"Description of the CAD-AM Process for 3D Bone Printing: the Case Study of a Femur"

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Abstract

The present work shows how 3D models extracted from a computerised tomography (CT) scan can be processed to be 3D printed into 1:1 orthopedic scale models, which find unquestionable utility in pre-operative surgical planning. Relying on the CAT-CAD methodology, which produces a 3D surface called "mesh" from diagnostic images of body parts, the CAD-AM process elaborates a volumetric bone model which a cost-efficient FDM printer can work with. The suitable materials for these applications are PLA polymers, due to their thermo-mechanical properties, affordability and ecological sustainability; these anatomic 3D printed models allows surgeons to accurately see bones injuries and trauma, resulting in a minimisation of risk and a much more flowing doctor-patient communication. Furthermore these 3D printed objects can be manufactured with specific density in order to simulate bone tissues, resulting in a useful tool through which experienced surgeons can pass on their knowledge to medical students at a very reasonable cost, overcoming the glaring limitations of two-dimensional images provided by CT scans. Here represented is a 3D printed 1:1 scale model of a femur donated to the Bone Bank of IOR- Rizzoli Orthopaedic Institute in Bologna.

Keywords

FDM printer, PLA polymer, Orthopaedic Reproduction Model, CT scan.

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1. Introduction

Over the last century, diagnostic imaging has undergone a process of constant improvement supported by a continual technological development. In the early 1900s, the only diagnostic imaging technique possible was radiology; today, even if this technology is still useful, it is supported by more modern acquisition systems such as CT computed tomography. The proposed methodology aims to support orthopaedic surgical planning with interesting applications of the 3D printing technology, hoping to take the diagnostic process one step forward, and enriching the growing interest for 3D printing technology in the surgical field (Matsumoto et al., 2015). The workflow here shown starts with the acquisition from a CAT scan of 3D images of the anatomic part at stake; these images are processed using a CAD procedure resulting in a 3D model as faithful as possible to the real anatomy of the patient. The 3D modeling aided by computer could be carried out in many ways and using different softwares; we chose to use open-source SWs such as Invesalius 3.1, Meshlab 2016, Blender 2.79 and Ultimaker Cura.

The CT machine acquires hundreds of bidimensional images by slicing the body at a chosen thickness that also depends on the quality of the CAT scan itself; these images are first set to reconstruct the 3D surface of the bone, that can be moved and revolved in every direction in order to have a first glimpse on what the pathology implies. This model is called "mesh" and it still has to undergo an accurate cleaning proceeding that needs to be changed and adapted depending on the specific bone of interest. Once the mesh is ready, it is possible to print a 1:1 scale model of the bone at a reasonable cost, and this possibility is expected to improve surgical planning in several respects.

In order to have a full understanding of the natural geometry of the patient, the convenience of a realistic 1:1 scale 3D printed model is extremely appreciable (Auricchio et al., 2016) and the convenience over multiple bidimensional images is undeniable (Meomartino, ?), allowing surgeons to have complete understanding of the specific pathology (Cameron, 2016), especially with severe or rare malformations. This technique may further encourage the use of novel minimally invasive approaches, reducing complications related to extensive surgical exposure. Furthermore, it enhances informed consent and promotes a clearer communication between doctors and patients (Rizzo, 2015): showing the printed model, surgeons can easily convey medical information and chosen treatments of the case, building a deeper bond of trust with the patients. Furthermore, printing three-dimensional reconstructions of anatomical parts improves medical education, providing a useful tool by which surgeons can teach precious knowledge to students and younger doctors, rather than the traditional training on cadavers. Here documented is our in-house production process of a 3D printed sterilizable model of a femur donated to the Bone Bank of IOR- Rizzoli Orthopaedic Institute in Bologna.

