Comparison of segmentation tools for structural analysis of bone tissues by finite elements

D Argüello¹, H G Sánchez Acevedo¹, and O A González-Estrada²
¹ Grupo de Investigación en Energía y Medio Ambiente, Universidad Industrial de Santander, Bucaramanga, Colombia
² Grupo de Investigaciones en Corrosión, Universidad Industrial de Santander, Bucaramanga, Colombia
E-mail: agonzale@uis.edu.co

Abstract. Medical image segmentation is one of the bases of development in the field of personalized medicine, which allows the reconstruction of parts of the human body to produce virtual models by classifying pixels to create a surface or volume with similar properties. This work is focused on image segmentation through open-source software for bone structure analysis using the finite element method. According to this approach, the aim of this study is to investigate the sequential process, based on the features and requirements of the reconstruction software, to assess the segmentation tools and provide a comparative analysis. The methodology focuses on the software that has been documented for the anatomical reconstruction of organs and tissues, accounting for algorithms of manual, semi-automatic and automatic handling. Three segmentation packages are analyzed: 3D Slicer with a semi-automatic process called Region Growing, ITK-Snap with its interactive mechanism Active Contour segmentation mode, and, finally, InVesalius with its automatic segmentation technique that identifies types of tissues and a simplified user-machine interface. A comparison is proposed based on the ease of the workflow, time for completion, the robustness of the tool, and precision of the semi-automatic and automatic methods, as opposed to the manual process, by statistic deviations and volume error obtained with Cloud Compare. The segmentation of a vertebra obtained from a DICOM© file in a computerized axial tomography was completed, and performance indicators were evaluated. The results showed that 3D Slicer – Grow from seeds is the best option to make the segmentation with a 9.59% of volume error and the fastest process among others.

1. Introduction
The segmentation of medical images is a fundamental step to develop personalized medicine. This approach has been used for preparing surgeries, analyzing and treating diseases[1–3], biomechanical studies [4], among others. The postprocessing of medical images is performed using manual, semiautomatic and automatic algorithms [5,6]. Manual tools are the most basic and most used, have good precision, but are time-consuming and it becomes necessary to know about the topology features of the tissues. There are several open source segmentation packages that allow developers to improve segmentation tools. Here, different software is evaluated by its performance, comparing semiautomatic and automatic segmentation [7,8].

The research of bone structures by means of finite element analysis (FEA) has facilitated the study of degenerative diseases such as osteoporosis and the evolution of patient prostheses [9–11]. Using FEA, it is possible to assess the structural integrity of the bone and fix the time of possible interventions of
patients to avoid complications. In this sense, it is necessary to guarantee good accuracy in the segmentation to get reliable results in the FEA [12].

In Colombia, although new technology has arrived for analysis and treatment of diseases, it is not enough to meet the needs of patients. In this way, personalized medicine through detection tools applying science and engineering concepts to create new procedures would improve the method of obtaining data and the quality of the process. In this work, we reconstruct a vertebra from computerized axial tomography (CAT) by means of different segmentation software. We compare the semiautomatic process against manual process with a feature table, average values of deviation, and a representation of cloud to mesh (C2M) signed distance measure using the software Cloud Compare. Finally, with the results of the statistic comparison and the analysis of the features of the software, we provide the best option for the vertebra segmentation process.

2. Materials and methods

2.1. Segmentation of the vertebra

The study focuses mainly on the effectivity of the segmentation process using open source software for medical image segmentation. The segmentation is done for CAT images from an L5 vertebra, with a slice thickness of 2.50 mm and a slice increment of 2.00 mm. The same vertebra is considered for each software. Five different methods were implemented for the reconstruction of vertebrae available in a DICOM file. Although each software has more than one method, only the most representative algorithms were used in this process. 3D Slicer [13] and its semiautomatic threshold Otsu [14] and Growing from seeds. 3D Slicer is characterized by its wide variety of segmentation tools, as well as the active interaction between users in the developer community. InVesalius [15] and a personalized adjustment of threshold and manual handle. It is specialized in magnetic resonance images (MRI) and computed axial tomography (CAT). Finally, ITK-Snap [16] with the semiautomatic Active contour segmentation mode process and manual handle, let users control the growing with an interactive display of the algorithm and has an easy workflow.

