



THREE-DIMENSIONAL PRINTING AND PATIENT-SPECIFIC SOLUTIONS IN ORTHOPEDIC SURGERY: A NARRATIVE REVIEW

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ABSTRACT

Three-dimensional printing, also known as additive manufacturing, has emerged as an important technology in orthopedic surgery. Unlike conventional subtractive manufacturing, three-dimensional printing creates physical objects layer by layer from digital models. This approach enables the production of patient-specific anatomical models, surgical guides, instruments, implants, orthoses, and tissue-engineering scaffolds. Orthopedic surgery is particularly suited to this technology because bones can be accurately reconstructed from computed tomography images and converted into printable models. Evidence published between 2010 and 2019 suggests that three-dimensional printing may improve the understanding of complex anatomy, facilitate preoperative planning, reduce operative time and fluoroscopic exposure, and increase the accuracy of selected procedures. Applications have been described in orthopedic trauma, arthroplasty, spinal surgery, deformity correction, orthopedic oncology, and medical education. Nevertheless, widespread adoption is limited by production time, cost, image-segmentation errors, material restrictions, regulatory requirements, and a shortage of high-quality comparative clinical studies. This narrative review discusses the workflow, principal orthopedic applications, potential benefits, limitations, and future directions of three-dimensional printing based on literature published from 2010 to 2019.

Key words: Three-dimensional printing; additive manufacturing; orthopedics; patient-specific instrumentation; surgical planning; custom implants; tissue engineering

1. Introduction

Advances in digital imaging, computer-aided design, and manufacturing have contributed to the development of personalized orthopedic treatment [1–3]. Conventional orthopedic implants and instruments are generally manufactured in standardized sizes. Although modularity allows surgeons to accommodate anatomical variation, standard devices may be inadequate in patients with complex fractures, severe deformities, substantial bone loss, unusual anatomy, or previous reconstructive

surgery [2,3].

Three-dimensional printing offers a method of converting radiological information into physical objects [1]. The technology creates an object by depositing, curing, melting, or binding material in successive layers according to a computer-generated design [2,4]. Early medical applications were largely confined to anatomical demonstration and surgical simulation. Between 2010 and 2019, however, orthopedic applications expanded to include patient-specific cutting and drilling guides, customized implants, porous metallic components, orthoses, prosthetic devices, and experimental biological scaffolds [2,3,5–10].

Several reviews published during this period described three-dimensional printing as an emerging technology with applications across orthopedic subspecialties [5,7,10,11]. Orthopedics is particularly suited to three-dimensional printing because mineralized tissue is clearly visualized on computed tomography [1]. Bone surfaces can therefore be segmented and reproduced as full-scale physical models. The dimensional accuracy of printed osseous models depends on image quality, segmentation methods, file processing, printer characteristics, and post-processing procedures [12].

2. Literature-Review Approach

A narrative review framework was used to examine publications concerning three-dimensional printing in orthopedic surgery. The publication period was restricted to January 2010 through December 2019. Relevant concepts included “three-dimensional printing,” “3D printing,” “additive manufacturing,” “orthopedic surgery,” “orthopedic trauma,” “patient-specific instrumentation,” “custom implant,” “spinal surgery,” and “arthroplasty.”

The literature from this period consisted predominantly of technical descriptions, case reports, case series, experimental studies, narrative reviews, and a limited number of comparative clinical studies [5–7,13–15]. Consequently, the findings should be interpreted as a summary of emerging evidence rather than as definitive proof of superiority over conventional treatment.

3. Technical Workflow

3.1 Image acquisition

The three-dimensional printing process generally begins with thin-slice computed tomography [1,12]. Magnetic resonance imaging may also be used, particularly when cartilage, tumors, ligaments, or other soft tissues must be represented [1,16]. Image quality is important because motion artifacts, metallic artifacts, thick slices, and inadequate contrast can reduce the accuracy of the final model [1,12].

3.2 Image segmentation

Digital Imaging and Communications in Medicine data are imported into specialized segmentation software. The anatomical region of interest is separated from surrounding structures using thresholding, region-growing, manual editing, or a combination of techniques [1,12,16].