2.Materials and Methods

This work presents a preliminary report of an ongoing research, investigating the feasibility and implementation of an "in-house" 3D printing service for clinical and surgical practice in pediatric orthopaedics and traumatology. Ethical Approval was obtained for the present study. [Figure 1] summarizes the steps of the workflow.

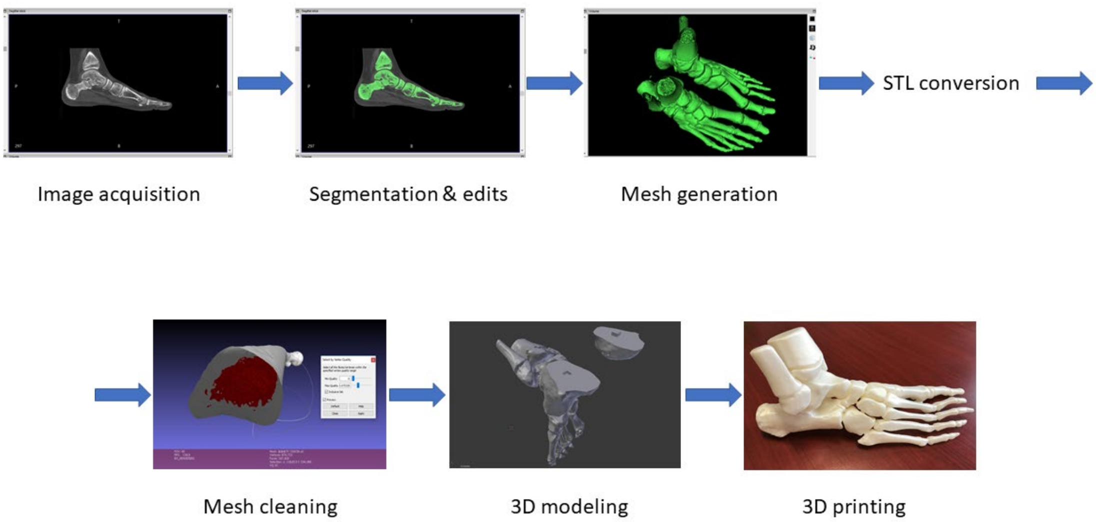

Figure 1. Steps of the workflow.

2.1 Imaging Acquisition and Mesh Processing

The proposed method relies on different open-source softwares in order to achieve the best anatomic accuracy possible. The process is divided in three main phases: the first step is to reconstruct the 3D surface starting from the DICOM images acquired by the CT scan, for which we decided to use InVesalius 3.1; the second phase is usually carried out with Meshlab 2016, a mesh manipulation and repairing software; the last step involves Ultimake Cura 3.4.1 and consists in preparing the obtained model for the printing process by setting up the printing parameters.

InVesalius 3.1 allows to work with DICOM files and visualize the internal structures of interest in three main axes of the human body: the axial, sagittal and coronal orientations. This software permits to choose different density ranges, according to the tissues of interest, and discarding unnecessary anatomical parts. It offers various density "masks" set up with medial values of adult and child bones and tissues, but due to the complexity and irregularity of human anatomy, it is also possible to manually select the range of density if segmentations errors occur [Figure 2 and 3].

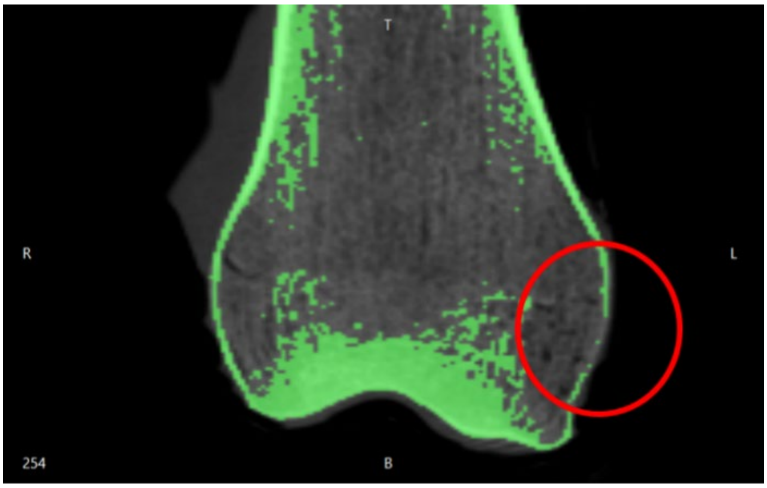

Figure 2. Segmentation errors in the medial epicondyle of a femur.