2.2. Comparison methodology

All these processes mentioned before were evaluated considering the processing time of the reconstruction, work difficulty, interaction with the users by Pop-ups, plugins, additional documents (as tutorials, updates, etc.) and options for exportation whether in a website or within the software. The main idea is to describe the experience between the software and the user.

There are many procedures to calculate differences between 3D models. One of those is the statistic method by Gaussian model that is common to compare the deviation of a solid in relation with a base model. Soodman et al. [17] show how this evaluation is possible with a standard deviation and an image representation of geometrical features. For this work, we compare all processes against the manual segmentation by standard deviation, the average percentage of volume and a representation of C2M signed distance that computes the distances of a solid relatively to a reference mesh in the program Cloud Compare. Cloud Compare is a free software for editing and processing 3D point clouds and triangular meshes that compare distances between a cloud and a mesh.

3. Results

3.1. 3D reconstructions

All final files were exported in STL format. Figure 1 shows the reconstructed vertebra using five different procedures and three different software: 3D Slicer, InVesalius and ITK-Snap. The images in Figure 1 show that the quality of the surface in models like ITK-Snap and InVesalius had some deformities in comparison with the manual process. Therefore, those areas are expected to turn into higher deviation values in the comparative assessment.
3.2. Development evaluation

Table 1 shows a brief reference about development during the reconstruction of the vertebrae and general features offered by the developers within the software or the official website. It indicates the segmentation method and time to completion, work difficulty from 1 to 3, being 1 the easiest and 3 the hardest procedure to the user, the availability of pop-ups and additional information, and the different export format options.

As it was expected, the manual process was time-consuming and hard to handle. Firstly, the semiautomatic process of threshold Otsu required more work than the others. This is because the algorithm only delimits the cortical tissue of the vertebra. Therefore, the rest of the segmentation process was manual. ITK-Snap was not the best option because the active contour model exceeded the limits of the vertebra. Thus, the most time was spent manually repairing the segmentation. The software InVesalius has an advantage, as its step-by-step methodology is very simple and reduce the time searching for information about the tool. Also, it has many export formats available, which is suitable
for further analysis in external tools. Finally, the semi-automatic Growing from seed process in 3D Slicer, although we had to prepare the contrast image and other adjustments, this procedure can segment any part of the human body in short steps and, in most of the cases, it was not necessary to use the manual tools. This tool is part of an integrated Pop-up. The capacity to easily incorporate new algorithms into the software is a considerable advantage of 3D Slicer.

Table 1. Description of segmentation method, processing time, work difficulty, pop-ups, additional documents and exportation in different segmentation software for the reconstruction of a vertebra.

| Segmentation software | Segmentation method                      | Processing time (minutes) | Work difficulty 1 to 3 | Pop-ups¹ | Additional documents² | Export formats |
|----------------------|----------------------------------------|---------------------------|------------------------|----------|-----------------------|---------------|
| 3D Slicer            | Semi-automatic threshold Otsu + manual | 60                        | 2                      | Yes      | Yes                   | .obj - .stl    |
| 3D Slicer            | Semi-automatic Growing from seeds       | 40                        | 2                      | Yes      | Yes                   | .obj - .stl    |
| InVesalius          | Threshold + manual                      | 40                        | 1                      | No       | Yes                   | .ply - .stl - .iv - .rib - .vtp - .obj - .x3d |
| ITK- Snap            | Semi-automatic Snake + manual           | 50                        | 2                      | No       | Yes                   | .vtk - .stl - .vyu |
| 3D Slicer            | Manual                                  | 90                        | 3                      | Yes      | Yes                   | .obj - .stl    |

³ (tools from developers)
⁴ (tutorials, updates, etc.)

