3D Printing for Surgical Planning and Resolution in Orthopaedic Surgery. Case Series

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ABSTRACT
Introduction: The popularity of 3D printing-assisted surgery has surged over the previous decade. The tool's limited use in our context prevents us from taking advantage of all of its applications and benefits for the patient. **Materials and Methods:** A retrospective study on lower limb disease in patients treated at our institution, analyzing each stage of the procedure and its applicability in planning, surgical execution, and implant development. **Results:** We describe 12 cases in which 3D printing was used to treat acetabular defects, bone tumor resections, and long bone sequelae. **Conclusions:** Our series and the literature reviewed demonstrate that 3D printing-assisted surgery improves plan predictability while also reducing surgical times, bleeding, and intraoperative radiation at a reasonable cost. Furthermore, no complications from this technology have been reported.
Keywords: 3D printing; additive manufacturing; anatomical models; custom implants.
Level of Evidence: IV

Impresión 3D aplicada a la planificación y la resolución quirúrgicas en la cirugía ortopédica. Serie de casos

RESUMEN
Introducción: La popularidad de la cirugía asistida con impresión 3D ha crecido en los últimos 10 años. El poco empleo en nuestro medio no permite aprovechar para el paciente todas las aplicaciones y los beneficios de esta herramienta. **Materiales y Métodos:** Estudio retrospectivo sobre enfermedad del miembro inferior en pacientes tratados en nuestra institución analizando cada etapa del proceso y su utilidad en la planificación, la ejecución quirúrgica y el desarrollo de implantes. **Resultados:** Se describen 12 casos en los que se utilizó la impresión 3D para tratar defectos acetabulares, resecciones tumorales óseas y secuelas en huesos largos. **Conclusiones:** Nuestra serie y la bibliografía revisada demuestran que la cirugía asistida con impresión 3D mejora la predictibilidad con lo planificado y reduce los tiempos quirúrgicos, el sangrado y la radiación intraoperatoria, a un costo accesible. Además, no se han comunicado complicaciones asociadas a esta tecnología.
Palabras clave: Impresión 3D; fabricación aditiva; modelos anatómicos; implantes a medida.
Nivel de Evidencia: IV

INTRODUCTION

3D printing, also known as additive manufacturing, was a pioneering technique when it was introduced, in the 1980s, for industrial and engineering purposes.[1] 3D printing technology is increasingly applied in the health sector, due to its decreasing cost and increased accessibility. Since 2014, there has been a rise in publications indicating a growing interest in this topic.[2] Currently, 3D printing of the bone segments to be treated is a tool that helps the understanding, planning, and execution of the surgical procedure, particularly in complex or atypical cases.[3] The prints are designed using DICOM (*Digital Imaging and Communications in Medicine*) tomography or magnetic resonance images, which are then segmented and printed according to the region to be treated. From a cost-benefit

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perspective, 3D printing-assisted surgery is an appealing option for institutions that cannot afford computer-assisted surgery.[4] These digital models can also be used to create patient-specific instruments such as cutting guides, final external fixators, and implant placement guides, as first described by Radermacher et al. in 1999.[5]

Because it is not yet standard practice in the orthopedic field, both surgeons and bioengineers have limited experience and require continual feedback between the surgeon's needs and the alternatives that the bioengineer can provide.

Our aim is to describe a series of cases in which 3D printing was used for the surgical planning and resolution of patients with an orthopedic condition, analyzing qualitatively the stages of use, benefits, and complications.

MATERIALS AND METHODS

We conducted a retrospective analysis of patients treated in the Lower Limb Sector of our institution's Orthopaedics and Traumatology Service from its beginning to March 2022. The inclusion criteria defined were: lower limb condition (from pelvis to foot) and use of 3D printing at any stage of the therapeutic process. Exclusion criteria were: follow-up <2 years in patients undergoing arthroplasty.

The following information was gathered from each case: the design and development process, the stage of use of 3D printing (planning, execution, or prosthetic design), the type of design for execution, and whether there were any complications associated with the printing.

