A clinician-run 3D-printing laboratory for orthopaedic preoperative planning: an illustrative case series

Rudolph G Venter,¹ Leon Kotze,² Nando Ferreira¹

¹ Division of Orthopaedic Surgery, Department of Surgical Sciences, Faculty of Medicine and Health Sciences, Tygerberg Hospital, Stellenbosch University, Cape Town, South Africa
² Institute for Biomedical Engineering, Stellenbosch University, Cape Town, South Africa

Corresponding author: rgventer@sun.ac.za

Abstract

Background
Orthopaedic surgery often benefits from innovation in biomedical engineering, with 3D printing being one of the latest examples. Proving cost-effectiveness and improved clinical outcomes remains challenging. Because of the reduced cost and increased accessibility, it has been possible to start an orthopaedic 3D-printing laboratory in a South African tertiary hospital, exploring the place for this emergent technology in orthopaedic practice. This case series aims to illustrate the clinical use of 3D-printed anatomical models and investigate the time and cost involved in their manufacture.

Methods
The design and manufacturing process is discussed, and a retrospective descriptive case series is presented of all models manufactured from January 2020 to April 2021. Using three illustrative cases, we elaborate on two main usage situations: intraoperative reference models (haptic maps) or rehearsal and templating (simulation models).

Results
In the study, 3D-printed anatomical models were manufactured for 16 patients. For 12 patients, these were simulation models, and for the other four patients, haptic maps were made. The mean time for manufacture was 33 hours (range 8–62), and the median cost per patient was ZAR 3 257.62 (range ZAR 927.17 to ZAR 7 177.09).

Conclusion
Considering the decreasing cost and ease of using 3D-printing technology, starting a clinician-run orthopaedic 3D-printing laboratory at a South African training hospital has become possible. In this series we illustrate how 3D printing has been used at our unit for planning and rehearsal of a wide range of orthopaedic cases, and we establish a baseline of time and cost expenditure. The cost-effectiveness of implementing 3D-printing technology in everyday orthopaedic practice warrants further investigation.

Level of evidence: Level 5

Keywords: additive manufacturing, 3D printing, orthopaedic preoperative planning, orthopaedic surgery

Introduction
Orthopaedic surgery has often benefitted from innovation in biomedical engineering, with additive manufacturing (AM) and 3-dimensional printing (3DP) being some of the most recent advances. AM refers to the process that builds 3D geometries by successive addition of material, with 3DP being one of the employed production techniques.²,³

New technologies are often expensive and technically inaccessible, progressively becoming more affordable and user friendly as refinements and developments occur.³ In the field of AM, this process has been accelerated by foundational patents having lapsed in the 2000s, drastically reducing costs.⁴

Improved accessibility and the intuitive knowledge that having a 3D model of the patient’s anatomy will aid the understanding of the pathology has resulted in many orthopaedic surgeons exploring 3DP.⁵,⁶ Clinical applications have included anatomical models for preoperative planning and surgery rehearsal, production of patient-specific instrumentation, manufacture of patient-specific implants and bioprinting.⁸,⁹ In their 2015 review of 3DP in medicine, Tack et al. reported on 227 papers that included 270 cases. In 45% of these cases, 3DP was used to produce patient-specific implants and anatomical models for planning orthopaedic surgeries. Most articles (72%) reported improved clinical outcomes, although quantitative data supported only 10% of these reports. Interestingly, 33% of studies mentioned an increased associated cost, while 64% of studies did not report cost at all, reiterating that cost is still an essential factor to consider.¹⁰

In 2018 we founded an in-house orthopaedic 3DP laboratory in collaboration with the Institute of Biomedical Engineering (IBE) at Stellenbosch University (SU) to explore the place for this emergent technology in orthopaedic practice and training. Since inception, we have identified several ways that 3DP could improve the...
planning of surgical procedures, the way we evaluate orthopaedic pathology and how we train future orthopaedic surgeons by adding haptic perception to traditional visual-only planning techniques.

This retrospective, descriptive case series aims to illustrate the clinical use of 3D-printed anatomical models and investigate the time and cost involved in their manufacture.