3.3. Statistic comparison

Table 2 shows the data obtained from Cloud Compare regarding the Gaussian process used to compute the standard deviation (STD deviation) and volume error, calculated using the manual process as a reference. Notice that all procedures exhibited a level of error, especially in InVesalius and ITK Snap which had more than 15% of volume error. This error was expected due to the irregular surface that resulted from the segmentation process using these two tools. In contrast, 3D Slicer had a low level of error due to the quality of the refinement of the surface and the tools to handle the images. Standard deviation did not indicate significant differences since the final models are relatively similar. The other values in the table are used to calculate the deviation.

Table 2. Gaussian data, deviation and volume error of all processes compare against manual segmentation.

| Software | Process       | Max. distance | Avg. distance | Max. error | Mean distance | STD deviation | Volume (cube units) | Volume error (%) |
|----------|---------------|---------------|---------------|------------|---------------|---------------|-------------------|------------------|
| Manual   | -             | -             | -             | -          | -             | -             | 68142.6           | -                |
| InVesalius| Threshold     | 4.25012       | 0.60614       | 0.39798    | 0.68407       | 0.766224      | 78691.3           | 15.48033         |
| ITK-Snap | Snake         | 4.54854       | 0.82185       | 0.37389    | 0.92964       | 0.839013      | 81621.7           | 19.78072         |
| 3D Slicer| Grow from Seeds| 4.41203       | 0.52442       | 0.36767    | 0.51102       | 0.786912      | 74677.5           | 9.590036         |
| 3D Slicer| Threshold Otsu| 19.8762       | 0.53800       | 0.38083    | 0.46629       | 1.114973      | 73984.8           | 8.573491         |

Figure 2 shows the color representation of C2M distance in Cloud Compare, with the manual segmentation as a reference. This type of comparison allows identifying the differences of distance by coloring the mesh on a hot scale. In the Figure, the last image shows the high accuracy for the Otsu algorithm in 3D Slicer. Otsu algorithm is good defining the cortical tissue, which constitutes a time-consuming task, leaving only the filling and separation of the vertebra to be defined.
Figure 2. Colour representation of C2M distance in Cloud Compare with manual process as reference (a) Invesalius – threshold, (b) ITK- Snap – Snake, (c) 3D Slicer – grow from seeds and (d) 3D Slicer – threshold Otsu.

4. Conclusions
To select the best option, it is necessary to analyse not only the time spent in the process, knowing that time is important, but the accuracy and robustness of the software. In all cases, each official website provides enough information to keep up about new releases, tutorials, downloads, among others.

Regarding ITK- Snap, although its application in many different medical studies has been documented, the accuracy in the segmentation of the vertebra was low, with a volume error of 19.78%. The threshold Otsu in 3D Slicer was outstanding, with only 8.57% of volume error, but it takes more time than the other software because filling and separating are manual tasks. Taking into account the processing time, InVesalius and 3D Slicer – Grow from seeds were the best options as segmentation processes to reconstruct the vertebra. But, in the statistic comparison, InVesalius had a volume error above 15%. That results in a considerable difference against 3D Slicer, with only 9.59%. In 3D Slicer, the surface arrangement was better than the other software, and the possibility to incorporate new processes to specific model conditions made it a good choice. Thus, the best option for the segmentation process when analyzing vertebrae is 3D Slicer, with its semi-automatic Grow from Seeds process. Although it is necessary to learn how to properly prepare the images and use the tools, the software offers a lot of possibilities to solve other kinds of medical images.

