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Technical note

Sensitivity analysis of geometric errors in additive manufacturing medical models

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ABSTRACT

Additive manufacturing (AM) models are used in medical applications for surgical planning, prosthesis design and teaching. For these applications, the accuracy of the AM models is essential. Unfortunately, this accuracy is compromised due to errors introduced by each of the building steps: image acquisition, segmentation, triangulation, printing and infiltration. However, the contribution of each step to the final error remains unclear.

We performed a sensitivity analysis comparing errors obtained from a reference with those obtained modifying parameters of each building step. Our analysis considered global indexes to evaluate the overall error, and local indexes to show how this error is distributed along the surface of the AM models.

Our results show that the standard building process tends to overestimate the AM models, i.e. models are larger than the original structures. They also show that the triangulation resolution and the segmentation threshold are critical factors, and that the errors are concentrated at regions with high curvatures.

Errors could be reduced choosing better triangulation and printing resolutions, but there is an important need for modifying some of the standard building processes, particularly the segmentation algorithms.

1. Introduction

For many years additive manufacturing (AM) models have been used in medical applications such as surgical planning, teaching aids and simulations, customized surgical implants, prosthetics and orthotics [1–4], with many benefits for patients and healthcare professionals [5,6].

Although there are different AM building technologies, most of them consist in adding material layer by layer until the desired shape is built [7,8]. The construction of AM medical models usually consists of four steps (Fig. 1):

1. Acquisition: The structure of interest is scanned using computed tomography (CT), magnetic resonance imaging or other three-dimensional imaging technology.
2. Segmentation: The object of interest is segmented out from the image using any of the available segmentation algorithms. The most standard ones are intensity thresholding and region growing.
3. Triangulation: The surface of the segmented object is approximated by a triangular mesh, which is then exported into a STereoLithography (STL) file.
4. Printing: The STL file is loaded into a computer that drives a 3D printer. This printer builds the AM model layer by layer.

Additionally, there might be a fifth process in which the AM models are infiltrated (manually or using vacuum pumps) with different materials to give them strength or other mechanical properties. Some AM techniques do not include the third step, thus the segmented datasets are directly exported into a slice format (e.g. SLC), which effectively bypasses the triangulation step.

Each of these steps involves choosing some methodologies and parameters. In CT, users need to set the voltage and current of the X-ray tube. Thresholds or similar parameters must be defined for the segmentation process and manual editions are sometimes needed for correcting the obtained results. The size (or size range) of the triangles must be selected a priori to define the resolution of the triangulation.

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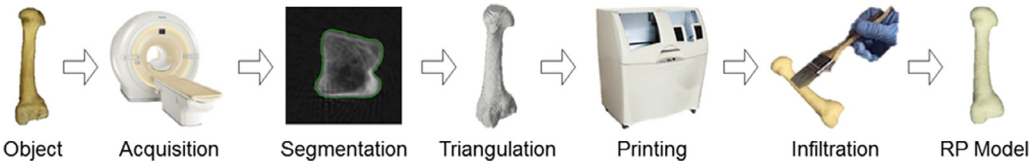

Fig. 1. Construction process of AM medical models.

The layer thickness and orientation must be set at the 3D printer, and thus the in-plane and through-plane printing resolutions are defined. Finally, if AM models are infiltrated, the material needs to be chosen.

Each of the building steps introduces errors, resulting in an AM model that is not geometrically identical to the object of interest. These errors are due to the inherent nature of each process, the presence of artifacts or the definition of non-optimal parameters. Some studies have given recommendations on how to choose thresholds and how to perform the CT acquisition, so that to reduce the effects of image artifacts [9,10]. However, it is not clear how much each building step contributes to the final error.

In medical applications, the geometric accuracy of models is very important, since it may affect the outcome of the treatment or of the chosen application. Several methodologies have been proposed to measure the accuracy of AM models. Some authors have used linear distances between anatomical landmarks to quantify geometric errors [2,3,11–16]. Some others have used colored surface representations to show local errors of the AM models [17–20]. Finally, Arrieta et al. [21] proposed local and global metrics to quantify unambiguously the geometric errors using image-processing techniques.

Few attempts have been made to quantify the error sensitivity to some of the building steps. Galeta et al. [22] measured the error sensitivity with respect to layer thickness and orientation of the printing process and three different infiltrating substances. They used linear distances between landmarks to quantify geometric errors. Fitzwater et al. [23] analyzed error variability with respect to the current of the X-ray tube, threshold values of the segmentation, and printing technology. They quantified the errors using a mixed metric of quality indexes and linear distances between landmarks computed with a coordinate measuring machine.