The work process for designing the prints was as follows (Figures 1 and 2):

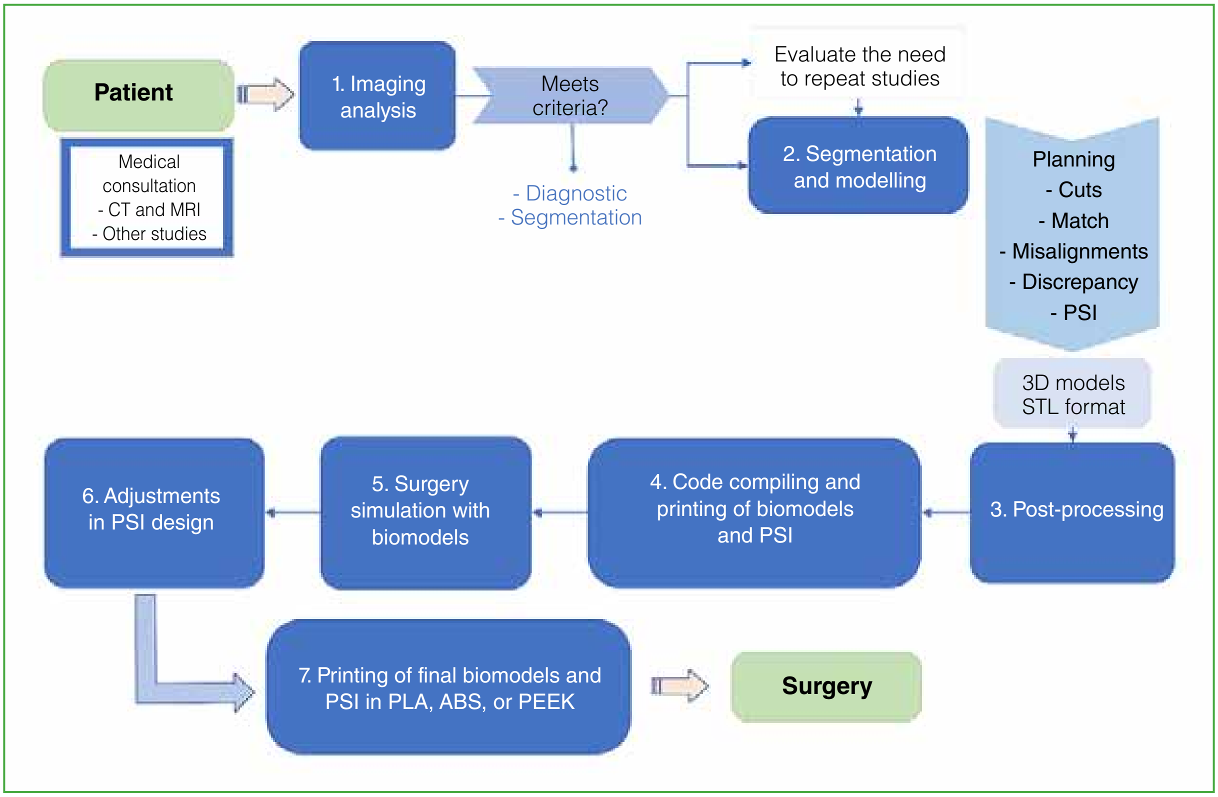

Figure 1. Standard work process for using 3D technology.

1. Image analysis in RadiAnt.
   a) CT scans (contrast-enhanced), 1 mm thick and 512 x 512 square matrix.
   b) MRI, without specific image acquisition parameters.
2. Segmentation and modeling in 3D Slicer.
3. Post-processing in MeshMixer and Blender.
4. Code compiling in Simplify for additive printing of a test 3D model with or without guide or implant design in AutoDesk Fusion.
5. Surgical simulation and evaluation of results in the models.
6. Design of guides and implants in AutoDesk Fusion according to tests.
7. Surgical procedure in the patient.

Steps 4, 5 and 6 can be repeated until the design meets the specifications of the case to be resolved. During the process, in-person or virtual meetings were held with the bioengineering team. When cases were more complex, a daily written record of progress and obstacles was also implemented in GoogleDocs.