Acknowledgements
The authors acknowledge the support from the project FM-2018-1, Convocatoria VIE, Universidad Industrial de Santander.
References

[1] Forbes J L, Kim R E Y, Paulsen J S and Johnson H J 2016 An open-source label atlas correction tool and preliminary results on huntingtons disease whole-brain MRI atlases front. Neuroinform. 10 1

[2] Abdelsamea M M, Pitiot A, Grineviciute R B, Besusparis J, Laurinavicius A and Ilyas M 2019 A cascade-learning approach for automated segmentation of tumour epithelium in colorectal cancer Expert Syst. Appl. 118 539

[3] Nadal Soriano E, Rupérez M J, Martínez Sanchis S, Monserrat Aranda C, Tur M and Fuenmayor F J 2017 Evaluación basada en el método del gradiente de las propiedades elásticas de tejidos humanos in vivo Rev. UIS Ing. 16 15

[4] Mejía-Blandón C, Bustamante-Goez L and Villarraga-Ossa J 2018 Influencia de las condiciones de carga en la generación de úlceras por presión internas en amputados transfemorales Rev. UIS Ing. 17 223

[5] Torsney-Weir T, Saad A, Moller T, Hege H-C, Weber B and Verbavatz J-M 2011 Tuner: Principled parameter finding for image segmentation algorithms using visual response surface exploration IEEE Trans. Vis. Comput. Graph. 17 1892

[6] Neubert A, Fripp J, Shen K, Salvado O, Schwarz R, Lauer L, Engstrom C and Crozier S 2011 Automated segmentation of lumbar vertebral bodies and intervertebral discs from MRI using statistical shape models Digit. Image Comput. Tech. Appl. 19 2865

[7] Akudjedu T N, Nabulsi L, Makelyte M, Scanlon C, Hehir S, Ambati S, Kenney J, O’Donoghue S, McDermott E, Kilmartin L, Dockery P, McDonald C, Hallahan B and Cannon D M 2018 A comparative study of segmentation techniques for the quantification of brain subcortical volume Brain Imaging Behav. 0 1

[8] Wallner J, Hoegger K, Chen X, Mischak I, Reinbacher K, Pau M, Zrnc T, Schwenzer-Zimmerer K, Zemann W, Schmalstieg D and Egger J 2018 Clinical evaluation of semi-automatic open-source algorithmic software segmentation of the mandibular bone: Practical feasibility and assessment of a new course of action PLoS One 13 1

[9] Shim V B, Pitto R P and Anderson I A 2012 Quantitative CT with finite element analysis: Towards a predictive tool for bone remodelling around an uncemented tapered stem Int. Orthop. 36 1363

[10] Mun D and Kim B C 2017 Three-dimensional solid reconstruction of a human bone from CT images using interpolation with triangular Bézier patches J. Mech. Sci. Technol. 31 3875

[11] Castilla R, Forero L and González-Estrada O A 2018 Comparative study of the influence of dental implant design on the stress and strain distribution using the finite element method J. Phys. Conf. Ser. 1159 012016

[12] Ardila Parra S A, González-Estrada O A and Quiroga Mendez J E 2018 Damage assessment of spinal bones due to prostate cancer Key Eng. Mater. 774 149

[13] Fedorov A, Beichel R, Kalpathy-Cramer J, Finet J, Fillion-Robin J-C, Pujol S, Bauer C, Jennings D, Fennessy F, Sonka M, Buatti J, Aylward S, Miller J V., Pieper S and Kikinis R 2012 3D Slicer as an image computing platform for the Quantitative Imaging Network Magn. Reson. Imaging 30 1323

[14] Vala H J and Baxi P A 2013 2013 A review on Otsu image segmentation algorithm 2 387

[15] Camilo A A, Amorim P H J, Moraes T F, Azevedo F D S and Silva J V L 2012 INVESALIUS: Medical image edition 1st International Conference on Design and Processes for Medical Devices (Italy: University of Brescia) p 279

[16] Yushkevich P A, Piven J, Hazlett H C, Smith R G, Ho S, Gee J C and Gerig G 2006 User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability Neuroimage 31 1116

[17] Soodmand E, Kluess D, Varady P A, Cichon R, Schwarze M, Gehweiler D, Niemeyer F, Pahr D and Woicinski M 2018 Interlaboratory comparison of femur surface reconstruction from CT data compared to reference optical 3D scan Biomed. Eng. Online 17 29