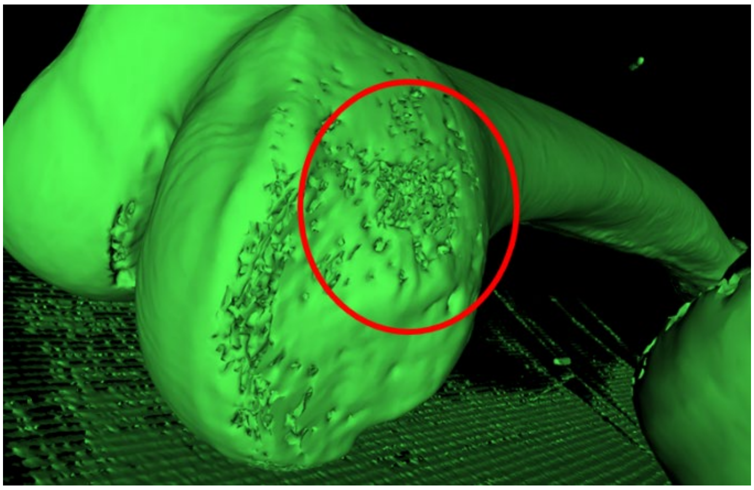

Figure 3. Holes in the mesh of the femur in the medial epicondyle area.

Because using the software masks was never accurate enough to highlight the 3D printable volume, we needed to adjust this first automatic selection with manual corrections. This first step is significant because the precision of the selected volume directly determines the accuracy of the final model. This surface was exported in "standard triangulation language" (.stl) format, then it was repaired and simplified using MeshLab 2016.

This second phase of mesh cleaning allows us to work with a much lighter file, by eliminating the mesh irregularities and errors derived from the image segmentation of InVesalius. This software comes with a variety of automatic and semi-automatic tools, such as the removal of the "orphaned" triangles both inside and outside the bone. Working with long bone surfaces, it is necessary to remove the bone marrow, resulting in an empty and lighter mesh. This is important because having an empty mesh allows us to choose the infill percentage for the 3D printing, a parameter which directly affects the overall printing time and the amount of material in use.

As shown in [Figure 4], this can be accomplished using the "Ambient Occlusion" filter, which is a shading technique used to calculate how exposed each point in a scene is to ambient lighting. This filter simulates a diffused global illumination that darkens enclosed areas, allowing us to select the internal points with a simple range instruction. It is recommended to select the Preview box and set the Min Quality Value = 0 and the Max Quality Value very close to the first one in order to avoid the elimination of the external mesh areas. This step leads us to a hollow 3D model that is significantly lighter than the surface obtained with InVesalius.

