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Escuela de Doctorado

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Advances in bone modelling and multilevel fracture simulation

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Publications

A large part of the work presented in this thesis has already been published or is being peer-reviewed to be published in scientific conferences and journals.

■ JCR-indexed journals

- Pérez Cano F.D., Luque Luque A. and Jiménez Delgado J.J. Towards a 2D cortical osseous tissue representation and generation at micro scale. A computational model for bone simulations. *Computer Methods and Programs in Biomedicine* 2020;197:105774.
Journal impact factor: 5,428. Q1 (13/110) in Computer Science, Theory & Methods Category
- Jiménez Delgado J.J., Parra Cabrera G., Pérez Cano F.D. and Luque-Luque A., "Generation and Validation of Osseous Fracture Patterns by Forensic Analysis," in *IEEE Access*, vol. 8, pp. 211506-211525, 2020.
Journal impact factor: 3,367. Q2 (65/161) in Computer Science, Information Systems Category
- Luque Luque A., Pérez Cano F.D. and Jiménez Delgado J.J. Complex fracture reduction by exact identification of the fracture zone. *Medical Image Analysis* 2021;72:102120.
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- Parra Cabrera G., Pérez Cano F.D. and Jiménez Delgado J.J. Fracture pattern projection on 3D bone models as support for bone fracture simulations. *Computer Methods and Programs in Biomedicine* 2022 ;224:106980.
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- Luque Luque A., Jiménez Pérez J.R., Pérez Cano F.D. and Jiménez Delgado J.J. A compact representation of the bone fracture area. Application to fractured bones of clinical cases. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization* 2021:1–8.

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- Pérez Cano F.D. and Jiménez J.J. Towards the Modelling of Osseous Tissue. *Proceedings of the 14th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications* 2019.
- Pérez Cano F.D. and Jiménez Delgado J.J. Macroscale Fracturation of Osseous Models. *VipIMAGE* 2019 pages:492–500.
- Jiménez-Delgado, J.J., Calzado-Martínez, A., Pérez-Cano, F.D. and Luque-Luque, A. Virtual Reality Environment for the Validation of Bone Fracture Reduction Processes. In *Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - GRAPP 2020*, ISBN 978-989-758-402-2; ISSN 2184-4321, pages 399-405.
- Parra Cabrera G., Pérez Cano F.D., Luque Luque A. and Jiménez Delgado J.J. Assisted Generation of Bone Fracture Patterns. *Bioinformatics and Biomedical Engineering* 2020 pages:825–34.
- Jiménez Delgado J.J., Parra Cabrera G., Pérez Cano F.D. and Silva A. Virtual reality for validation of automatic bone frac-

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Abstract

The aim of this dissertation is to obtain advances in the representation and fracture of bone models from a macroscopic and microscopic perspective. Most of the literature is based on the study from a macroscopic point of view, ignoring the influence of bone structures which are part of the bone at the smallest scales and are fundamental in all the phenomena that occur regarding bones. The thesis presents an exhaustive analysis of the literature in order to identify the best techniques to represent bone at macroscale, and proposes new techniques for the representation of bone at microscale as well as new techniques for bone fracturing at different scales.

The results obtained will enable us to progress in the studies on macroscopic bone fracturing, by a combination of the most important approaches for bone fracturing, as well as in the simulations at the microscopic level through the proposed representation model.

Resumen

Esta tesis doctoral pretende obtener avances en la representación y fracturación de modelos óseos desde una perspectiva macroscópica y microscópica. La mayor parte de los trabajos se basan en el estudio desde un punto de vista macroscópico obviando la influencia de las estructuras óseas que forman parte de las escalas de menor tamaño y son fundamentales en todos los fenómenos que ocurren sobre los huesos. La tesis presenta un análisis en profundidad de la literatura que existe en este ámbito, identificando las mejores técnicas para representar el hueso a nivel de macroescala, y propone nuevas técnicas para la representación del hueso a nivel de microescala, así como nuevas técnicas para la fracturación ósea a diferentes escalas.

Los resultados obtenidos permiten avanzar en los estudios sobre la fracturación ósea macroscópica, mediante la combinación de los enfoques más importantes en el área de estudio, así como en las simulaciones a nivel microscópico a través del modelo de representación que se propone.

List of acronyms

AO/OTA - AO Trauma International and Orthopaedic Trauma Association Representatives
ASBMR - American Society for Bone and Mineral Research
BEM - Boundary Element Method
BMD - Bone Mineral Density
BV - Bone Volume
CCD - Charge Coupled Device
CNN - Convolutional Neural Networks
CT - Computed Tomography
DAQ - Data Acquisition System
DICOM - Digital Imaging and Communication in Medicine
FEM - Finite Element Method
GANs - Generative Adversarial Networks
LEFM - Linear Elastic Fracture Mechanics
Max.On.Dm - Maximum Diameter of an Osteon
MC - Marching Cubes
Min.On.Dm - Minimum Diameter of an Osteon
N.On - Number of Osteons
N.Po - Number of Pores
OBB - Oriented bounding box
On.Ar - Osteonal area
On.Dn - Osteonal density
On.Dm - Diameter of an Osteon
PCA - Principal component analysis
Po - Porosity
s.H.Ar - Single Haversian Canal Area
s.Lc.Ar - Single Lacunae Area
s.On.Ar - Single Osteon Area
TV - Tissue Volume
UE - Unreal Engine

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Chapter 1

INTRODUCTION

The increase in life expectancy in recent years is causing an increase in cases of hip fractures in older people, since as the years go by bones wear out and become weaker. There are recent studies documenting that the number of fractures has been multiplying considerably over the years, rising from 1.26 million cases in 1990 to 4.5 million in 2050 [15]. The impact on patients goes beyond the physical and mental impact, and the mortality rate after hip surgery has been reported to be between 5% and 10% during the first month and to increase significantly over time during the first year [16].

In this situation, computer graphics applied to medicine has come to play a major role. This is a field of research that has many open lines of research and continues to grow due to the progress of new technologies. This evolution has allowed the creation of computer-assisted techniques in the field of traumatology and bone fractures which on the one hand help medical specialists to reduce intervention time and on the other, minimize the risk of error thanks to the previous study of the fractures.

One of the first obstacles in carrying out work in this field is the dif-

difficulty in obtaining human bones to carry out studies, so it is common to find studies based on the use of animal bones. This is precisely the great inconvenience, since animal bone models have properties, shapes and dimensions that vary from those of humans [17].

Previous literature has shown a clear tendency to perform studies on bone at the macroscopic level without considering the hierarchical structure of the bone. However, the direct influence that the osseous structures that compose the bone have at the microscopic level on the different phenomena that affect the bones has been demonstrated [18].

