Towards the Modelling of Osseous Tissue

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Abstract: The virtual representation of bone tissue is one of the pending challenges of infographics in the field of traumatology. This advance could mean a reduction in the time and effort that is currently used in the analysis of a bank of medical images, as it is done manually. Our proposal aims to lay the foundations of the elements that must be taken into account not only geometrically, but also from a medical point of view. In this article we focus on the segmentation of a bone model, establish the limits for its representation and introduce the main characteristics of the microstructures that form in the bone tissue.

1 INTRODUCTION

Computer graphics applied to medicine is a field of research with many open lines and continues to boom due to the advancement of technologies. In the field of traumatology, the creation of computer-assisted techniques has made it possible to reduce the intervention time, minimise the risk of error and advances in research to microscopic levels in order to predict and reduce the possibility of suffering a fracture. Studies at microscopic levels are generally based on the use of computed tomographic images (CT). These images contain more detailed information than X-rays and are 2D grayscale images, which can be converted into a 3D volume, where the intensity of the pixel corresponds to the coefficient of absorption of the material. In addition to the difficulty of obtaining a quality image bank to work, the radiation used to obtain the images can cause serious tissue damage and mean a significant health risk to patients. Therefore, there is a need to find a way to replace them. Our main objective is the generation of virtual bone tissue that will allow us to advance through the substitution of these images by providing a much richer and more varied database than the one traditionally obtained with CT images without endangering the health of patients. In addition, it will make it possible to analyse and obtain certain data that normally have to be examined manually which take a long time. To compare the results obtained with those of specialists in the study of bone tissue, the generation of tissue must be in 2D although the importance of certain structural aspects of the bone and the effects on the different structures that form the bone at microscopic levels make it necessary for it to be previous representated in three dimensions.

The structure of the article is as follows: section 2 reviews current knowledge of bone tissue representation. The representation of the model, the selection of boundaries and the main characteristics of the microosseous structures are described below. Finally, the conclusions obtained as well as the future work is highlighted.

2 RELATED WORK

2.1 Hierarchy of Osseous Structures

The hierarchical structure of bones is a fundamental point to take into account for this study. They have a very complex structure that, in addition to providing mechanical support, allows the reserve of minerals. The complexity of this structure causes the bones to have a great resistance. The following is a description of the hierarchical structure of bone, from the macroscale to the nanoscale (Fig. 1):

- Macroscale: this is the level of the entire bone that includes both types of bone: cortical and trabecular. In cortical bone, the lamellae come together in concentric circles to form osteons, while in trabecular bone they come together irregularly to form trabeculae.
- Mesoscale: this layer represents both the cortical bone, which is composed of osteons embedded in the interseptal bone, and the trabecular bone composed of a porous network of trabeculae with irregular shapes (Sabet et al., 2015).

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- Microscale: lamellae are assembled to form two different types of bone tissue: cortical and trabecular.
- Sub-microscale: at this level, collagen fibers are assembled into sheet-like structures.
- Nanoscale: this level is composed of mineralized collagen fibers.