**Methods**

**Design and manufacturing process**

The primary surgeon proposed cases, usually because they faced new clinical situations and wanted to augment their established planning techniques or rehearse the case in the lab to compare different plans. They would then discuss the pathology and their surgical plan with our biomedical engineering team member. To create an anatomical 3DP model, high-quality volumetric imaging (CT/MRI scans) is required. All images were anonymised using the Philips Picture Archiving and Communication System (PACS) viewing software package (Philips iSite; Philips Healthcare, Andover, MA, USA) and assigned a unique patient identifier code. Institutional ethics approval was obtained before creating any models.

Images were then imported into software for segmentation. Image segmentation refers to the process of creating a digital shape (surface mesh) from the scan data using a set of digital tools. Both open-source software, like 3D Slicer (Slicer Community) and licenced software, like Rhino3D Medical (Mirrakoi SA, Switzerland), were used for image processing.

When the desired areas of bone had been separated from the surrounding soft tissue, the surface meshes were exported as surface geometry files (*.stl or *.obj) and imported into 3D-modelling software, e.g. Meshmixer (Autodesk Inc., San Rafael, Calif) or Blender (Blender Foundation, Amsterdam, The Netherlands), to smooth and mark the 3D model with the pre-generated patient identifier codes.

When the models were ready for printing, they were uploaded into a slicing software package specific to the 3D printer that was going to be used (e.g., Simplify3D [Simplify3D, Ohio, USA] or Z-SUITE [Zortrax, Poland]). Two 3D printers are currently being used in our laboratory, both acquired through institutional equipment grants: the Leapfrog Bolt Pro (Leapfrog Co., Alphen aan den Rijn, Netherlands) and the Zortrax M300 Dual (Zortrax SA, Olsztyn, Poland). Both use fused deposition modelling (FDM) technology, creating an object by layering melted plastic filament. The choice of printing material largely depended on the intended applications of the model, with some materials being tougher and more resistant to heat and chemicals than others. The final part of the workflow was post-processing, consisting of cleaning the newly printed models and preparing them for use (e.g. removing support material, ethylene oxide gas sterilisation and packaging). Figure 1 illustrates the design and manufacturing workflow.

In manufacturing and using the models, we identified two distinct usages that influence how the models were designed: models for reference only and models for surgical simulation. We refer to models intended for intraoperative reference as haptic maps. The exterior surface of these models was the primary priority, while the internal architecture of the bone could be ignored during the segmentation process. In these instances, care was taken in choosing the material and the sterilisation process as some materials deform when subjected to the high temperatures and pressures in an autoclave.

**Data collection**

A retrospective, descriptive review of cases between January 2020 and April 2021 was undertaken.

'‘Total manufacturing time’ was calculated as the sum of ‘labour time’ (time spent on the segmentation process, slicing and post-processing) and ‘3D printing time’.
Each case’s ‘total cost’ was determined using a cost analysis model developed at our lab with the help of the IBE, according to the following formula:

$$C_{\text{total}} = C_{\text{lab}} + C_{\text{mat}} + C_{\text{mach}}$$

where $C_{\text{total}}$ is the total cost; $C_{\text{lab}}$ is the labour cost per hour (image segmentation, mesh processing, slicing and removal of secondary support structures); $C_{\text{mat}}$ is the material cost per gram (3DP filament); and $C_{\text{mach}}$ is the machine running costs per hour (calculated according to annual maintenance and depreciation rate).

Values for each of these variables change depending on: the operator doing the work (experienced vs inexperienced operator); 3D printer used (Leapfrog Bolt Pro vs Zortrax M300 Dual); and specific filament chosen and how much the filament cost at the time of purchase: acrylonitrile butadiene styrene (ABS) vs polylactic acid (PLA) vs polyethylene terephthalate glycol (PETG) vs Nylon. Values used for the different variables are shown in Table I. Time and cost were calculated per patient because, in some instances, multiple models were used to rehearse a case more than once.