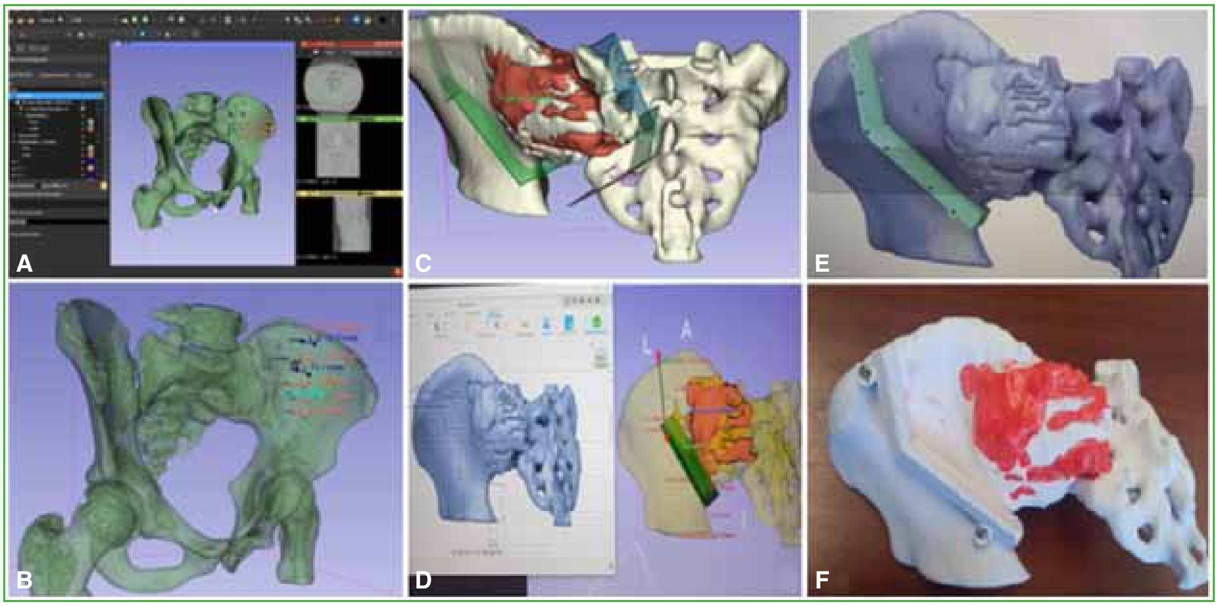

Figure 2. Workflow for cutting guides for a grade 2 chondrosarcoma in Enneking's zone IV of the pelvis. **A.** Segmentation, analysis and marking of the surgical margin. **B.** Determination of the plane of iliac osteotomy. **C.** 3D model (tumor in red) with iliac and sacral osteotomy planes. **D.** Cutting guide design according to planning. **E.** Final guide design and congruence test. **F.** Biomodel and printed guide ready for testing.

RESULTS

Our series included 12 cases where 3D printing was used for diagnosis, planning and treatment. In eight patients, the process was performed entirely in our hospital, while the remaining four required the assistance of another institution for titanium implant printing. With regard to patient-specific instruments, cutting guides were designed in five cases as well as a custom mold for the spacer with antibiotic cement. Three custom acetabular implants were created, two of which required additional screw placement guides (Figure 3).

Figure 3. Case 1. 53-year-old woman with severe acetabular defect. Development of custom implants and screw guide. **A-C.** Intraoperative images. **D.** Anteroposterior radiograph of both hips. Postoperative outcome.

As for the patients, five were women and seven were men. The average age was 39 years. In young patients (average 26 years), tumor disease or sequelae were more common, while in older patients (average 60 years), complications of arthroplasty were most common.

The treated conditions were: correction of posttraumatic deformities, clubfoot sequelae, bone oncology resections and reconstruction of complex acetabular defects (Table).

Table. Description of the clinical picture and the application of 3D printing for its treatment.

Patient	Sex	Age	Disease	Planning	Execution *(PSI)*	Customized implant	Process
1	F	53	Acetabular defect	Yes	Screw guide	Yes	External
2	M	82	Acetabular defect	Yes	Screw guide	Yes	External
3	F	63	Tibial malunion	Yes	External fixator		Institutional
4	M	25	Tibial nonunion	Yes	Cutting guide		Institutional
5	M	17	Clubfoot sequelae	Yes			Institutional
6	F	12	Chondrosarcoma of the sacrum/pelvis	Yes	Cutting guide		Institutional
7	M	24	Osteosarcoma of the sacrum/pelvis	Yes			Institutional
8	M	21	GCT of the distal femur	Yes	Cutting guide		Institutional
9	F	26	Post-traumatic femoral sequelae	Yes	Cutting guide	Yes	External
10	M	59	Infected periprosthetic fracture	Yes	Spacer mold		Institutional
11	M	47	Acetabular defect	Yes		Yes	External
12	M	21	GCT of the distal femur	Yes	Cutting guide		Institutional

M = male; F = female; GCT = giant cell tumor.