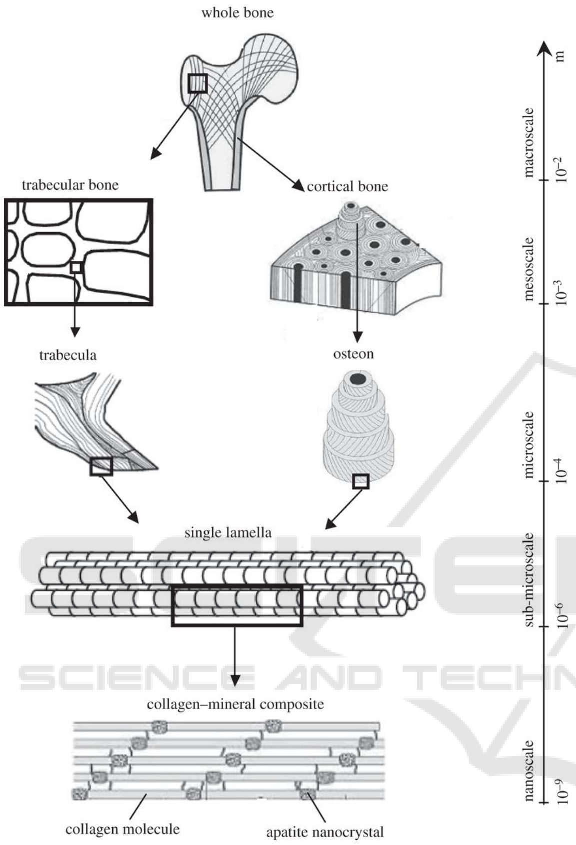

Figure 1: Hierarchical structure of the bone, from macroscale to nanoscale in (Sabet et al., 2015).

Most studies usually focus on predicting the risk of fracture in a bone or on the influence of microstructural features on the behaviour of the propagation of a crack through a bone (Ural, 2011).There seems to be a consensus among the main author on the fundamental microstructural parameters that influence fractures such as the percentage of osteonal area (On.Ar), the density of osteons (On.Dn) and the percentage of porosity(Po) (Demirtas et al., 2016; Tong et al., 2015). Currently, there are no tools to represent bone tissue and the microscopic structures (microstructures) that compose it. Therefore, these studies use approximation of the microstructure, as the one carried out by Demirtas (Demirtas et al., 2016) where it uses an approximate representation in which only the relevant characteristics for its study are included, when the importance of their shape is proved by Raeisi Najafi et al. (Najafi et al., 2007). Some of the most important microstructures which compose the cortical bone are osteons, trabeculae, lamellae or pores, haversian canals, etc. In addition, it must be borne in mind that the bone structure is not homogeneous, so the properties must be determined individually according to the structural level taking into account their involvement at the global level.

2.2 3D Representation of Bone

The irregularity of the cortical bone as well as some parameters depending on the longitudinal axis (Gao et al., 2013) of the bone make representation at macroscale level a fundamental preliminary step when generating bone tissue. There are many approaches to obtaining the representation of a bone structure in three dimensions. All forms of representation are based on 3d scanning or 2D image analysis. The process to scan a model consists of different stages: calibration, scanning, noise removal, scan alignment and merging of the aligned parts to close the gaps. Sometimes it is also necessary to close certain parts manually because of the noise. As for image analysis, there are different techniques based on the sheetness measure (Descoteaux et al., 2006), region growing (Justice et al., 1997) or graph cuts (Boykov and Funka-Lea, 2006) that allow us to segment and classify 2D images to obtain a geometric model in three dimensions. Paulano (Paulano et al., 2014) described a method which needs a user to place a seed within a region that forms a bone. To segment several fragments of bone would have to repeat the process. After placing the seeds, an algorithm based on the growth of a 2D region is used for each seed and all seeds are propagated through the image pile discarding those regions containing a certain noise, in other words, very small regions. A curvature flow filter is also applied to each cut before each 2D segmentation process to smooth the images. This algorithm also resolves certain special cases where overgrowth occurs in the regions.

2.3 Microstructure of Bone Tissue

Our study focuses on the virtual representation of the cortical part of the bone at microscopic levels. The two main structural features of the cortical bone are: the osteons and the Havers canal. There are several studies aimed at increasing knowledge of biomechanics or the peculiarities of these structures such as those performed by Britz (Britz et al., 2009) or Doblaré (Doblaré et al., 2004) which parameters such as the size, shape or distribution of osteons are analyzed. It is generally accepted that osteons are circular in cross-section and that deviations of this shape are attributed to deviations of longitudinal orientation. The study conducted by Hennig (Hennig et al., 2015) shows that osteons are not circular in the cross section, but tend to be elliptical in shape, and that there is no clear way to explain the deviation from the circular shape(Fig. 2). In the same study, it is also suggested that parameters such as age most affect the shape of the osteons regardless of their orientation. Therefore, the typical and classical idea of representing these structures as perfect circles is far from their natural shape. In terms of their distribution, articles such as written by Gao (Gao et al., 2013) show that osteons have a random distribution and are embedded in an interstitial matrix surrounded by a thin layer known as the cement line.