Our ability to locate landmarks precisely is limited, and we are prone to introduce some artificial variability into that process [2]. Additionally, measuring geometric errors with linear distances can result into an ambiguous metric that cannot always encode those errors accurately [21].

The objective of our research is to characterize and measure the contribution of each building step to the overall geometric error. In order to overcome the ambiguities associated with landmarking processes and metrics based on linear distances, we used the approach proposed by Arrieta et al. [21] to quantify the geometric errors. Thus, we could identify the most sensitive steps and parameters of the building process of AM medical models.

2. Materials and methods

AM medical models were constructed from three cadaveric phalanges (Fig. 2) obtained from the Department of Anatomy of our University, using a standard fabrication process. The cadaveric phalanges were scanned in a CT (GE HiSpeed NX I Dual) with the following parameters: helical acquisition, 80 kV, 80 mA, slice thickness 1 mm, field of view 6 cm × 6 cm and matrix resolution 512 × 512 pixels. Phalanges were segmented from the CT images with a standard software (Mimics™ 13, Materialise®, Leuven, Belgium), using a thresholding segmentation. The operator manually edited the segmentations in order to correct for erroneously segmented voxels. The surface of the segmented object was triangulated and exported into an STL file using the same software (Mimics™ 13). The STL file was uploaded into

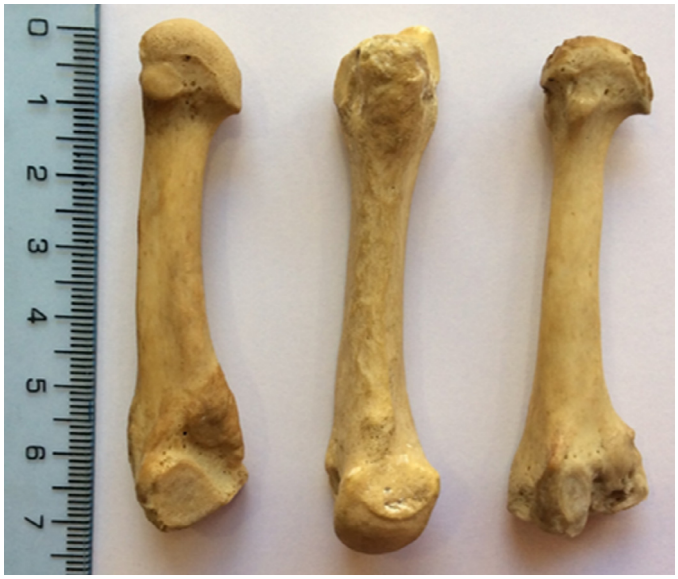

Fig. 2. Cadaveric phalanges.

a personal computer running ZPrint (Z Corporation, release 7.11.6-2), which drives a 3D printer (ZPrint™ 310 Plus, 3D Systems™, Rock Hill, South Carolina, USA). AM models were printed with in-plane resolution of 0.0875 mm using ZP150 powder (Z Corporation) and Zb60 binder (Z Corporation). Finally, AM models were infiltrated with Vinylester resin standard (PlastiQuimica, Santiago, Chile) to give them strength. The infiltration was performed manually with a brush and then AM models were dried at 60°C for 90 min.

We acknowledge the existence of other commercially available software for AM applications, which include some options of image segmentation algorithms. For example: Analyze® (AnalyzeDirect®, Overland Park, KS), Anatomics™ (Brisbane, Queensland, Australia) and 3D Slicer (www.slicer.org). Because of its simplicity, speed, and intuitive operation, most of these software packages include thresholding strategies, making this algorithm a widely accepted one.

We also acknowledge the existence of different AM techniques including, selective laser sintering (SLS), PolyJet™ and three-dimensional printing (3DP™). Although it is still under discussion, some authors have indicated PolyJet™ as the most accurate AM technique [24,25]. Although 3DP™ seems to be the least accurate technology, it is still used for several medical applications or studies [26–30], because of the low cost and speed of the printing process. Additionally, 3DP™ has by far the longest track record in medical modeling, followed by SLS and fused deposition modeling (FDM). Therefore, it is of relevance to characterize the errors associated to this technology.

In order to study the geometric accuracy sensitivity of each AM processing step, we varied one parameter at a time according to Table 1. CT acquisition parameters of the phalanges were chosen according to clinical protocols [31–33].

The sensitivity of each variation was quantified by measuring global and local errors of the AM models according to [21]. Using this approach, we compared the CT scan of the cadaveric phalanges with those corresponding to the AM models. CT scans were aligned