This dissertation aims to study the hierarchical structure of bones in order to carry out simulations from a macroscopic and microscopic point of view. For this purpose, bone properties are analysed and multilevel representations of cortical bone are performed. Finally, fracture features are identified in order to carry out fracture simulations on the multilevel representations of the bone obtained throughout the study.

1.1 Aims and objectives

Considering the problems identified above, the main purpose of this thesis is to investigate and develop methods that allow the virtual representation of bones at different scales in order to carry out fracturing simulations. Since there are several techniques for the reconstruction of complete bone models, the main effort will be concentrated on the representation of the cortical tissue of human bone at the microscopic level. In addition, new methods for fracturing the models generated previously are investigated and developed. The objectives pursued are:

- To identify and apply the main methodologies for bone reconstruction from a macroscopic point of view.
- To research and develop new algorithms for the representation of cortical bone at a microscopic level.
- To research and develop techniques that allow the identification and representation of the fractured zone of a bone.

- To research and develop new methods for bone fracturing at the macroscopic level.
- To research and develop new methods that allow the fracturing of cortical bone from a microscopic point of view.
- To analyse and evaluate the results obtained with the proposed methods.

1.2 Organization of this document

This dissertation is organized around the aims and objectives described in the previous section. Two large blocks can be distinguished: the first deals with the studies carried out on the whole bone (chapters 3-5) and the second studies bone tissue at the microscopic level (chapters 6-7).

In Chapter 2, a review is carried out of the work currently available in the literature related to bone representation and fracturing techniques. This review is performed from a macroscopic and microscopic point of view. In addition, the hierarchical structure of bones and the most characteristic parts are defined. Throughout this thesis special emphasis is given to the femur, since it is one of the most fractured bones and the main bone involved in hip fracture cases.

Chapter 3 analyses the different methods for the virtual representation of a bone and the different techniques for the representation of a fractured zone. Each representation of the fracture zone is associated with a methodology for obtaining the representation, as well as the validation process followed to evaluate the results obtained.

Chapter 4 focuses on fracture simulation at the macroscale level. This level of the hierarchical structure of the bone is the one that represents the bone in a complete way. In this chapter, the characteristics of Blast, the tool used to carry out the simulation, are analysed. The algorithm proposed mixes an approach based on the patterns obtained in the previous chapter with a physics-based approach. For this purpose, a prefactured model is obtained using the fracture patterns and only those fragments

that are damaged by some physical component during a simulation are separated. To determine the elements of the prefractured model to be separated, a number of preset mechanical and physical properties are used. Finally, the results are displayed and evaluated.

Chapter 5, which closes the first section, presents a study involving different areas of knowledge. In this case, the study focuses on bone fracturing through mechanical experimentation. All the bones fractured during the experimentation, as well as the results obtained, have been evaluated from a computational point of view by taking precise measurements of all the features of the bone, from a mechanical point of view by analysing the behaviour of the bone at the moment of fracture, and from a clinical point of view through analysis by experts.

As already mentioned, in the second block there is a change in the expository line by focusing on the microscope level. This block focuses on the view of the bones at the microscope level. Thus in chapter 6, as opposed to traditional methods in which manual segmentations are performed on microscope images, a procedural algorithm is proposed. This algorithm is responsible for generating a representation of the bone structures in a given area of the bone which are only visible from a microscope. The validation of the models generated is carried out from a statistical point of view and by means of an analysis performed by experts in the field of study.

Chapter 7 shows an original study in which an algorithm for fracture simulation is developed on the model generated in the previous chapter. The algorithm fractures the entire cortical tissue and not just a single part of it as in the previous cases studied. The features of the bone tissue determine the growth of the fracture until a stop condition is reached. In addition, it also includes the expert evaluation process.

Finally, the last chapters show the general conclusions obtained after the work carried out, as well as new lines of work that have been opened after the advances obtained through this doctoral thesis.



Chapter 2

RECENT ADVANCES IN BONE MODELLING, SIMULATIONS AND FRACTURING

This chapter presents a review of the available techniques for bone modelling and fracturing at multiple levels. The chapter is structured to begin with the definition of the hierarchical structure of the bones in order to identify the different levels of scale on which all the research has been carried out. Then the different techniques to represent the bone models and how to fracture them at different scales are presented.

2.1 Bone structure

The structure of bones is a very complex area of study. This hierarchy provides mechanical support and serves as a reserve of minerals. The levels of the hierarchical structure of bones ranges from the macroscale to the nanoscale (Fig. 2.1). The most important levels of bone structures are described as follows:

- Macroscale: the entire bone is represented at this level.
- Mesoscale: this level represents the two bone tissues: cortical and trabecular. The cortical bone is hard and compact that makes up the external part of the bones and surrounds the trabecular part. The trabecular part is spongy and it is found in the interior of the bones, which provides more strength and structural stability due to its low rigidity and shock absorption capacity. At this level of representation, small structures that are part of both tissues can be identified.
- Microscale: in microscale, the lamellae are assembled to form the structures that compose the two types of bone tissue. In the case of cortical bone, osteons stand out, which are embedded in the interseptal matrix of the bone, while in the trabecular bone a porous network of irregularly shaped trabeculae can be found [1].
- Sub-microscale: the collagen fibers are assembled in lamellar structures at this level. Each lamella is composed of fibers arranged into geometrical patterns similar to composite lamellae [19].
- Nanoscale: this level allows to identify the collagen fibers. Each collagen fibers consists of a bundle of mineralized collagen fibrils.

Some authors use a minor number of levels as a reference because they group some of the previously defined. In this dissertation the focus is on the first three levels since both the sub-microscale and nanoscale levels are representations that are very small to be taken into consideration to advance in the field of bone fracture. Macroscale studies usually