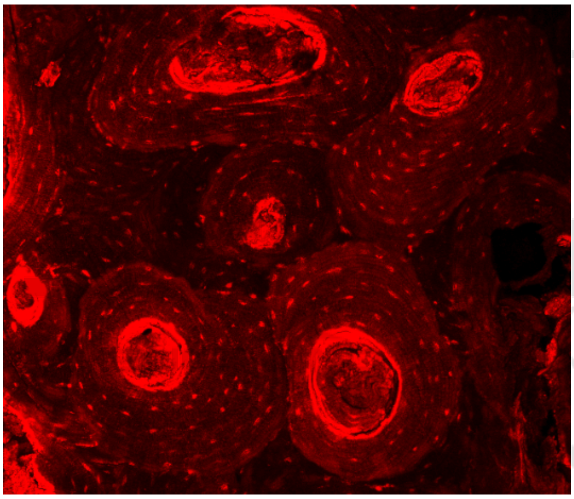

Figure 2: Computed tomography image (CT).

In most of the studies where CT images have been used as a reference, the microstructure has been analyzed manually, carrying a slow and tedious process for a large volume of data. The work done by Törnquist (Törnquist, 2017), is as similar as we can find in terms of the virtual representation of bone tissue. Törnquist performs segmentation, analysis and modeling of bone tissue through CT images maintaining the main geometric characteristics and without using approximations as occurs in the studies of Gao (Gao et al., 2013) and Nobakhti (Nobakhti et al., 2014) where bone tissue is represented without much accuracy.

3 MODELLING VIRTUAL BONE TISSUE

Due to the limitations that currently exist to achieve advances in the field of health, the generation of virtual bone tissue is a fundamental issue to achieve advances that are not currently reached due to lack of data and time. Most of the research at microscopic levels within the health field focuses on the analysis of CT 2D and 3D images manually.

3.1 Model Representation

For the generation of virtual bone tissue, it is essential to have good input data. The irregularity of the bone and the dependence on microstructural features such as the distribution of the osteons /cite-Het1994 or their inclination within the cortical bone /citeGao2013 make their representation at the macro level a necessary preliminary step for the generation of bone tissue. To obtain this representation, we have studied two different approaches: 3D scanning of a bone model and segmentation of a bone from CT images. The biggest problems of the first approach are the time it takes to perform the scan and the segmentation of the model, the difficulty to have real bones and that in the model obtained we only have information from the external but not the internal cortical part. The second approach solves most of the problems of the first approach, and although obtaining medical images can be a problem, it is a much faster, more precise process and allows us to obtain information about the internal part of the cortical bone. Paulano (Paulano et al., 2014) conducted a study focusing on segmentation of fractured bones from CT images. This study concludes that traditional methods of segmentation work well for segmentation of healthy bones, but are unable to identify fractured bones. Since our input data contain healthy and fractured bones, we have used a method based on 2D region growing [(Justice et al., 1997),(Fan et al., 2005)], proposed by Paulano (Paulano et al., 2014), because the results obtained are better as demonstrated in their article(Fig. 3).

The segmentation of bone models, besides helping us to generate virtual bone tissue, could also help us to create a bank of bone fractures using different methods such as those studied in (Pérez et al., 2018) where the suitability of a library of geometric fracturing is analyzed for the different fracture approaches of geometric models examined by Paulano (Paulano-Godino et al., 2017).

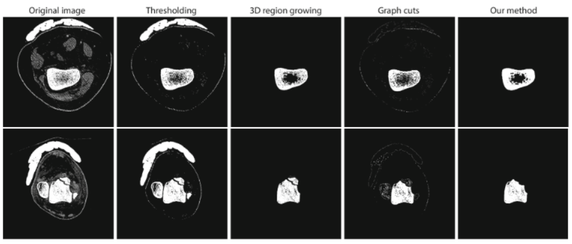

Figure 3: Results obtained by the different methods in (Paulano et al., 2014). The first row corresponds to a healthy bone while the second row corresponds to a fractured bone.