Segmentation is one of the most important stages of the process because an error introduced during segmentation can be reproduced in the final anatomical model, surgical guide, or implant [6,12]. Complex anatomy, poor contrast, metal artifacts, and incomplete imaging may increase the risk of segmentation error.

3.3 Digital model preparation

The segmented anatomy is converted into a three-dimensional surface file, commonly in standard tessellation language format [1,16]. The model is then refined to remove artifacts, close surface defects, smooth irregularities, and establish the required wall thickness.

For patient-specific instruments, the intended osteotomy plane, drilling direction, implant position, resection margin, or correction angle must be determined collaboratively by surgeons and engineers [3,16,17]. The completed digital model should be reviewed by the operating surgeon before manufacturing.

3.4 Printing and post-processing

The digital file is transferred to a three-dimensional printer. Printing techniques used during the review period included fused-deposition modeling, stereolithography, selective laser sintering, selective laser melting, electron-beam melting, material jetting, and binder jetting [2,4,6,9].

Plastic or resin models may be adequate for education, communication, and preoperative planning [3,6]. Surgical guides require materials that can maintain dimensional stability and tolerate an appropriate sterilization method [6,16]. Permanent implants generally require biocompatible materials such as titanium alloys, cobalt-chromium alloys, or selected medical-grade polymers [2,4,8].

Metallic additive manufacturing allows the production of complex porous structures that may be difficult to manufacture using conventional machining [2,4,8]. Post-processing may include removal of supporting material, cleaning, ultraviolet curing, polishing, heat treatment, dimensional inspection, sterilization, and mechanical testing [6,9,16].

4. Applications in Orthopedic Surgery

4.1 Preoperative planning and surgical simulation

Patient-specific anatomical models allow surgeons to examine complex anatomy outside the operating room [3,6,7]. A printed model can be rotated, measured, cut, drilled, and used to simulate fracture reduction, osteotomy, or implant placement [16,17].

This approach may be valuable when two-dimensional radiographs and cross-sectional images do not adequately communicate the spatial relationships among fracture fragments, deformities, tumors, joints, and neurovascular structures [3,7,17].

Printed models may assist with:

- ☐ Selection of the surgical approach;
- ☐ Identification of important anatomical structures;
- ☐ Planning of fracture reduction;
- ☐ Measurement of deformity;
- ☐ Selection of implant dimensions;
- ☐ Assessment of screw trajectories; and
- ☐ Precontouring of fixation plates.

Anatomical models can also support multidisciplinary communication among surgeons, radiologists, engineers, trainees, and patients [3,16].

4.2 Orthopedic trauma

Complex fractures of the pelvis and periarticular regions represent important applications of three-dimensional printing. A preliminary study of unstable pelvic fractures demonstrated the use of printed models for planning internal fixation through a minimally invasive approach [18].

Three-dimensional models have also been described in the management of acetabular, pelvic-ring, tibial-plateau, calcaneal, distal-humeral, and proximal-humeral fractures [13]. These injuries may contain multiple displaced fragments that are difficult to appreciate fully on conventional radiographs.

Printed fracture models may allow surgeons to rehearse reduction maneuvers, select an appropriate exposure, estimate implant dimensions, prebend fixation plates, and anticipate difficult screw trajectories [13,17]. The models may also provide a realistic method of teaching fracture anatomy and operative planning [19].

Literature from the review period suggested possible reductions in operative duration, blood loss, and fluoroscopic exposure [13]. However, the available studies were heterogeneous and frequently involved small patient groups. The clinical effectiveness of three-dimensional printing therefore remained uncertain, particularly regarding long-term functional outcomes and cost-effectiveness [15].

4.3 Patient-specific instruments

Patient-specific instruments are custom guides designed to fit a particular region of a patient's anatomy [3,7]. Their contact surface conforms to the underlying bone, while cutting slots or guide holes direct saw blades, drill bits, pins, or screws.

Potential applications include:

- ☐ Corrective osteotomy;
- ☐ Total knee arthroplasty;
- ☐ Shoulder arthroplasty;
- ☐ Pedicle-screw insertion;
- ☐ Tumor resection;
- ☐ Complex fracture reconstruction; and
- ☐ Treatment of post-traumatic malunion.