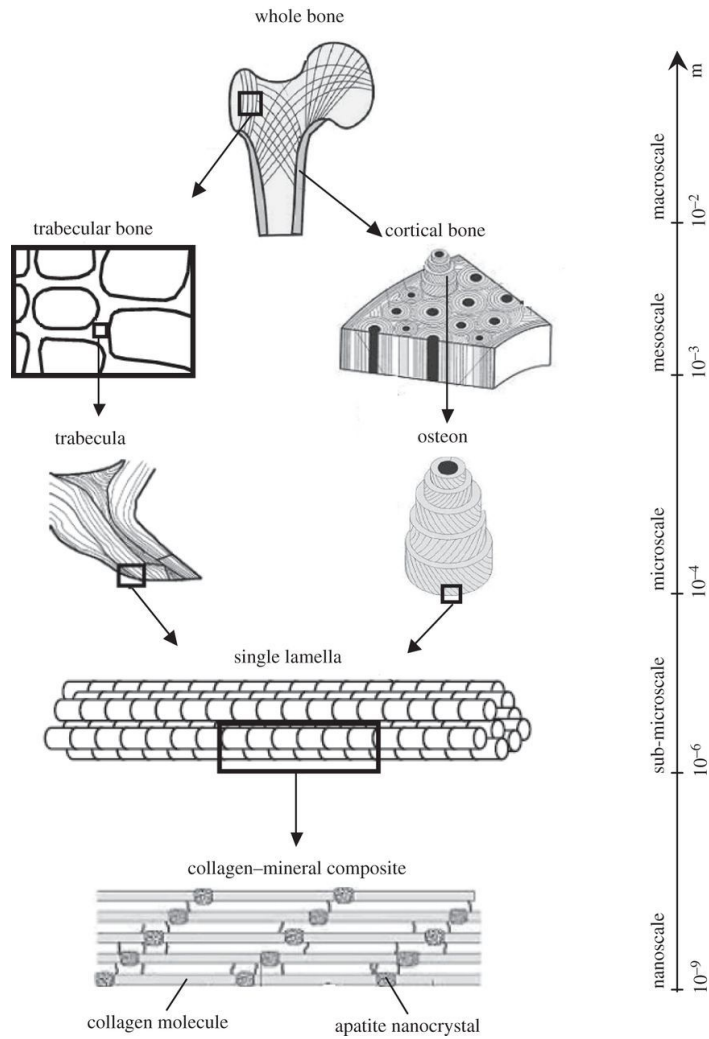


Figure 2.1: Hierarchical structure of bone from macroscale to nanoscale performed by Sabet et al. [1].

focus on predicting fracture risk and fracture reduction, while mesoscale and microscale levels are usually combined on the studies and focus on assessing the influence of microstructural features on the behaviour of

crack propagation on bone tissue [18]. As mentioned above, two types of bone can be distinguished: cortical and trabecular. This thesis focuses on the cortical bone as it is the main tissue involved in fracturing as well as in the fracture reduction process.

Each bone has its own characteristic areas that allow to distinguish them from each other, although they can be classified into long and short bones. Figure 2.2 represents the three main segments of the long bones formed by the diaphysis and the two ends. In addition, the main regions of the femur are also shown. In this dissertation, I focus on long bones, with special emphasis on the femur, since it is the most frequently fractured bone. With the increase in life expectancy, it has become more common to find cases of hip fracture, since the slightest trauma can cause a fracture in fragile bones [20]. Over the years, bone wear and tear increases and a fracture of this type is an injury with serious consequences for the population. Recent studies show how the data varies by country but estimates that 18% of women and 6% of men will be affected by a fracture and that fractures are expected to increase from 1.26 million in 1990 to 4.5 million in 2050 despite the halt in world population growth but an aging population is also occurring [15]. Smith et al. [16] analysed the factors which increase mortality after hip fracture surgery. The estimated mortality rate is between 5% and 10% in the first month and increases over the recovery period.

The microscopic levels, the mesoscale and microscale level, can be analysed through a special optical device. The optical devices allow to identify the structures that make up the cortical tissue. Figure 2.3 shows the two different tissues and highlights the main details of the cortical tissue. Osteons and Haversian systems, which are embedded in the interstitial matrix of bone [21], are the primary microstructures of cortical bone. Osteocytes reside in the osteons, which contain a mineral matrix. Osteons are made up of a series of concentric layers called lamellae, which surround a central cavity through which blood vessels and nerves pass referred as Haversian canals. Thus, the shapes of the osteons vary from circular to elliptical in radial transverse cross-section of cortical bones [22]. There are small open spaces between the lamellae created by the

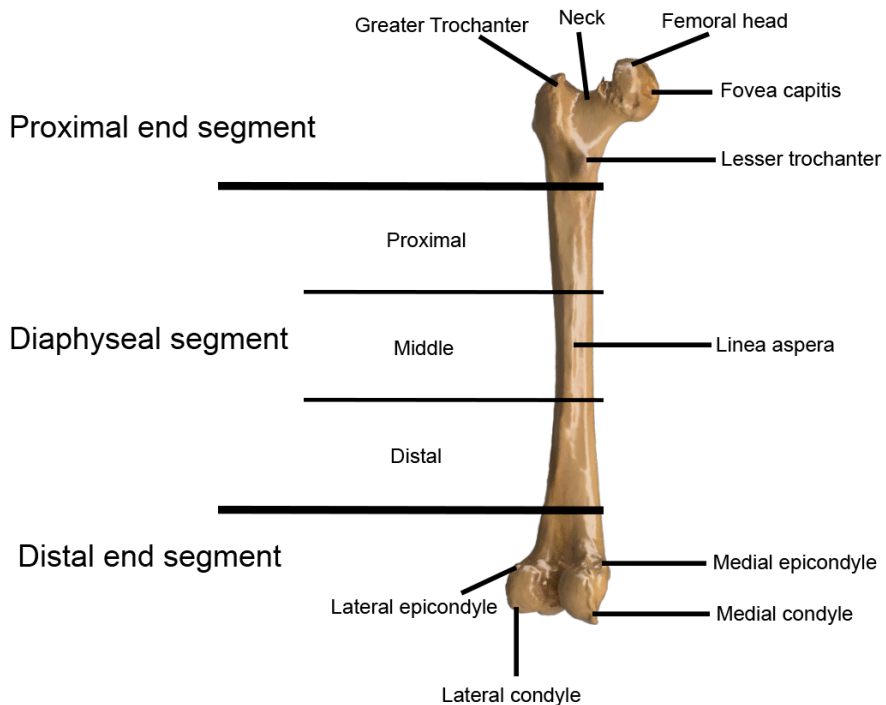


Figure 2.2: Femur with all characteristic areas highlighted.

osteocytes called lacunae. The Haversian canals allow blood vessels and nerve cells to travel through them so that they communicate with the bone cells located in the lacunae. There are numerous articles about these cavities that study their main features [23, 24]. Furthermore, a border identified as the cement line divides osteons from the remaining osseous tissue [25, 26]. In addition, there are other microstructures such as pores and microfractures which are also part of the cortical tissue. These structures are essential to study and understand the process of bone fracturing as they interfere in the growth of a bone fracture. The impossibility of analysing fracture growth at the microscopic level in real time causes that most studies focus on analysing the characteristics of each bone structures

rather than on analysing the fracture itself.