3.2 Setting Boundaries

As the automatic generation of all bone tissue from a bone can be a slow process and most scientific articles focus on the manual analysis of 2D images, we consider that the generation of virtual bone tissue should be in 2D. This will allow us to compare the results obtained directly with the values obtained by specialists when studying bone tissue.Therefore, for the generation of the tissue we have used a plane to manually select the area of the bone over which we want to generate the bone tissue (Fig. 4).

Figure 4: Representation of the bone and the plane to delimit the area to be generated.

In order to be able to work in 2D, the points of contact of the bone and the plane are aligned with the Z axis by applying a series of simple transformations. The points of contact between the bone geometric model and the plane form the inner and outer limits of the area of the fabric to be generated (Fig. 5). So we have to use an algorithm to establish which points form each of the limits like the alpha shape algorithm [(Edelsbrunner et al., 1983), (Akkiraju et al., 1995)], based on the extraction of polygons from a cloud of points. The criterion used to obtain the smallest value with which the algorithm is capable of detecting both parts has been to start from the mean distance between the different points forming the collision zone and reduce the value iteratively by a percentage established by default at 1. The problem with this approach is that it greatly decreases the precision of the areas delimiting the cortical part of the bone and is not valid for obtaining limits in areas where the bone is fractured (Fig. 5c). Therefore, the criterion that we have followed has been the union of the adjacent points by distances. In some cases it may be necessary to manually clean some points, which would cause a certain loss of precision, but the morphology of a natural bone and the process to virtualize it followed throughout this article make this type of cases very isolated. To determine the points that form part of the different limits that can form part of the virtual bone tissue, we have used the smallest value that the alpha shape algorithm needs to generate two polygons. From the outer limit of the bone structure calculated with the alpha shape algorithm and this value, we can delimit which points are within and out of range, thus generating the inner and outer limits. As can be seen in (Fig. 5), the algorithm used improves precision and has no problems when it comes to delimiting the limits for generating bone tissue in fractured areas. This will allow us to obtain measurements of greater weight compared to other studies based on approximate representations.

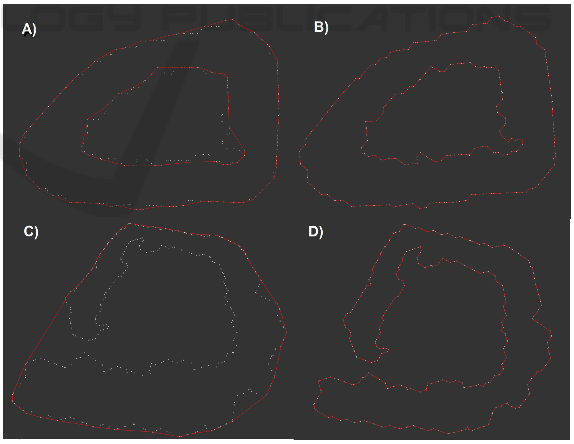

Figure 5: Comparison between the results obtained with the alpha shape algorithm(A,C) and with our method(B,d). Images A and B correspond to a healthy bone while images C and D correspond to a fractured area. The white dots are obtained by projecting the areas of contact between the bone and the plane while the red lines delimit the contour of the area where the bone tissue will be generated.

Once the limits have been established, we can take the next step in our research and focus on the creation of the different microstructures that make up the

Figure 6: CT image used to obtain the model with which tests have been carried out.

bones, taking into account all their characteristic features, without using perfect or accepted forms that may cause changes in the morphology of the bone structure, and thus achieve the creation of a quality virtual bone tissue that facilitates future research. Our study could be validated since we limit ourselves to the use of real medical images of human bones, so the geometric models we use are replicas as similar as possible to the real ones. Figure 7 (Fig. 6) corresponds to an image of the computed axial tomography scan (CAT) used to recreate one of the models used throughout this study. As can be seen, the limits of the bone are almost identical those obtained by the study in figure (Fig. 5d).