**Table I: Values to be substituted for variables in ‘total cost’ ($C_{\text{total}}$) calculation equation**

<table>
<thead>
<tr>
<th>Labour costs ($C_{\text{lab}}$)</th>
<th>Senior lab technician/ experienced operator</th>
<th>ZAR 519.11 per hr (post level 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Junior lab technician/ inexperienced operator</td>
<td>ZAR 300.92 per hr (post level 7)</td>
</tr>
<tr>
<td>Wanhao PLA, 1.75 mm, natural</td>
<td>ZAR/g 0.35</td>
<td></td>
</tr>
<tr>
<td>Wiiboox PLA, 1.75 mm, white</td>
<td>ZAR/g 0.41 (range ZAR/g 0.41 to ZAR/g 0.56)</td>
<td></td>
</tr>
<tr>
<td>Zortrax ABS, 1.75 mm, white</td>
<td>ZAR/g 0.66 (range ZAR/g 0.50 to ZAR/g 1.10)</td>
<td></td>
</tr>
<tr>
<td>Zortrax PETG, 1.75 mm, black</td>
<td>ZAR/g 0.82</td>
<td></td>
</tr>
<tr>
<td>Zen Nylon, 1.75 mm, white</td>
<td>ZAR/g 0.47</td>
<td></td>
</tr>
<tr>
<td>Machine costs ($C_{\text{mach}}$)</td>
<td>Zortrax M200 FDM</td>
<td>ZAR/hr 31.49</td>
</tr>
<tr>
<td></td>
<td>Zortrax M300 Dual FDM</td>
<td>ZAR/hr 50.65</td>
</tr>
<tr>
<td></td>
<td>Leapfrog Bolt Pro FDM</td>
<td>ZAR/hr 64.17</td>
</tr>
</tbody>
</table>

*Filament cost per gram (ZAR/g) can vary as prices fluctuate.*
<table>
<thead>
<tr>
<th>Case number</th>
<th>Diagnosis</th>
<th>Usage</th>
<th>3D printer model</th>
<th>Material</th>
<th>3D printing time (hr)</th>
<th>Labour time (hr)</th>
<th>Total cost (R)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No 1:</td>
<td>C-epilis and upper femur</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>32.73</td>
<td>9.97</td>
<td>42.70</td>
<td>Total cost (R) 42.70; Labour time (hr) 9.97; Total cost (R) 42.70. Intraoperative reference for resection of callus.</td>
</tr>
<tr>
<td>No 2:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>18.22</td>
<td>7.11</td>
<td>25.33</td>
<td>Planned revision of proximal tibia and fibula.</td>
</tr>
<tr>
<td>No 3:</td>
<td>Left radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>12.45</td>
<td>3.02</td>
<td>15.65</td>
<td>Planning of femoral and pelvic osteotomies; Previously implanted hardware was removed.</td>
</tr>
<tr>
<td>No 4:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>5.35</td>
<td>2.00</td>
<td>7.35</td>
<td>Previously implanted hardware was removed digitally. For planning new osteotomies and templating a fixation device.</td>
</tr>
<tr>
<td>No 5:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>3.87</td>
<td>2.12</td>
<td>6.00</td>
<td>MRI was done to assess for bony bars across the growth plate; model manufactured to plan correction.</td>
</tr>
<tr>
<td>No 6:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>21.02</td>
<td>3.409 5</td>
<td>24.42</td>
<td>Marked superior migration of acetabulum; used as intraoperative reference.</td>
</tr>
<tr>
<td>No 7:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>1.25</td>
<td>1.56</td>
<td>2.81</td>
<td>Marked superior migration of acetabulum; used as intraoperative reference.</td>
</tr>
<tr>
<td>No 8:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>7.65</td>
<td>9.22</td>
<td>16.87</td>
<td>Marked superior migration of acetabulum; used as intraoperative reference.</td>
</tr>
<tr>
<td>No 9:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>6.76</td>
<td>4.97</td>
<td>11.73</td>
<td>Marked superior migration of acetabulum; used as intraoperative reference.</td>
</tr>
<tr>
<td>No 10:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>3.00</td>
<td>3.00</td>
<td>6.00</td>
<td>Model used to plan correction of malunion.</td>
</tr>
<tr>
<td>No 11:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>927.17</td>
<td></td>
<td></td>
<td>Both CT and MRI were available to aid in the design of the model.</td>
</tr>
<tr>
<td>No 12:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>331.97</td>
<td></td>
<td></td>
<td>Planning of pelvic and femoral osteotomies; previously implanted hardware was removed.</td>
</tr>
<tr>
<td>No 13:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>927.17</td>
<td></td>
<td></td>
<td>Planning of pelvic and femoral osteotomies; previously implanted hardware was removed.</td>
</tr>
<tr>
<td>No 14:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>927.17</td>
<td></td>
<td></td>
<td>Planning of pelvic and femoral osteotomies; previously implanted hardware was removed.</td>
</tr>
<tr>
<td>No 15:</td>
<td>Right radius, ulna and disal humerus</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>927.17</td>
<td></td>
<td></td>
<td>Planning of pelvic and femoral osteotomies; previously implanted hardware was removed.</td>
</tr>
<tr>
<td>No 16:</td>
<td>Right tibia and fibula ×2</td>
<td>Simulation</td>
<td>Zortrax M200</td>
<td>Zortrax ABS filament</td>
<td>927.17</td>
<td></td>
<td></td>
<td>Planning of pelvic and femoral osteotomies; previously implanted hardware was removed.</td>
</tr>
</tbody>
</table>