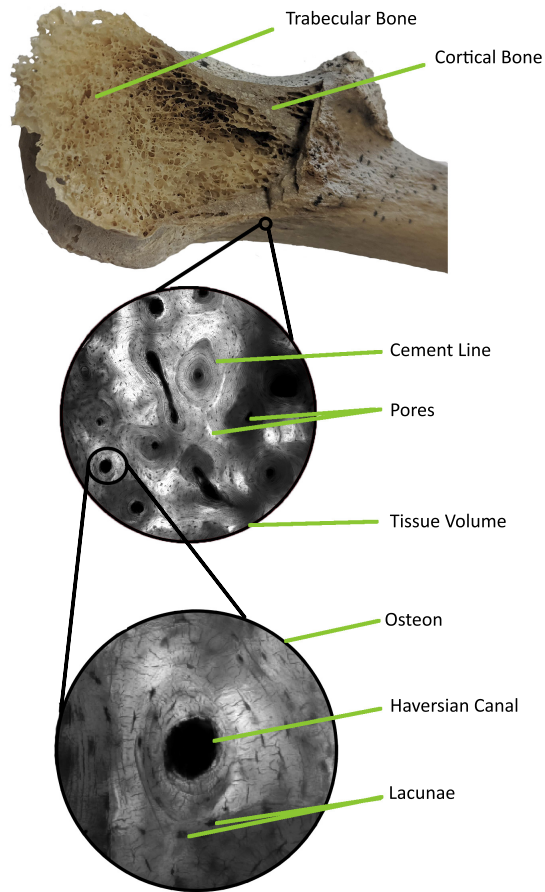


Figure 2.3: Highlights of the cortical bone tissue.

2.2 Bone modelling at macroscopic level

The generation of a virtual representation of the bones and fragments is an artificial step required in order to obtain helpful models to work with

in a simulation. Depending on the purpose, these models can be points clouds, volumes or triangle meshes. Figure 2.4 represents the different methods to represent a bone model.

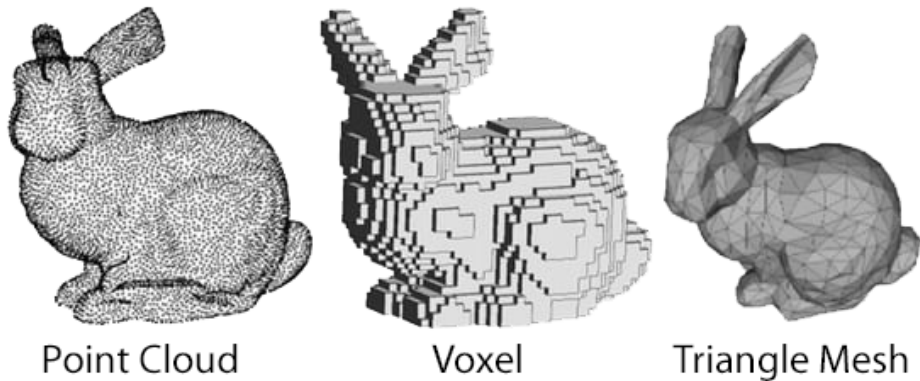


Figure 2.4: Various 3D representations of the Stanford bunny [2].

The representation of geometric models with point clouds is very common. 3D scanners are usually used to obtain the point cloud that represents a geometrical model. The main problem to use this representation for bone models is the difficulty to represent a model in a realistic way with respect to the remaining options, since the model does not look compact and the spaces between the points are visible. In addition, the capacity to carry out realistic simulations are limited.

Volumetric representations are very common in the medical field to display the image in 3D. This representation is based on the use of voxels. A voxel is the smallest cubic unit representing a three-dimensional object. To determine each voxel, the matrix of pixels that make up a 2D image is used as a reference. Pixel colors are used to delimit the borders of the model. In the case of 3D models, a stack of images of the model is used and the space it occupies is subdivided into a three-dimensional grid with the smallest size of the elements that compose it (voxel) so that the pixel values of each of the images are used to determine the voxels that compose the model. This representation is common in the medical field

as it is often used to work with images and stacks of medical images. The main disadvantage is the high memory requirement which is compounded by the need to use high voxel resolution to accurately represent a bone (Fig. 2.5) as well as the limited amount of algorithms to work with this representation because it is mainly used for visualization. Bones are full of irregularities so the computational cost for rendering and performing simulations is considerably higher than other options.

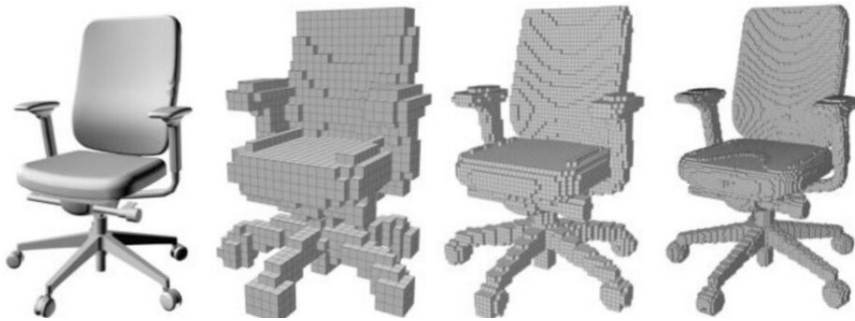


Figure 2.5: Voxel grid representation of the chair shown on the left with an increasing voxel resolution [3].

Triangle meshes are sets of vertices connected to each other to form triangles. Triangles are used to form faces that allow to represent the model in a 3D space. It is a very common data structure employed to render 3D models. This representation solves the visualization, memory and computational problems of the representations discussed previously, so it is the representation chosen to represent the bones in this dissertation.

There are many approaches to obtaining the digitally representation of a bone at macroscale level through triangle meshes. These methodologies differ according to whether bones are available or whether images of clinical cases, which are usually easier to obtain, are available. All techniques of representation are based on 3D scanning or 2D image analysis. If bones are available, 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. An important point to take into consideration in the case of bones involves the use of one type of scanner or other according to the type of study to be carried out. The dimension or geometry of the bone cortex are crucial in some studies since they allow to establish landmarks on the bones and analyse factors such as the risk of fracture [27, 28, 29]. The main problems with this approach are the difficulty in obtaining human bones, the time to perform the scan and process the mesh to close it, and that only the external side of the bone is represented. Therefore, important aspects such as the thickness of the cortical bone are not known and the studies that can be performed on these models are limited. The solution is to perform Computed Tomography (CT) scans to reconstruct the bone models in three dimensions using image analysis techniques. CT is the most appropriate and accessible tool for distinguishing bone from other tissues and thus, for performing the segmentation of bone fragments [30]. CT images are usually stored in Digital Imaging and Communication in Medicine (DICOM) format. A DICOM image stores the radio-density in each pixel obtained during the CT scan. The identification of bone fragments from medical images requires segmenting and labelling the bone regions. There are different methods based on the sheetness measure [31], region growing [32, 33] or graph cuts [34] that allow us to segment the images to obtain bone models. Lee et al. [35] propose a multi-region segmentation approach in which the seeds are automatically placed by looking for pixels that have an intensity value higher than a threshold and then propagate based on the region growing algorithm. 3D Slicer [36] is an image computing platform for the analysis and visualization of medical images with several algorithms for bone image segmentation. Paulano et al. [4] described a method in which it is necessary to establish some seeds 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 al-

gorithm also resolves certain special cases where overgrowth occurs in the regions. In this study they also compared their algorithm with other approaches to segmentation discussed above and showed how their method identified the cortical zone of the bone more accurately (Fig. 2.6). Classical algorithms such as Marching Cubes (MC) generate a large amount of geometry and do not take into consideration the topology of the bones, so they are not usually taken into consideration. However, some methods use MC or derivatives once they have generated and applied the segmentation mask to obtain the 3D model.