3.3 Microstructure Modelling

Most studies study the modelling of microstructures at sub-microscale and smaller scales which collagen fibers are assembled into sheet-like structures. In this section we will focus on the different characteristics and inputs that must be taken into account for the representation of the cortical bone tissue at microscopic levels. Osteons are the most important structure of the compact bone. The shape of the osteons is a key point in studies of the spread of fractures through the cortical bone (Najafi et al., 2007). They consist of a series of concentric layers called lamellae, which surrounding a central canal, which is a cavity through which blood vessels and nerves pass, known as the Havers canal. Osteons are limited by a line known as the cement line that separates them from the rest of the bone tissue. The part of the osseous tissue between two osteons is formed by some layers known as interstitial laminae. These parameters can be studied through image analysis such as the study about bone porosity by Cardoso (Cardoso et al., 2013) or the study conducted by Lin (Lin and Xu, 2010) that focused on the analysis of the lacunar-canalicular network (Fig. 7). Although they do not focus on the microstructures that make up the bone tissue directly, their different characteristics are studied due to their importance and involvement in them.

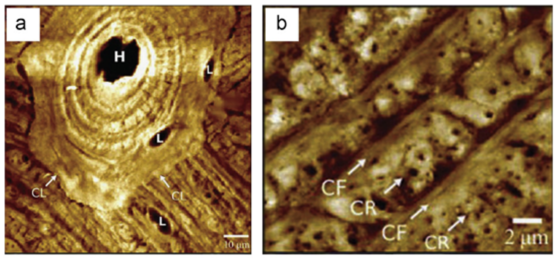

Figure 7: Microscopic images of the osseous structures obtained from Cardoso's study (Cardoso et al., 2013) Labels in panel a indicate the Haversian canal (H), lacuna (L), and cement line (CL). In panel b, canaliculi rich (CR) and canaliculi free (CF) areas are distinguished.

For the representation of the virtual osseous tissue it is necessary to know the characteristics of different elements that compose the tissue. In addition to geometrical parameters such as dimensions, shape or distribution of them, it is necessary to know other parameters such as porosity (Po), osteons density(On.Dn), osteonal area (On.Ar), tissue volume (TV), canal volume (Ca.V) or bone volume(BV) as demonstrated in the studies of Demirtas or Tong (Demirtas et al., 2016; Tong et al., 2015) . These parameters are key to obtaining a realistic tissue as well as for its study in fields such as fracturing. So, to represent the virtual osseous tissue realistically, it is necessary to go beyond the geometric representation of the structures allowing it to be useful and to replace the basis for future research.

4 CONCLUSIONS

The generation of virtual bone tissue is an unexplored field. There are many studies that focus on microscopic analysis of bones. In these studies, manual analysis of CT images is performed. The development of a virtual bone generation tool can help significantly reduce the time spent analyzing microscopic images of bones and provide more information for further analysis. In addition, most of the geometric representations that exist on the bone tissue, use approximations and do not follow the standards that are used within traumatology, so their validity when representing these microstructures remain in no man's land and can not be exploited by specialists. This study aims to lay the foundations for the virtual generation of bone tissue not only from a geometric point of view, but also from a medical point of view. The study of the segmentation of the bone model, how it should be generated in order to evaluate and compare it later, and the establishment of a series of limits serve as a starting point for achieving this ambitious objective. For the future it would be interesting to generate the different microstructures that make up the bone tissue taking into account all those elements that are scientifically relevant such as the different measures used. What other types of structural parameters could be included to make the tissue generated more useful within the different fields of study?

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REFERENCES

Akkiraju, N., Edelsbrunner, H., Facello, M., Fu, P., Mucke, E., and Varela, C. (1995). Alpha shapes: definition and software. *IEEE Transactions on Information Theory*, 63(1):66–70.

Boykov, Y. and Funka-Lea, G. (2006). Graph cuts and efficient n-d image segmentation.

Britz, H. M., Thomas, C. D. L., Clement, J. G., and Cooper, D. M. (2009). The relation of femoral osteon geometry to age, sex, height and weight. *Bone*, 45(1):77–83.