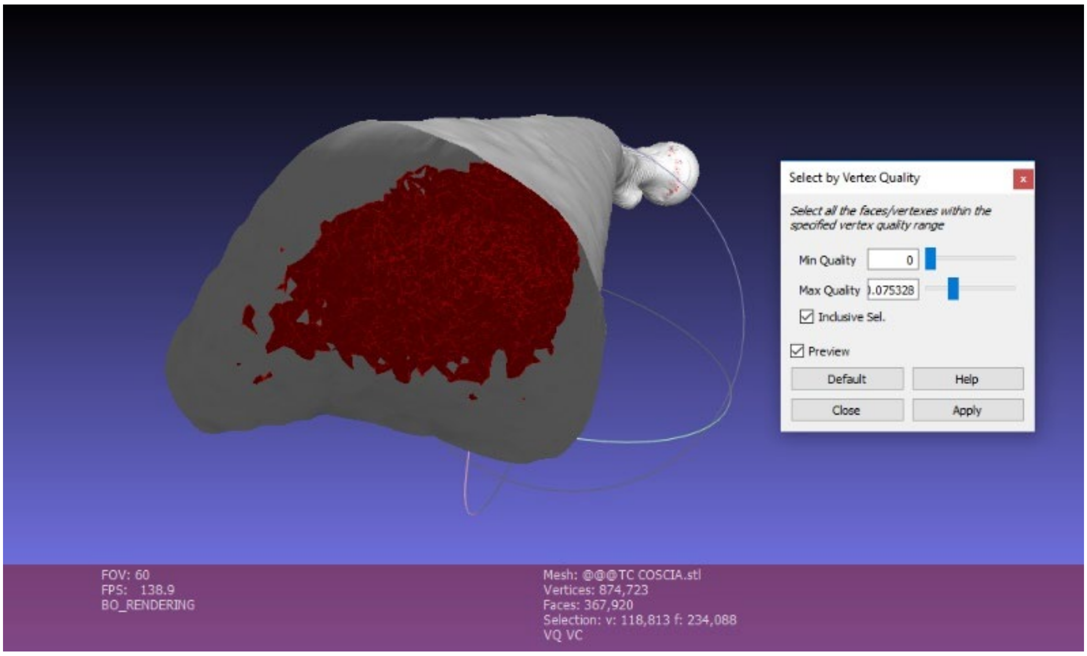

Figure 4. Mesh Cleaning in Meshlab 2016 through Ambient Occlusion filter.

Finally, we use Blender 3.4.1. to perform the last corrections on the mesh: we filled holes, smoothed the surface, and cut the model [Figure 5]. This last operations is necessary for two reasons: first, the 3D printing process requires a flat bottom area to guarantee adherence to the extruded fibers, and secondly because the femur was 463 mm long but the building volume of the printer is only 320 mm height. Through boolean operations we were able to create pins and sockets in order to join the three bone sections we cut [Figure 6 and 7].

Figure 5. Separation of the femur in three parts on Blender.

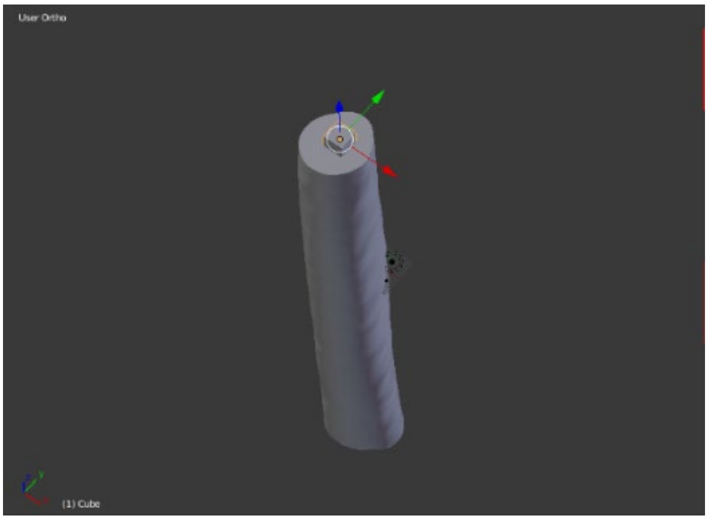

Figure 6. Pin positioning in Blender.