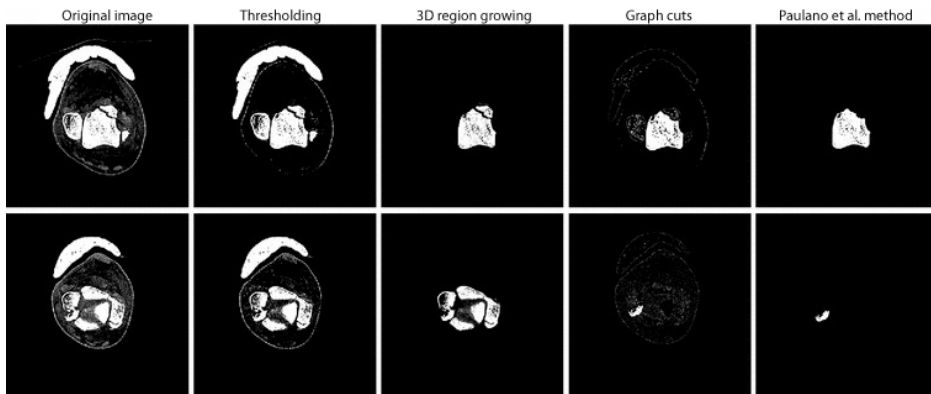


Figure 2.6: Comparison performed by Paulano et al. [4] to identify the cortical zone on fractured bones in which it is necessary to identify the fragments individually.

The result is a hollow model with a thick layer of cortical tissue. Inclusion of the inner cortical region would lead to overgrowth of the model to the trabecular tissue areas. Consequently, the inner region has to be cleaned up to remove all excess geometry. Algorithms for the detection of disconnected regions and their elimination can be used for this purpose.

The generated models can be post-processed in order to obtain desirable properties. Smoothing, simplification or re-meshing are the optimization techniques that are most commonly applied to improve the features of the models. The application of smoothing techniques to bone models aims at denoising the area surrounding the bone and to extrap-

olating missing information. This step is especially necessary when the image resolution is not good enough since the reconstructed model can present ripples. This technique should be used with caution as excessive smoothing may result in the removal of useful information from the model and not just the noise. There is a wide literature on smoothing in which new methods are proposed and existing methods are reviewed [37, 38, 39].

The goal of simplification algorithms is reduce the size of the models and minimize the impact on their morphology and properties. Nonetheless, it is crucial to avoid oversimplification of the bone models in order to preserve their original features. Simplification facilitates simulations, visualization and interaction with the models. Several studies have been published in order to compare strategies to simplify 3D meshes [40, 37, 41].

Re-meshing procedure intended to improve the quality of a geometric model. It is very useful for visualization. A common issue with medical images is the noticeable distance between two adjacent pixels with respect to the gap between consecutive slices. A complete review of re-meshing techniques is presented in [42].

2.3 Bone model simulations and fracturing at macroscopic level

Most of the literature has focused on the study of bone features. Simulations using bone models usually aim at bone fracture healing by reducing the fracture [43, 44, 45] and the analysis of bone health problems such as biodegradation or the corrosion rate [46]. Hambli et al. [47] designed a system to study the process of bone remodeling and the behavior of a fracture through the use of continuum damage mechanics to predict the fracture pattern using the whole bone.

The fracturing of geometric models has been a challenge due to the high computational cost involved. Classical techniques used for fracturing conventional geometric models can be used for fracturing bones at the

macroscale level. A large catalogue of techniques for fracturing geometric models can be found in the scientific literature. Among some recent contributions, potential approaches to be used on bone models can be identified [48, 49, 50]. These approaches may be highlighted as follows:

- **Geometry-based approach:** focuses on the use of pattern to simulate geometric fractures in order to obtain a high degree of control over the fracture in aspects such as the size or shape of the fragments generated. These patterns allow to determine the zone in which the fracture propagates as well as the size and the number of fragments that are generated after the fracture. This strategy does not focus on the physical description of the fracture phenomenon [48]. This approach is usually faster to simulate over other approaches although its main weakness is the difficulty to simulate the fracture in real time. Recent works focuses on the use of pre-fractured models for the purpose of real-time simulation [51, 52, 53, 54]. The main drawback encountered using this approach is that there is not enough information about the fracture area and it is essential for bone models.
- **Physics-based approach:** this approach aims to obtain more realistic fractures through the simulation of the mechanical properties of the material. It is a very complex approach because the mechanical properties of the materials need to be identified. In addition, it must be taken into consideration that there are many materials that are not homogeneous so that the properties of the models may be different from one area to another, the environment and, in some cases, there is also a factor of randomness that makes unique each model. In order to avoid this problem, authors such as Gobron and Chiba [55] propose the use of semi-physical methods to facilitate the study of fracture propagation. Glondu et al. [56] present a technique for the fracturing of fragile bodies, taking into account the damping properties of the bodies on which the fracture occurs. The algorithm starts from an initial point and a direction in which the fracture propagates through a 2D mesh, that represents the geomet-

rical model, through the visit of the neighbour positions and a series of criteria that determine the end of the fracture. Hahn and Wojtan [57] have also presented a method to perform physical based fracture simulations following the assumptions of linear elastic fracture mechanics (LEFM) with a high degree of detail through the use of the boundary element method (BEM).

- **Example-based approach:** consists in the use of a set of methods in order to obtain fractures with real appearance by the copy of the behaviour of a natural fracture. Templates are used to extract various parameters to replicate the appearance of the fracture. Some authors look for landmarks in the models to copy the fracture guidelines of the example models in the model to be fractured [58]. Thus, the fracture is adapted to the points used as reference and it is not a complete copy of the reference fracture. Desbenoit et al. [59] also use images of real fractures that help to determine the parameters that guide the fracture propagation in order to produce a fracture with the same key points as the examples used.