Cardoso, L., Fritton, S. P., Gailani, G., Benalla, M., and Cowin, S. C. (2013). Advances in assessment of bone porosity, permeability and interstitial fluid flow. *Journal of Biomechanics*, 46(2):253–265.

Demirtas, A., Curran, E., and Ural, A. (2016). Assessment of the effect of reduced compositional heterogeneity on fracture resistance of human cortical bone using finite element modeling. *Bone*, 91:92–101.

Descoteaux, M., Audette, M., Chinzei, K., and Siddiqi, K. (2006). Bone enhancement filtering: Application to sinus bone segmentation and simulation of pituitary surgery. *Computer Aided Surgery*, 11(5):247–255.

Doblaré, M., García, J., and Gómez, M. (2004). Modelling bone tissue fracture and healing: a review. *Engineering Fracture Mechanics*, 71(13-14):1809–1840.

Edelsbrunner, H., Kirkpatrick, D., and Seidel, R. (1983). On the shape of a set of points in the plane. *IEEE Transactions on Information Theory*, 29(4):551–559.

Fan, J., Zeng, G., Body, M., and Hacid, M.-S. (2005). Seeded region growing: an extensive and comparative study. *Pattern Recognition Letters*, 26(8):1139–1156.

Gao, X., Li, S., Adel-Wahab, A., and Silberschmidt, V. (2013). Effect of random microstructure on crack propagation in cortical bone tissue under dynamic loading. *Journal of Physics: Conference Series*, 451:012033.

Hennig, C., Thomas, C. D. L., Clement, J. G., and Cooper, D. M. L. (2015). Does 3d orientation account for variation in osteon morphology assessed by 2d histology? *Journal of Anatomy*, 227(4):497–505.

Justice, R., Stokely, E., Strobel, J., Ideker, R., and Smith, W. (1997). Medical image segmentation using 3d seeded region grow-ing. *Medical Imaging 1997: Image Processing*, 3034:900–910.

Lin, Y. and Xu, S. (2010). AFM analysis of the lacunar-canalicular network in demineralized compact bone. *Journal of Microscopy*, 241(3):291–302.

Najafi, A. R., Arshi, A., Eslami, M., Fariborz, S., and Moeinzadeh, M. (2007). Micromechanics fracture in osteonal cortical bone: A study of the interactions between microcrack propagation, microstructure and the material properties. *Journal of Biomechanics*, 40(12):2788–2795.

Nobakhti, S., Limbert, G., and Thurner, P. J. (2014). Cement lines and interlamellar areas in compact bone as strain amplifiers – contributors to elasticity, fracture toughness and mechanotransduction. *Journal of the Mechanical Behavior of Biomedical Materials*, 29:235–251.

Paulano, F., Jiménez, J. J., and Pulido, R. (2014). 3d segmentation and labeling of fractured bone from CT images. *The Visual Computer*, 30(6-8):939–948.

Paulano-Godino, F., Jiménez-Pérez, J. R., and Jiménez-Delgado, J. J. (2017). Issues on the simulation of geometric fractures of bone models. In *VipIMAGE 2017*, pages 467–475. Springer International Publishing.

Pérez, F. D., Jiménez, J. J., and Jiménez, J. R. (2018). Blast Features and Requirements for Fracturing Osseous Models. In García-Fernández, I. and Ureña, C., editors, *Spanish Computer Graphics Conference (CEIG)*. The Eurographics Association.

Sabet, F. A., Najafi, A. R., Hamed, E., and Jasiuk, I. (2015). Modelling of bone fracture and strength at different length scales: a review. *Interface Focus*, 6(1):20150055.

Tong, X., Burton, I. S., Isaksson, H., Jurvelin, J. S., and Kröger, H. (2015). Cortical bone histomorphometry in male femoral neck: The investigation of age-association and regional differences. *Calcified Tissue International*, 96(4):295–306.

Törnquist, E. (2017). Segmentation, analysis, and modelling of microstructure in cortical bone, based on x-ray microtomography. Student Paper.

Ural, A. (2011). Cohesive modeling of bone fracture at multiple scales. *Procedia Engineering*, 10:2827–2832.