who used the Barrow Biomimetic Spine, a lumbar spine model, alongside a reference article on Schwab osteotomy grading, performed significantly better on the posterior column and 3-column osteotomies compared with those who only studied the reference article[44]. This enhanced performance was only evident in Schwab grade 4 osteotomies, while no significant difference was observed for grade 2. This suggests that the primary advantage of the 3D model lies in its effectiveness in teaching more complex aspects of 3D spinal anatomy. Both groups reported that while the anatomy seemed intuitive while reading the article, the difficulty arose when trying to translate this information into 3 dimensions[44]. This becomes even more challenging when dealing with spinal tumors, as the architectural relationship between the tumor and vital surrounding structures such as nerves, vessels, peritoneum, and abdominal organs forms the basis of surgical planning[45]. Hu et al. demonstrate that residents and fellows who used a 3D-printed model to study several spinal tumor cases were able to better describe the involvement of paraspinal structures, as well as discriminate the relationship between the tumor and surrounding large vessels[45]. While CT and MRI scans are the most common imaging modalities for the spine, the 3D-printed models allow new trainees to retain a stereoscopic image of what is seen in imaging. In addition, participants reported that the model increased their ability to communicate case information among their colleagues[45]. Effective communication is crucial, as spine surgeons often work alongside oncologists, pathologists, and other healthcare professionals to manage cases.

Medical Students

Three-dimensional printing has also been used as a modality to teach medical students. A study by Cai et al. assessed the use of a 3D-printed knee joint simulator in educating year-first medical students on knee joint biomechanics[31]. Students who used the 3D-printed model scored significantly better on multiple choice questions based on locking and unlocking the knee joint than didactic learning alone. The use of this technology for teaching spatial anatomy and fractures has also been investigated. Yan et al.'s study evaluated medical students' ability to understand pelvic fractures, as it is often challenging for learners at this stage[46]. After randomizing 100 students, they found that students who used a 3D-printed model had a significantly higher rate of identifying the correct pelvic fracture through Young-Burgess identification and an improved accuracy of identifying the injury mechanism. Moreover, 83% of students reported that they would use the model again for further surgical education. Other studies have focused on using 3D printing to teach pelvic, limb, and spinal anatomy[47,48]. While these studies found 3D models to be superior for teaching pelvic and spinal anatomy, they reported no significant advantage for teaching upper and lower limb anatomy compared with traditional methods[47,48]. Once again, this suggests that the benefit of this technology is its use for teaching intricate anatomical sites. While 3D-printed models are beneficial in anatomical education and can improve students' learning experience, it is important to note that they also provide

TABLE III Summary of Findings Regarding the Use of 3D Printing for Spinal Procedures

Study	Procedure	Spinal Region	Sample Size (N Residents)	Assessment	Significant Improvement in Surgical Performance Using 3D-Printed Models
Hong et al.[38]	Pedicle Screw fixation	L1-L3	4	Screw placement accuracy and procedure time	$p < 0.05$
Park et al.[43]	Pedicle Screw fixation	L1-L5	2	Screw placement accuracy and procedure time	$p < 0.001$
Carbone et al.[33]	Pedicle Screw fixation	Thoracolumbar	1	Screw placement accuracy and procedure time	Yes, no p-value reported
Bohl et al.[44]	Schwab grade 2 and 4 osteotomy	L3-L5	6 medical students, 2 residents	Successful removal of specific bone segments	$p = 0.025$
Hu et al.[45]	Tumor resection	Not specified	16 residents, 20 fellows	Understanding the involvement of paraspinal organs and describing the relationship between the tumor and large vessels	$p = 0.019$

limited representativeness to nonbone conditions, such as ligament ruptures, intervertebral disc dehydration, and neurogenic tumors[48]. Therefore, combined approaches using 3D models in addition to traditional imaging approaches, such as MRI, are suggested for these cases.