In deformity correction, a virtual osteotomy can be planned before surgery. A patient-specific cutting guide transfers the planned osteotomy to the operative field, while a reduction or repositioning guide may help achieve the intended correction [17]. This approach may improve reproducibility in complex multiplanar deformities.

Patient-specific instrumentation also received considerable attention in arthroplasty. Proposed advantages included simplified bone preparation, reduced violation of the intramedullary canal, fewer conventional instrument trays, and shorter operative time [20].

However, evidence regarding improvements in mechanical alignment, implant positioning, and clinical outcomes was inconsistent [20]. Errors in imaging, segmentation, guide production, cartilage representation, guide positioning, or intraoperative fit may reduce accuracy [6,20].

4.4 Customized orthopedic implants

Three-dimensional printing enables an implant to be designed around an individual anatomical defect rather than requiring the patient's anatomy to accommodate a standardized implant [2,3,8].

Customized implants may be useful in:

- ☐ Major pelvic reconstruction;
- ☐ Severe acetabular bone loss;
- ☐ Revision arthroplasty;
- ☐ Spinal reconstruction;
- ☐ Limb-salvage surgery;
- ☐ Congenital deformity; and
- ☐ Reconstruction following tumor resection.

Additive manufacturing also allows controlled production of porous implant surfaces [2,4,8]. Porosity may reduce implant stiffness, improve mechanical compatibility with bone, and provide an interconnected architecture that supports bone ingrowth.

Metallic powder-bed manufacturing techniques can produce graded structures, irregular geometries, and internal pores that would be difficult to manufacture using traditional methods [2,8]. Nevertheless, implant performance depends on pore size, porosity, surface characteristics, mechanical strength, fatigue resistance, and biological response.

Patient-specific implants may improve anatomical restoration in selected complex cases. However, they are usually more expensive than standard implants and require close cooperation among surgeons, engineers, manufacturers, and regulatory authorities [6,9,16]. The possibility of future revision surgery should also be considered during implant design.

4.5 Spinal surgery

Three-dimensional printing has been applied in scoliosis, congenital vertebral abnormalities, spinal tumors, complex revision surgery, craniovertebral-junction abnormalities, and pedicle-screw planning [12,14].

Printed spinal models may improve visualization of abnormal pedicles, rotational deformity, vertebral fusion, and the relationship of osseous structures to surrounding anatomy [12,14]. Surgeons may use these models to plan implant placement and rehearse technically demanding procedures.

Patient-specific drill guides have been investigated as a method of improving pedicle-screw placement [14]. These guides are designed to fit the posterior vertebral surface and direct instruments along preplanned trajectories.

Although promising accuracy was reported in experimental studies and small clinical series, the evidence available by 2019 remained dominated by relatively low-level studies [14]. Stronger comparative and economic evidence was required before routine adoption.

4.6 Orthopedic oncology

Orthopedic tumor surgery requires a balance between obtaining adequate oncological margins and preserving healthy bone, joints, and soft tissues. Three-dimensional printing may assist in defining tumor extent, planning resection planes, manufacturing patient-specific cutting guides, and designing implants for the resulting defect [3,7,9,16].

In pelvic and periarticular tumors, the anatomy may be highly complex and standard implants may not restore the resected region adequately. Customized implants can potentially reproduce the patient's anatomy and provide fixation options suited to the remaining bone [3,8].

Important limitations include:

- ☐ Changes in tumor size between imaging and surgery;
- ☐ Difficulty representing soft-tissue tumor margins;
- ☐ Infection risk;
- ☐ Implant cost;
- ☐ Manufacturing time; and
- ☐ Mechanical challenges following extensive resection.

Therefore, three-dimensional printing should be integrated with oncological imaging, histological diagnosis, and established principles of tumor surgery.

4.7 Education and patient communication

Printed models provide tactile and spatial information that cannot be obtained from a conventional monitor alone [3,16,19]. They may be used to teach anatomy, fracture classification, surgical approaches, implant positioning, and operative techniques.