*Table II: Detailed summary of 3D anatomical models manufactured from January 2020 to April 2021*
Results

From January 2020 to April 2021, 3D-printed anatomical models were manufactured for 16 patients. The series showed significant variation in pathology and anatomy. Most instances (n = 7, 44%) were paediatric reconstructive procedures, including four hip pathologies, two foot deformities and one post-traumatic elbow deformity case. When considering that both hand surgery cases, both hip arthroplasty cases and one limb reconstruction case was also for original paediatric orthopaedic pathology, it is clear that paediatric pathology dominated the indications for acquiring 3DP models. For 12 patients, these were simulation models, and for four patients, these were haptic maps (Table II).

The mean ‘total manufacturing time’ was 33 hours (range 8–62). The mean ‘total manufacturing time’ for the haptic map group was 28 hours (range 8–43), and for the simulation model group was 34 hours (range 8–62). The mean ‘labour time’ was 5.95 hours (range 1.60–21.77). There were two outliers in this group of 21.77 hours (case 24JB) and 15.45 hours (case 21AM) respectively, both ‘simulation models’. In both cases the segmentation process was technically difficult and took longer than usual. Mean ‘3D printing time’ was 26.68 hours (range 5.35–56.37). The variability in this group was primarily because of model size, complexity or the number of models required for repeated rehearsals.

The median ‘total cost’ per patient were ZAR 3 257.62 (range 927.17–7 177.09). The median ‘total cost’ for the haptic map group and the simulation model group was ZAR 2 517.46 (range 927.17–4 267.94) and ZAR 3 330.13 (range 929.22–7 177.09), respectively. Details regarding the time and cost involved in each case are listed in Table II.

Examples of unique usage

Example 1: Haptic map for TB spine with multilevel deformity

A 7-year-old patient presented with pronounced kyphosis secondary to multilevel vertebral body destruction in the upper thoracic spine. The diagnosis of TB spine was made, and reconstruction was planned after an initial period of skeletal traction. A haptic map was requested to augment the initial surgical planning, characterise the deformity better and take it to theatre as an intraoperative reference. Figure 2 demonstrates the segmentation process (left) and the completed surface mesh (right). The model was designed
to be full scale and printed with PETG that is relatively heat resistant and could be sterilised. A white soluble support filament was used during printing to make post-processing time shorter (Figure 3).

**Example 2: Simulation models for rehearsal of total hip arthroplasty (THA) in achondroplastic dwarfism**

An 18-year-old female known with achondroplastic dwarfism had developed arthritis of both hips. Considering the patient’s small stature and the amount of dysplasia, there was uncertainty whether conventional arthroplasty implants would be appropriate or if patient-specific custom-made implants would be required, even after conventional digital planning was employed.

Two sets of simulation models, right and left, were manufactured to rehearse the procedures (Figure 4). The femoral canals were included in the design, and the hemipelvii were each designed so that putting them flat on a table simulated the patient lying in the lateral position. The ideal implant sizes and optimal implant positions could be determined preoperatively by rehearsing the procedure with the manufacturer sets and trial implants in the 3DP lab (Figure 5). This confirmed that patient-specific custom-made implants were unnecessary, reducing the potential cost of the operation.

**Example 3: Simulation models for preoperative frame application in recurrent clubfoot deformity**

A 16-year-old patient presented with a recurrent clubfoot deformity and was treated with soft-tissue procedures. After a second recurrence, gradual correction with an external fixator was planned. A simulation model was manufactured to characterise the deformity better and establish the rotation needed to realign the foot (Figure 6). The model was designed so that the midfoot could be broken apart at the level of the talonavicular and calcaneocuboid joints to simulate movement at the joints. The model was then used to pre-build a hexapod circular external fixator butt frame optimally and ensure that the minimum strut exchanges would be needed during the correction (Figure 7).