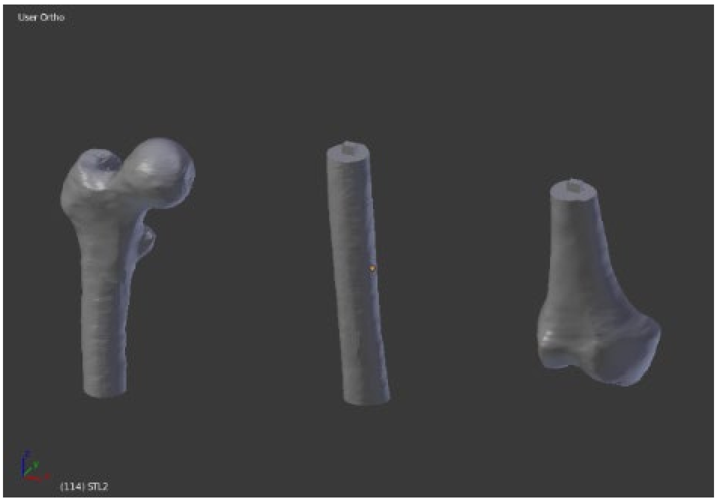

Figure 7. Three sections of the femur with pins and sockets.

2.2 3D Printing

As we obtained an accurate 3D model of the bone, we could start the 3D printing process with Ultimaker Cura [Figure 8]. We chose a low budget EZT3D model T1 3D printer [Figure 9], an entry level Delta printer with which we were able to obtain a great surface finishing due to the low inertia of the moving parts. The material that best suited our needs was High Temperature Poly-Lactic Acid (HTPLA) by ProtoPasta: this PLA based polymer has enhanced thermo-mechanical properties, making it possible to face the standard sterilization (Mitsouras et al., 2015) process for medical devices in use at our hospital, that is carried out by a steam heat (Cisa Production S.r.l., Lucca, Italy); furthermore, its property of biocompatibility and easy printing allowed us to use simple printers (Ghidotti, ?) avoiding the need for closed chamber and filters to manage toxic gasses, like ABS or Nylon fibers require. The duration of the cycle, from heating to cooling down is about 60 min and the temperature is set to 134 °C; in order to bear the cycle and maintain the required mechanical properties, it was necessary to anneal the model, using a laboratory oven with the following baking process: the model undergoes a heating ramp for 30 min up to 115°C, then remains one hour at 115°;in the end a cooling ramp for 30 min. After the annealing, the model can withstand up to 140°C. Additional volumes were added to avoid heat strain by guaranteeing homogeneous cooling.

Printing parameters directly control the finishing quality of the model and we had to experience different parameters calibrations in order to obtain the final print [Tables 1 and 2]. We observed that an excessive height of the layers creates a stair step effect on the external surface, and the extruder multiplier could affect surface quality as well: extruding too much material could result in excess plastic that can ruin the outer dimensions of the model, although not extruding enough material could result in bad layer adhesion, up to layers separation and holes in the top layers. We also experienced that the infill percentage considerably influences printing time as we summarized in [Table 3].

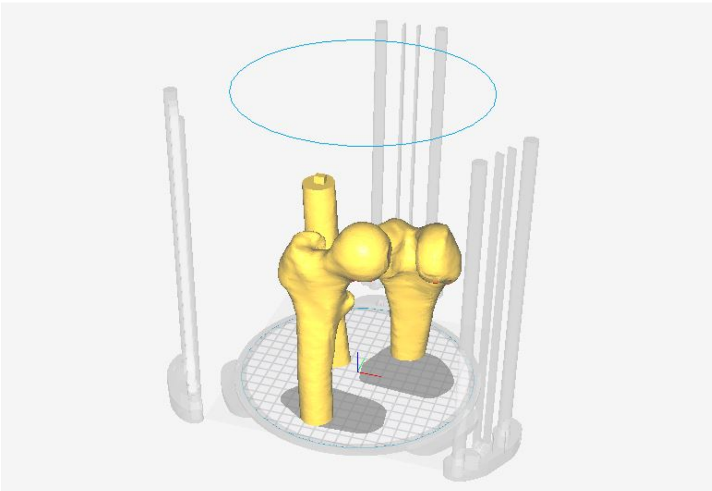

Figure 8. 3D printing set up in Ultimaker Cura.