All cases included digital planning, with the programs available mainly for measuring and determining oncology margins, osteotomy angles, quantifying the required graft volume, and bone stock available for implant insertion. Surgical procedures were developed as planned, with the printed biomodels. No additional intra-surgical procedures were needed. In patients with tumor and allograft disease, the initial surgical plan was modified according to the availability of biomodels; these modifications consisted mainly of the location of the resection planes (Figure 4). In allograft reconstruction, two simultaneous surgical teams were formed, one for oncology resection and the other for bank graft processing; a similar situation occurred with the custom cement spacer, where one team was in charge of debridement and another formed the spacer.

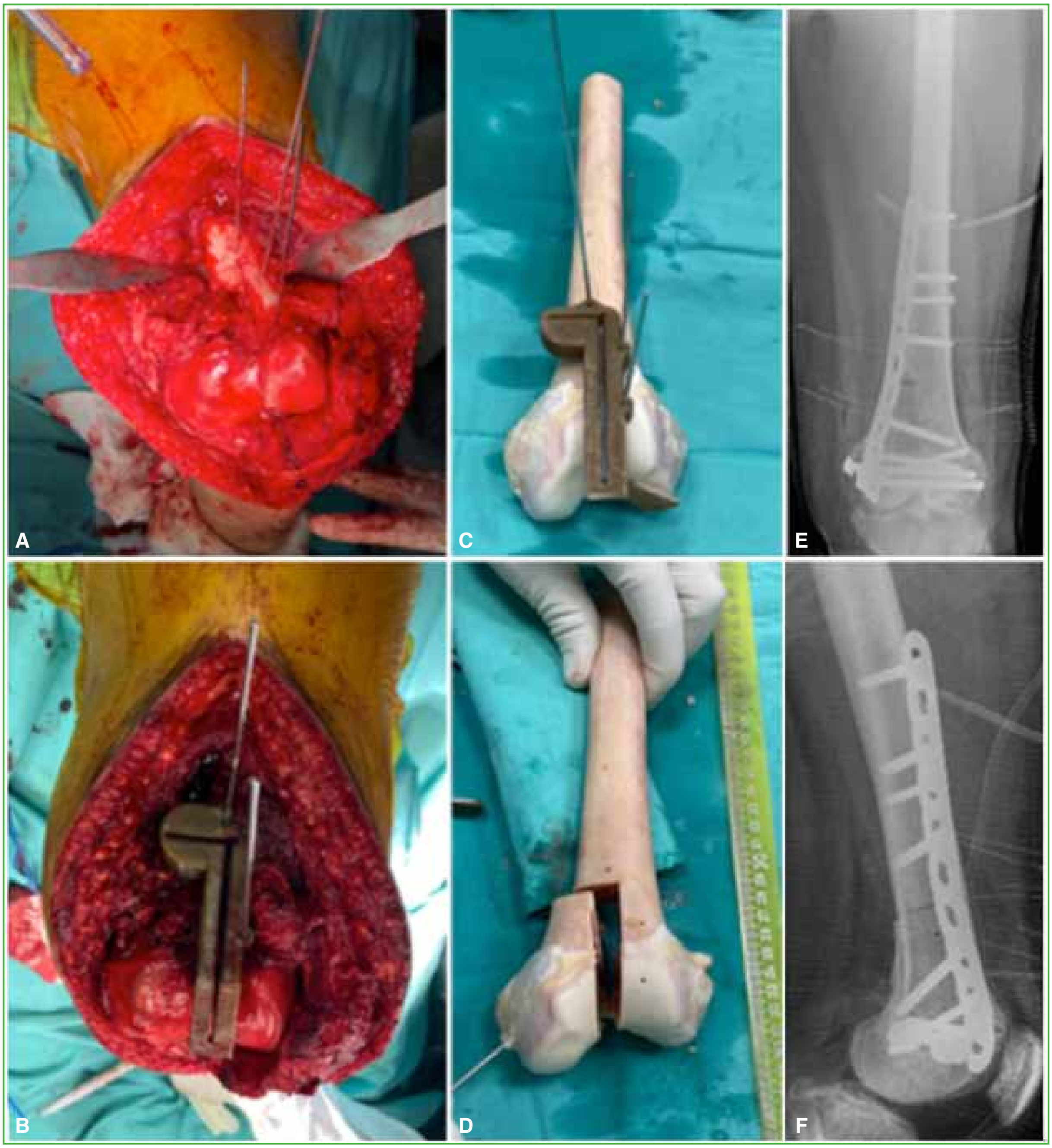

Figure 4. Case 8. 21-year-old male. Tumor resection and reconstruction with structural bone graft. **A and B.** Tumor resection with 3D guidance. **C and D.** Structural bone section with guide for proper congruence with the patient's bone. **E and F.** Radiographs of the left knee. Post-surgical control.