Trainees can rehearse drilling, osteotomy, reduction, or instrumentation without exposing a patient to additional risk [16,19]. Models may also be useful where access to cadaveric specimens is limited.

During informed consent, patients can view and handle a representation of their own anatomy. This may improve their understanding of the condition, the planned operation, and the intended implant or correction [3,16].

However, educational benefit should not be assumed automatically. Learning outcomes depend on model accuracy, teaching methods, learner experience, and whether the model provides meaningful information beyond conventional imaging [6,15].

4.8 Orthoses and prosthetic devices

Additive manufacturing may permit the production of lightweight, ventilated, and anatomically conforming splints, braces, orthoses, and prosthetic components [9–11].

These devices can be designed from surface scans or imaging data and modified digitally without remaking a physical mold. Potential advantages include improved fit, reduced material use, rapid design modification, and improved cosmetic appearance.

Limitations include uncertain durability, printer availability, material restrictions, production time, and the need to verify pressure distribution and mechanical safety [6,9].

4.9 Bone and cartilage tissue engineering

One of the most ambitious applications of additive manufacturing is the fabrication of biological scaffolds that support the regeneration of bone or cartilage [2,4,8,9].

A scaffold may be designed with controlled:

- ☐ Pore size;

- ☐ Interconnectivity;
- ☐ Degradation rate;
- ☐ Mechanical strength;
- ☐ Surface properties; and
- ☐ Anatomical shape.

Scaffolds may also be combined with cells, growth factors, antibiotics, or osteoconductive materials [9].

Bone is particularly suitable for scaffold-based applications because porous structures can imitate some features of trabecular architecture [2,4,8]. However, creating a clinically useful living construct remains difficult. Major challenges include vascularization, cell survival, nutrient diffusion, mechanical loading, immune response, sterilization, reproducibility, and regulatory approval [8,9].

By 2019, bioprinting remained largely experimental and could not be considered an established replacement for conventional bone grafting or cartilage-repair techniques.

5. Clinical Advantages

5.1 Improved anatomical understanding

A physical model may make complex spatial relationships easier to interpret than two-dimensional images [3,7,19]. This is particularly relevant in pelvic trauma, spinal deformity, intra-articular fractures, and orthopedic oncology [13,14,18].

5.2 Detailed preoperative planning

Surgeons may simulate surgery, compare approaches, evaluate implant options, and identify technical difficulties before entering the operating room [3,16,17].

5.3 Transfer of virtual planning to surgery

Patient-specific guides provide a connection between computer-based planning and operative execution [3,17,20]. They may reduce dependence on freehand estimation during selected osteotomies, resections, and drilling procedures.

5.4 Potential improvement in operative efficiency

Preoperative plate contouring, implant selection, and surgical rehearsal may reduce intraoperative decision-making [13,18,19]. Studies from the review period reported possible reductions in operative time, blood loss, and fluoroscopic exposure, particularly in complex trauma cases [13].

These potential savings must be balanced against the time required for imaging, segmentation, design, printing, post-processing, and sterilization [6,15].

5.5 Personalization

Customized guides and implants may accommodate anatomical differences that cannot be managed adequately with standard devices [2,3,7,8]. This may be especially important in severe deformity, major bone loss, and complex revision surgery.

6. Limitations and Challenges

6.1 Quality of clinical evidence

Many publications from 2010 to 2019 were case reports, small case series, laboratory investigations, or technical descriptions [5–7,13–15]. Few randomized or adequately controlled studies evaluated patient-reported outcomes, complication rates, revision rates, long-term implant survival, or cost-effectiveness [6,15,20].

Publication bias may also have been present because technically successful or unusual cases were more likely to be reported than unsuccessful applications.

6.2 Production time

The complete production process may require several hours or days [6,16]. Image segmentation,

model design, communication with engineers, printing, post-processing, sterilization, and quality assurance must all be completed before surgery.

This requirement limits the usefulness of three-dimensional printing in emergency trauma cases, where treatment cannot be delayed [13].