Layer Thickness [mm]	Printing Time [h:m]	Measured Error
0.05	28 h and 28 min	0.23% ± 0.32%
0.1	15 h 7 min	0.45% ± 0.15%
0.2	7 h and 37 min	0.68% ± 0.45%
0.3	4 h and 58 min	0.83% ± 0.52%

Table 1. Layer thickness calibration (extruder multiplier 100%; infill 15%).

Table 2. Extruder multiplier Calibration (layer thickness 0.2mm; infill 15%).

Extruder Percentage [%]	Printing Time [h:m]	Type of Error
90	7 h 37 min	Weak Infill ; Under-Extrusion; Gaps in Top Layers; Gaps Between Infill and Outline
100	7 h 37 min	None
105	7 h and 37 min	Blobs and Zits; Over-Extrusion
110	7 h 37 min	Blobs and Zits; Over-Extrusion; Curling or Rough Corners

Figure 9. EZT3D model T1 3D printer

Table 3. Infill percentage calibration (layer thickness 0.2 mm; extruder multiplier 100%).

Infill Percentage [%]	Printing Time [h:m]	Type of Error
10	5 h 7 min	Gaps in Top Layers
15	7 h 37 min	None
20	10 h and 17 min	None
25	12 h 42 min	None

2.3 Cost Analysis

Fixed costs for in-house production include purchasing the printer and the filament: the cost for the printer was 180,00 Euros while 1kg of HTPLA was bought at 68,00 Euros. The overall time of processing averaged 10-16 h, requiring 1 to 4 h for software processing and printer preparation. Mean production time ranged from 7 to 10 h for printing at 15% infill. The 3D printed femur weighed 150 g, it required postproduction modification like sanding or removal of support elements whose needed time was approximately 30-60 min including the delivery of the model. Other 60-90 min were required for the sterilization process. We were able to exclude the printing time from the labor costs as we performed our printings overnight or during the day without supervision. Considering the hourly rate (30 Euros) of a senior technology employee at our hospital and an approximate labor time of 2 to 4 h per week, we could estimate the price for the femur model that was worth 1302 Euros.

3. Results

Our workflow allowed us to print three sections of the femur [Figure 10] that were assembled through pins and sockets in one printed bone [Figure 11]. Having chones the High-Temperature PLA it was possible to sterilize it through the steam heat in use at our hospital, letting the doctors evaluate all the orthopaedic aspects and appropriate treatment (Osti et al., 2019).

Figure 10. 3D printed sections of the femur.

Figure 11. 3D printed femur assembled.

4.Conclusion

This methodology allows to handle a detailed and realistic representation of the anatomical region of interest, producing a high-customized copy of the patient bone, contributing to improve orthopaedic surgery in several respects. Diagnostic is upgraded with the possible manipulation of a 3D object instead of bidimensional images acquired with MRI or CT machines, allowing the surgeons to thoroughly understand the anatomy of complex deformities, and reducing the CT scans needed to achieve a good perspective on the specific pathologies (Gindro, 2019). Moreover, our user-friendly workflow is based on the adoption of open-source SWs and low-budget printers and materials, depicting an appealing and advantageous investment especially for small and less affluent hospitals that could benefit from this high-versatile process. Medical education from experienced doctors to students is enhanced, as well as doctor-patient communication and operation planning for surgical teams, that could benefit from looking at the 3D model even during the surgeries, by having the printed and sterilized copy of the bone next to the patient, leading to the reduction of extensive surgical exposure. The growing availability of 3D printing technologies and materials let us hope for a near future where engineers will be part of surgical teams and hospitals, as the scientific community demand for interdisciplinary support develops becoming the standard for the next generation of pratictioners.

4.References

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