The difficulty of realistically simulating biomechanical forces is a major challenge given the lack of prior information and the impossibility to study a real time bone fracture. Paulano et al. [49] analysed the drawbacks to simulate fractures in bone models and concluded that there is no clear alternative. Recently, Ural [60] has discussed the benefits of studying the fracturing of bone models at different scale levels as well as some of the most important results obtained for each of them. Furthermore, it is necessary to take into consideration the added difficulty when evaluating a fracture on a bone model, that is also highlighted by other works, such as those conducted by Sabet et al. [1] and Muguercia et al. [48], in which it is suggested that it should be done from both a geometric and clinical point of view. To our knowledge, there are no studies on this major challenge. Hambli et al. [61] performed an analysis of bone fractures using a continuous damage in a bone model through force displacement curves. The fracture begins in the femoral neck area and as the load increases, the damage grows rapidly following an oblique path to the top surface. The

fracture pattern was calculated through the different levels of propagation of the cracks in relation to the force displacement curve. The problem with this approach is that the results obtained can differ considerably with the real shape of a fracture.

Other authors focus on the study of the fracture area of bone models. Some studies [62, 63] select points that expand to select the fracture area. Curvature analysis has also been used to identify fractured surfaces. Winkelbach et al. [64] proposed a method for identifying vertices of the fractured area by comparing its normal relation to the bone axis. Willis et al. [65] address the problem with a statistical algorithm that classifies the points as either belonging to the fracture region or not. Fürnstahl et al. [66] use a normal-based filter to identify the points that belong to the fracture surface in humerus, whereby a connected component analysis is applied in order to remove outliers. In [67] an algorithm is proposed based on the use of curvature scale-space for matching characteristic features between fragments that make up the fracture. Okada et al. [68] present a curvature-based procedure for obtaining fracture lines in a interactive process similar to carry out in [69, 70]. These fracture area identifications are often used to develop algorithms for bone fracture reduction. The main issue of these studies resides in obtaining sufficient quantities of clinical cases to be able to make accurate conclusions.

2.4 Bone modelling at microscopic level

The different levels that constitute the hierarchical structure of bones must be taken into consideration. The sub-microscale and nanoscale levels are too small to be useful for bone simulations, so in this section and in the following one the focus will be on the mesoscale and microscale level.

Concerning methods for the representation of bone tissue at mesoscale and microscale levels, there is not much literature focused on these aspects. Studies are mainly focused on the analysis of the structures that make up the bone tissue and their influence on physical phenomena as well as the effects of aspects such as age or sex on them [71, 72]. Most

of the studies do not use representations of the cortical bone, they use image analysis techniques on images obtained through optical microscopes [23, 24]. To obtain these images from the microscope, it is necessary to cut a fragment of the bone with a size of less than one millimeter to allow the light of the microscope to pass through the bone (Fig. 2.7).

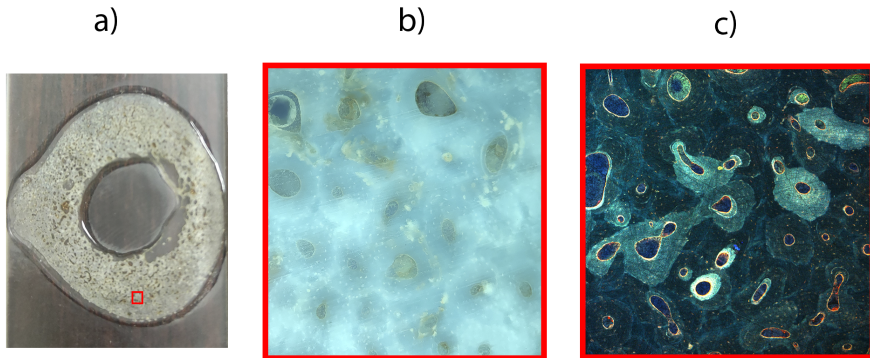


Figure 2.7: Representation of the cortical bone. Figure a represents a cut in the diaphysis area of a femur to be analysed using a microscope. Figure b shows the cortical bone tissue view from an optical microscope while c shows the representation of the cortical tissue obtained after launching a series with different laser intensities and colours of the microscope.

Gao et al. [7] concluded in their study that the osteons have a random distribution. Moreover, the length of the osteons is variable and they are inclined between 5 and 15 degrees with respect to the longitudinal axis of the bone [73]. However, in areas such as the proximal end segment of the femur, the femoral head extends at an angle varying between 109 and 136 degrees with respect to the longitudinal axis of the femur. Therefore, this approach is only valid for the diaphysis area of the bone since it is a part with only one direction of growth. In addition, longitudinal studies are quite rare because the width of the cortical bone is narrow enough to cut a millimetric section to be able to place it under the microscope. This

random distribution and inclination, combined with the lack of information about the structures, makes the representation of bone tissue in three dimensions a great challenge that has not yet been solved. Demirtas et al. [5] introduces a possible 3D representation of cortical tissue which consists of extruding the 2D model obtained through Finite Element Method (FEM) techniques. The remaining 3D microscopic level works focuses on the characterization of bone mineralization and bone porosity using three-dimensional techniques, but does not use any type of representation of the bone [74, 24, 75].

As for the 2D representations, most of the models are based on the use of the FEM method. This representations are achieved after a process of analysis of microscopic images which are converted to two dimensional sketches by identifying the microstructural characteristics of osseous tissue. Mischinski and Ural [76] identified the main structures of the cortical tissue, based on approximations of osteons, to generate numerical artefacts in order to make finite element simulations. The scientific community accepts that osteons have a circular shape despite their irregular shape. Therefore, it can be used as a criterion to identify and delimit them. There is also previous literature in which a similar approach is followed to represent the bone tissue using the ellipse shape as the most accurate microstructural feature for both osteons and Haversian canals [5, 6]. Tong et al. [77, 78] also worked on the recognition of the cortical and trabecular areas of the bone through microscope images using the shape of the bone microstructures as target. Although the accuracy of the representations is quite high when using microscope images as a reference, it is evident how the number of images used in the studies is very small and not very representative since each microscope image represents a single point of the cortical part in which only a few osteons appear. One of the main goals of this dissertation is to solve the previous problem using a procedural algorithm to fill with bone structures a bone area similar to the one used in microscopes (Fig. 2.7).