Patients

In addition to medical students, residents, and attending physicians, 3D-printed replicas have been shown to benefit patients as well. Published articles focus on the use of these models to educate patients before surgery on complex articular and pilon fractures, as well as hand and wrist pathology[49–54]. This method is not recommended for diaphyseal fractures, since investigation with a CT scan is not indicated in this case[49]. While numerous commercially available 3D plastic models can be used for patient education, they generally depict only normal bony, muscular, and tendinous anatomy, excluding complex pathology[54]. Presenting 3D models to patients allows for illustration of their specific pathology, the required surgical procedure, and potential complications that may arise if the condition remains untreated[49]. This can help patients and their families coordinate surgical treatment with physiotherapy/occupational therapy and improve compliance[51]. When surveyed, patients reported improved comprehension of their cases, enhanced trust, better doctor-patient communication, and overall high satisfaction with the use of these models[49,50,52,53]. Therefore, this novel teaching method provides an opportunity to facilitate the process of informed consent and ultimately promotes shared decision making.

Discussion

Among the various applications of 3D printing, this narrative review highlights the growing utility of 3D printing as an educational tool in orthopaedic surgery. Its educational benefits can be seen across various subspecialties and apply to medical students, residents, and even attending surgeons. In addition, these 3D-printed models have proven to be effective in facilitating patient education and promoting better communication among healthcare professionals.

In fracture management training, studies showed significant benefits in classification and reduction when 3D-printed models were used compared with conventional modalities such as lectures, radiographs, and CT scans. These models improved diagnostic accuracy, interobserver agreement, and confidence among trainees. It is important to note that these benefits were particularly evident in cases of complex fractures and junior trainees. The observed improvement highlights the importance of tactile learning in developing diagnostic capabilities, and with 3D-printed models, a repeatable three-dimensional learning experience is made possible without concerns of patient risk or ethical constraints.

3D-printed simulators mitigate the steep learning curve associated with indirect visualization of musculoskeletal anatomy. In arthroscopy, it improves motor skills and procedural accuracy and is more cost-effective than VR simulators and cadaveric laboratories. In spine surgery, a key limitation of surgical training is concerns for patient safety and surgical efficiency. With 3D-printed models, trainees can improve their pedicle screw placements and osteotomy techniques without any cadaveric or patient limitations.

The application of 3D printing in medical student education and patient communication is equally promising. Visualizing complex musculoskeletal anatomy with little to no prior exposure can be challenging. These models offer a tangible way to visualize different conditions, bridging the gap between theory and practice for medical students and enhancing shared decision making with patients.

Despite these benefits, 3D printing is not without limitations. A key limitation is its inability to replicate real-life surgery. Most of the 3D-printed models assessed in the literature are based on bone CT images, which lack information about adjoining soft tissue and vasculature. The use of 3D CT in surgical education, while used heavily in practice, was not assessed in published studies. Similarly, although virtual reality models are emerging in surgical training, few studies have assessed its efficacy alongside 3D printing. Three-dimensional printing technology also needs specific software, professionals, and 3D printers, which will undoubtedly increase expenses. Therefore, future studies should include a cost-effectiveness analysis of 3D-printed models compared with didactic learning and 3D CT imaging. Finally, there was little standardization between studies, and most enrolled only a small number of participants. To confirm these results, more rigorous, longitudinal, and randomized controlled trials with large sample sizes are required.

Conclusion

The use of 3D-printed models is enhancing orthopaedic education by offering customizable ways to develop essential skills. This technology bridges the gap between traditional teaching methods and the evolving demands of modern surgical practice. As advancements continue, 3D printing is set to become a cornerstone of orthopaedic training, enhancing both the competence of trainees and the quality of patient care. Future research requires a focus on larger, more diverse study populations and includes long-term follow-up to better assess the impact of 3D printing on education and patient outcomes. In addition, improving cost-efficiency and developing models that simulate real-life surgical conditions will be key to making this technology more accessible and practical. ■

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