6.3 Cost

Costs may include:

- ☐ Imaging;
- ☐ Segmentation software;
- ☐ Printers;
- ☐ Printing materials;
- ☐ Equipment maintenance;
- ☐ Engineering support;
- ☐ Trained personnel;
- ☐ Sterilization;
- ☐ Quality control; and
- ☐ Regulatory compliance.

A printed model may reduce operating-room time, but economic benefit depends on case complexity, production method, equipment utilization, and institutional workflow [6,9,15].

6.4 Accuracy and error propagation

The printed object is only as accurate as the data and processes used to create it [1,12]. Errors may arise from:

- ☐ Imaging artifacts;
- ☐ Inappropriate slice thickness;
- ☐ Segmentation;
- ☐ Surface smoothing;
- ☐ File conversion;
- ☐ Printer resolution;
- ☐ Material shrinkage;
- ☐ Post-processing;
- ☐ Sterilization; and
- ☐ Incorrect positioning of a surgical guide.

The cumulative effect of small errors may become clinically significant, particularly when a guide controls screw placement near neural or vascular structures [12,14].

6.5 Sterilization and biocompatibility

Not all printable materials are suitable for tissue contact or sterilization [6,9,16]. Heat may deform some polymers, while chemical sterilization may alter material properties.

Devices intended for implantation require evaluation of biocompatibility, corrosion, wear, fatigue, mechanical failure, and particle generation [2,4,8].

6.6 Regulation and professional responsibility

Customized medical devices raise questions regarding design ownership, manufacturer responsibility, surgeon participation, documentation, quality assurance, and liability [6,9,16].

A clear regulatory and institutional approval process is required before a printed guide or implant can be used clinically.

6.7 Requirement for multidisciplinary expertise

Successful implementation requires cooperation among orthopedic surgeons, radiologists, engineers, technicians, infection-control personnel, and regulatory specialists [3,6,16].

Miscommunication during planning may result in an anatomically accurate product that does not

meet the intended surgical objective.

7. Future Directions

Research published up to 2019 indicated several directions for future development [6,9,10].

Automated and artificial intelligence-assisted segmentation may reduce planning time and operator variability. Integration with navigation, robotics, augmented reality, and intraoperative imaging may allow virtual plans to be updated or verified during surgery [9,10].

Improved metallic and polymeric materials may enable implants with optimized stiffness, porosity, surface properties, and drug-delivery capabilities [8,9]. Decentralized hospital-based printing may also shorten production times for anatomical models and selected surgical instruments [6,16].

However, institutional printing requires standardized quality-management systems, trained personnel, validated software, and clearly defined professional responsibilities [6,9,16].

Future studies should evaluate:

- ☐ Surgical accuracy;
- ☐ Complication rates;
- ☐ Revision rates;
- ☐ Functional outcomes;
- ☐ Patient-reported outcomes;
- ☐ Radiation exposure;
- ☐ Complete production costs;
- ☐ Environmental impact; and
- ☐ Long-term implant survival.

Consistent reporting standards would enable more meaningful comparisons among technologies and clinical indications [15].

8. Conclusion

Three-dimensional printing represents an important development in personalized orthopedic surgery [3,5,7]. Between 2010 and 2019, the technology progressed from the production of demonstration models to applications in surgical planning, patient-specific instrumentation, customized implants, spinal surgery, trauma reconstruction, orthopedic oncology, education, orthoses, and tissue engineering [3,7–11,13,14].

Its greatest immediate value appears to be in carefully selected complex cases where conventional imaging or standardized instrumentation does not provide an adequate solution [3,13,17]. Anatomical models may improve spatial understanding and surgical preparation, while patient-specific guides can transfer a virtual plan to the operating room [14,17,19].

Customized porous implants offer additional possibilities for reconstructing major defects [2,4,8]. Nevertheless, enthusiasm should be balanced by recognition of the limitations in the available clinical evidence [6,15].

Cost, production time, technical error, sterilization, regulation, and uncertain long-term outcomes remain important concerns [6,9,16]. Three-dimensional printing should therefore be regarded as an adjunct to established orthopedic principles rather than as a substitute for clinical judgment. Standardized workflows and stronger comparative evidence are required before many applications can become routine components of orthopedic care.

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