Most of the studies we have found in the literature use a 2 dimensional model representation of bone tissue due to the lack of information to obtain a three dimensional representation of bone tissue as well as a

method to validate them. Demirtas et al. [5, 6] have incorporated in their microscale studies some 3D versions of the bone models on which they have carried out different tests (Fig. 2.8). Ascenzi et al. [79] also used a 3D representation to perform stress tests on the tissue at the microscopic level. For this purpose, they based on a volumetric representation of the bone in which each voxel of the model was considered as a 3D region of bone cortical tissue. Each voxel contain a representation of the main bone microstructures. However, although the appearance was three-dimensional, the structures generated were only performed on one side of the voxel with 2D information and the stress simulations were performed using a 2D representation.

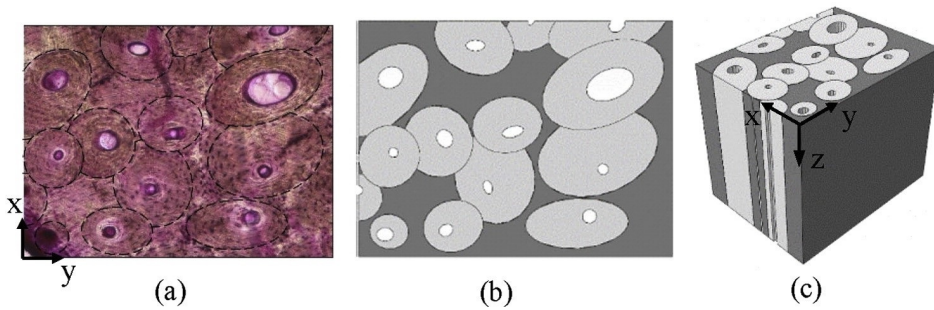


Figure 2.8: Scheme for obtaining the microscopic model carried out by Demirtas et al. [5, 6] through manual segmentation. Figure a represents a sample transverse microscopy image of cortical bone, figure b is a detailed 2D sketch based on image a and c represents the 3D finite element model obtained by extruding the 2D sketch of figure b.

2.5 Bone model simulations and fracturing at microscopic level

Most of the studies ignore the architecture of the bones at microscopic levels. Fracture reduction simulations analysed at the macroscale level do

not consist only of the joining of two separate pieces, it involves an internal process in which the microstructures that make up the bone and are visible in these lower hierarchical levels are regenerated through a process called remodelling [80, 81]. The lack of analysis at the microscopic level of the bone makes the studies somewhat incomplete and potential for improvement, for example, by studying how to accelerate the remodelling process to speed up recovery after a fracture reduction.

It is scientifically documented that bone microstructures are involved in phenomena such as mechanical loads and fracture propagation. The bone microstructural elements are responsible for determining the path that the fracture follows during its propagation [18, 1, 82, 83, 84]. The solutions presented in the literature for the fracturing of cortical bone tissue at microscopic levels are mostly based on FEM for the high reliability and accuracy approach in bio-mechanical applications [85]. These types of fractures can be classified as physical based fractures. Andreaus and Colloca [86] have studied the structural behavior under physiological loadings and boundary conditions in intact and implanted human femurs obtaining as result important information about the stress that the bones receive in the most common movements. Abdel-Wahab et al. [87, 83] has analysed the propagation of a fracture through bone tissue under the influence of tissue heterogeneity as well as the influence of osteons. Some studies have developed a FEM based approach which demonstrated the importance of osteons in determining fracture growth as well as the effect of microscale properties in assessing the risk of a whole bone fracture [88, 89, 90]. Other authors have studied the effect of features as the age or the gender on fracture propagation and bone modelling [91]. Gao et al. [7] focus in the behaviour of the cortical bone under dynamic loading (Fig. 2.9). Budyn et al. [92] tried to implement a multiscale approach in order to experiment with fracture forces, from the microscale level, and study their influence on fracture growth. Strength and elastic modulus were found to be altered due to orientation variation in lamellae and existence of osteocyte lacunae [93]. Tang et al. [12] analysed the shear deformation and fracture of human cortical bone using a fluorescence microscopy and a device to damage the cortical tissue sample until

it fractures. As result, they conclude how the Haversian lamellae play an important role in the fracture growth process. Demirtas et al. [5, 6] focused on the study of the distribution and density of bone microstructures and how this affects fracturing.

As mentioned in the previous section, most of the studies use as a starting point the segmentation of 2D microscope images of bone structures, made manually, using FEM (Fig. 2.9). The few three-dimensional representations that can be found are extrusions of the two-dimensional models as shown in figure 2.8.

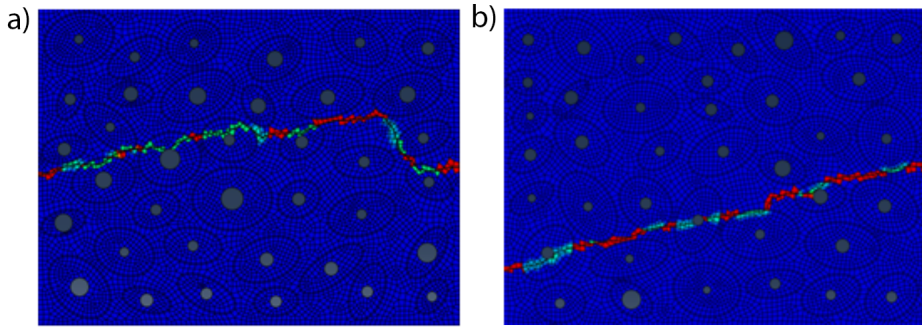


Figure 2.9: Final fracture paths using two different random (a and b) representation of bone microstructures realized by Gao et al. [7].



MACROSCALE MODELLING AND FRACTURE PATTERNS

Macroscale bone modelling refers to the acquisition of a virtual model of a complete bone in order to carry out simulations. In the previous chapter, the principal methods to represent a geometric model were analysed, as well as the main techniques to convert a real human bone into a digital model. This chapter describes in greater detail the representation and techniques used to obtain these models. In addition, the steps required to obtain bone fracture patterns for use in the following chapters and to carry out fracture simulations are also detailed.

3.1 Bone modelling

Chapter 2 has detailed the different options we have to represent a bone model virtually: point clouds, volumetric models and triangle meshes. In order to decide between these options, it is necessary to take into consideration the purpose for which the bone models are to be used. The

point cloud representation is not very useful because the visualization of these models limits the perception of the details of the models as well as the simulations that can be performed. However, both volumetric representation and triangle meshes solve these issues (Fig. 3.1).