**Discussion**

Because of the reduced cost and increased accessibility, it has become possible to make 3DP part of practice and training in the orthopaedics department of a South African tertiary hospital. The current literature discusses various potential uses in orthopaedic surgery, from improved communication with patients and simulating basic procedures to sub-specialist surgeons’ planning and rehearsal of advanced pathology. Our study focuses on the use of 3DP anatomical models to plan and simulate critical steps in a surgical procedure, taking a part of the embodied learning experience out of the high-stress environment of the operating room.

Proving cost-effectiveness and improved clinical outcomes will remain challenging due to the complexity of the cases for which 3DP is typically used. Advanced pathology and abnormal anatomy necessarily mean limited case controls for comparison and imply multiple factors that affect the traditional measures like theatre time, fluoroscopy use, blood loss and hospital stay. Even so, in their 2019 systematic review about the applications of 3DP in orthopaedic trauma, Morgan et al. collated data from 17 studies, representing a dataset of 922 patients. The most consistently measured outcomes were surgical time, intraoperative blood loss and fluoroscopic exposure. Overall, they found a 20% reduction in theatre time, a 25% reduction in intraoperative blood loss and a 28% reduction in fluoroscopic usage.

In the same review the reported costs varied widely from $2 (ZAR 30) to $330 (ZAR 4 951). The range in our lab varied from ZAR 927.17 to ZAR 7 177.09. The likely cause for this wide variation in the literature is a lack of standardisation regarding cost calculation and reporting. The lower values in the ranges are likely only to include filament cost, and the higher values are likely to incorporate a range of factors, including labour cost. These inconsistencies in the literature complicate an assessment of cost-effectiveness and limit comparison with our lab. The total manufacturing time (3D printing time and labour time combined) in our lab was 8–62 hours and is comparable to the reviewed studies, where times ranged from 5–72 hours, even though it is likely that similar inconsistencies regarding calculation and reporting are present.

Regarding the use of 3DP in orthopaedic surgical planning specifically, there has been a gradual increase in publications since 2015, especially single case studies. A recurrent theme in these articles is the need for close communication between the clinicians and the engineers providing the design and manufacturing service. This paper illustrates how the process could be streamlined by developing the capacity to design and manufacture these models in-house. Since starting the lab, we have identified the need to differentiate the models for planning (collectively referred to as anatomical models in some publications) into simulation models and haptic maps, each with a different design philosophy. Their applications are illustrated in the three case studies above.

Limitations of this series include its retrospective nature and the fact that no intraoperative metrics on the effect of 3DP models
during surgery were recorded. This is partly because these cases had advanced pathology without obvious case controls for comparison. This article also did not discuss the potential of creating patient-specific instrumentation in the form of drill and cutting guides. Continuing research in our lab focuses on validating the design and manufacturing process, ensuring that the shapes and sizes of the models remain accurate after sterilisation.

**Conclusion**

Considering the decreasing cost and ease of using 3D-printing technology, starting a clinician-run orthopaedic 3DP lab at a South African training hospital has become possible. In this series we illustrate how 3DP has been used at our unit for planning and rehearsal of a wide range of orthopaedic cases, and we establish a baseline of time and cost expenditure. The cost-effectiveness of implementing 3D-printing technology in everyday orthopaedic practice warrants further investigation.

**Acknowledgements**

The authors would like to acknowledge Dr Sanesh Miseer, Dr Koos Jordaan and Dr Etienne Joubert for their contribution to the publication.

**Ethics statement**

The authors declare that this submission is in accordance with the principles laid down by the Responsible Research Publication Position Statements as developed at the 2nd World Conference on Research Integrity in Singapore, 2010. Ethical approval for this study was obtained before the commencement of data collection from the Health Research Ethics Committee (HREC) of Stellenbosch University: S20/08/190.

All procedures were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

**Declaration**

The authors declare authorship of this article and that they have followed sound scientific research practice. This research is original and does not transgress plagiarism policies.

**Author contributions**

RGV: conceptualisation, study design, preparation of case studies, data analysis, manuscript preparation and manuscript review

LK: study design, data collection, data analysis

NF: conceptualisation, study design, manuscript preparation and manuscript review

**ORCID**

Venter RG [https://orcid.org/0000-0003-0022-6969]

Kotze L [https://orcid.org/0000-0003-2750-0833]

Ferreira N [https://orcid.org/0000-0002-0567-3373]

**References**