A similar situation occurred with the pre-assembly of the circular external fixator (Figure 5), which was designed on a printed biomodel and then sterilized after assembly. At the time of the intervention, it was only necessary to position the Schanz screws in the planned sites according to 3D planning and attach them to the rings.

Fluoroscopy was used only to examine the osteotomy plans and the positioning of implants and grafts at the end of the procedure.

Figure 5. Case 3. 63-year-old woman. Malunion. The segment to be treated is printed to ensure appropriate and precise assembly before surgery.

It took an average of five meetings between medical and bioengineering professionals per patient. When specific implants or devices were designed, there were more meetings than when digital planning was used alone.

No custom implant presented loosening at two years of follow-up.

In the series of cases described, there were no post-surgical complications associated with the use of this tool, both in implant placement and cutting guides.

DISCUSSION

3D printing is a tool that provides information for professional education and training, as well as planning and treatment in complex or atypical surgical scenarios. In a review of 227 articles, it was shown that the application of this technology decreases surgical time, improves outcomes and reduces radiation exposure.[6] This was also the case in our series, as the formation of two simultaneous teams allowed to reduce the processing times of grafting or forming spacers. The use of cutting guides resulted in the decrease of the total fluoroscopy time, as it was not necessary to determine the level of the osteotomies or perform new measurements during surgery.

The circular external fixator was already created, which reduced the amount of time required for intraoperative assembly.

In a 2019 publication, the change in assessment and planning of distal tibia fractures by new and experienced surgeons was examined. After using 3D printing for planning, 74% and 9%, respectively, changed their plan and approach.[7] In our series, the biomodels allowed us to anticipate difficulties and improve the accuracy of the surgical plan, such as in the case of triplanar deformities, where various circular fixator configurations were tested until a suitable design was achieved and compatible with the proposed osteotomies, or bone bank allograft cases, where the cutting planes were modified to maximize anatomical compatibility between donor and recipient.

An experimental study with 10 cadaveric specimens was conducted to evaluate the design of cutting guides for tumor resection in the pelvis, and a non-statistically significant mean error was found when compared to computer-assisted procedures.[8] Furthermore, it decreases the learning curve and experience required to obtain comparable outcomes among young surgeons and trained professionals.[7] In our patients, the guidelines enabled accurate reproducibility between what was planned and what was executed in the operating room. Another application for cutting guides was to achieve adequate congruence in peek reconstructions in patients undergoing oncology resections, in accordance with the principles of surgical techniques, in order to maximize the possibilities of integration.[8,9]

The material used in the printings for planning was PLA (polylactic acid), a plastic from raw materials, such as starch, tapioca or sugar cane. This plastic is ecological and renewable, and at a certain temperature and humidity, it can be biodegradable, a quality that makes it safe for the environment. The material chosen for the cutting guides was PEEK (polyetheretherketone), a polymer used for the design and manufacture of prostheses and implants with adequate mechanical strength and biocompatibility, since we have a printer suitable for this material.[10,11]

The application of 3D technology offers qualitative and tactile perception benefits that other methods do not; at this point, comparison with other cutting-edge technologies such as computer navigation, augmented reality and robotics is difficult. To date, we have not found studies comparing the results of all these techniques with each other.

We believe the small sample size and heterogeneous composition to be weaknesses of this study. For custom implants, long-term follow-up is only two years (1 case with 5-year follow-up).

When analyzing the disadvantages or complications in 3D printing-assisted surgeries, we have not found complications associated with the use of this tool; therefore, we consider it a safe tool for the procedure. As a disadvantage, because we are still in the learning stage, planning and design required many hours of work and feedback from bioengineers to get the desired outcomes.

It is important to emphasize that it is the first program of assisted surgery with 3D printing with surgeons and bioengineers of the same public institution in the country.

CONCLUSIONS

3D printing, as a complementary tool to surgical procedure planning and execution, improves reproducibility between what is planned and what is executed, resulting in shorter surgery times, less radiation exposure, and the ability to detect potential complications in advance. We must also emphasize that it is a tool that does not represent high costs, unlike computer-assisted surgery, and that no complications have been documented as a result of its use.

Conflict of interest: The authors declare no conflicts of interest.

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