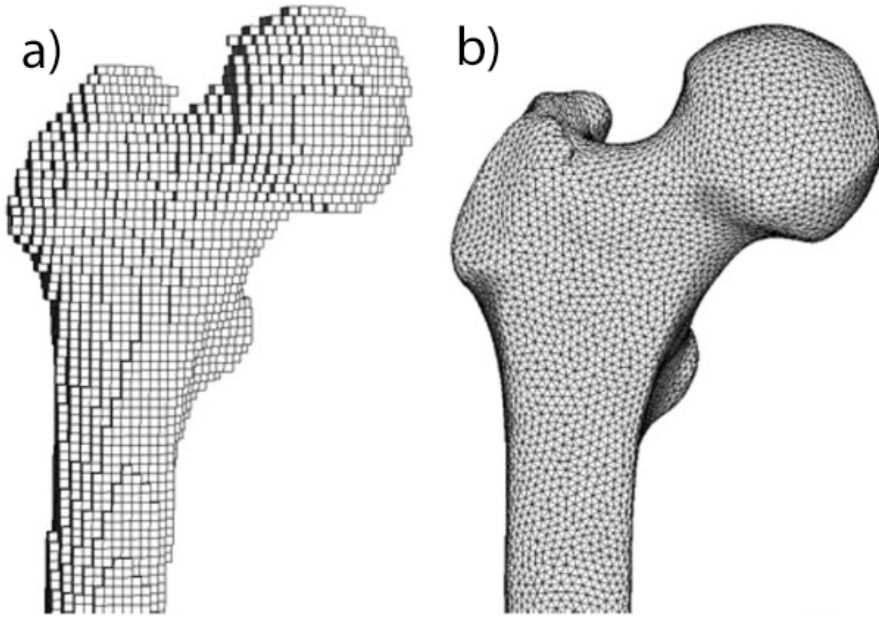


Figure 3.1: Illustration of the different approaches to representing bone models. Figure a represent a voxel-bashed method and figure b a triangle mesh.

The volumetric representation using voxels is very common in the medical field because it is easy to obtain since the images that are usually used as a reference come from CT scans. These scans provide a stack of images that can be segmented to convert the pixels of the images into voxels to obtain a 3D representation of a bone. However, the triangle mesh representation is performed in a two-step process: reconstruction of the surfaces of the bone based on the contours of the segmented CT scan and the conversion of all the identified vertexes into a mesh with triangular topology. Sas et al. [94] performed a literature review of models for frac-

ture prevention in patients with metastatic bone disease. In this review they show several studies based on both representations [95, 96, 97, 98], concluding that although the voxel representation is easier to obtain, the representation obtained with triangle meshes is considerably more accurate, especially considering the large amount of deformity on the surface of human bones. This results in inaccurate stress concentrations on the surface of a volumetric model [97, 99], so the most common representation used to carry out simulations are triangle meshes. In this case, as one of the objectives is to focus on fracturing simulations, we will use triangle meshes to represent the bone models.

To obtain the triangle mesh it is necessary to use an algorithm that allows the reconstruction of the bone model through bone images. The classical scanning techniques are not considered since this dissertation takes into account the different hierarchical levels of the bones. Moreover, these techniques restrict the triangle mesh that we can obtain to the external surface of the bones. Thus, they do not allow to delimit the cortical area inside the bone. Consequently, the best starting point is to use CT scan images because they enable the complete delineation of the cortical area of the bone.

The techniques for segmentation of bone models are quite advanced so we have used some algorithms from the reviewed literature to obtain the representation of human bones. The CT scans used have been obtained from the Complejo Hospitalario de Jaén. Most algorithms can reconstruct bones made up of a single fragment using a simple procedure. 3D Slicer [36] has been used in these cases as it is the most powerful platform for the analysis and visualization of medical images and includes several algorithms for image segmentation. However, it is not always possible to have a complete bone to scan, it is easier to obtain medical images of clinical cases in which a bone fracture, with several fragments, is usually present. In these cases, the previous tool does not work as well, so it is better to use other techniques such as the one proposed by Paulano et al. [4]. This implementation is designed to identify all the bone fragments that appear in a 3D scan independently of each other. This method use several seeds within a region that is part of a fragment of the bone in

order to detect all the pieces that compose the bone fracture. After placing the seeds, they are propagated through the CT image stack to discard regions which contains some noise. 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. Although the main objective is to use the models to perform fracturing simulations, throughout the dissertation we have also worked with fractured models to perform other simulations at the macroscopic level. In addition, simulations at microscopic levels can also be performed on fractured areas. Thus, models have been reconstructed using both tools. Figure 3.2 shows an overview of the segmentation process from real bone to the 3D model in which the reconstruction of a complete humerus and a fibula composed of two fragments is shown.

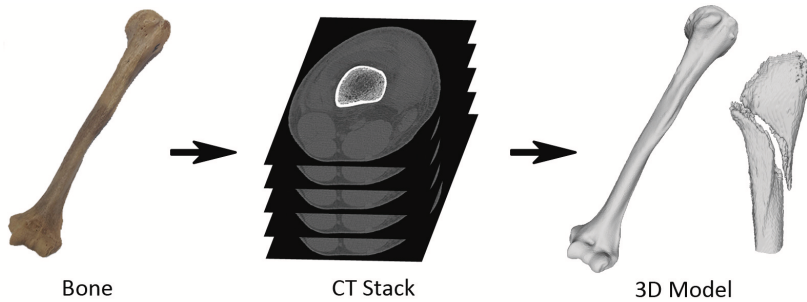


Figure 3.2: Process from the real bone to the 3d model.

Once the models have been segmented and the mesh is built, there is usually a 3D aliasing effect that will affect the operations applied on the surface of the geometric model. To avoid these disturbances, a slight smoothing is applied to the bone model, which generates more continuous regions avoiding sharp artificial changes in the curvature of the surfaces.

3.2 Fracture patterns

A fracture pattern is an abstract model that represent the fractured area of a bone. It acts as a template to enable a replication of a fracture with similar features in other bones or other areas of the same bone. As mentioned in previous chapters, this methodology will be used to fracture bone models in the dissertation, so in this section we are going to focus on obtaining fracture patterns and its representation.

There are different ways to represent a fracture pattern. The most common methods are by a bitmap, map of heights and spherical coordinates. The following subsections show the way in which the information is represented and how it is obtained with all the methods presented above. Thus, the best approach to represent the fracture zone can be identified to perform fracturing simulations.

3.2.1 Bitmap

These fracture patterns use 2D images and are the easiest and simplest. The color of each pixel is represented as a binary number so the whole image is represented with black and white color. The black color represents the zones where there is no fracture line while the white zone represents the fracture line. Each image represents the fracture line from one of the view of the geometric model. Figure 3.3 shows the main aspects of the bones: anterior, posterior, lateral and medial.

These fracture lines can be identified by a process of manual analysis of the fracture are of real bones. For this purpose, a camera system is placed in front of the bone model to capture the fracture lines when they appear on the bone model. Since the fracture is not uniform across the entire bone and this representation is based on information from only one aspect of the bone, the most accurate way to obtain fracture lines is to capture the exact moment at which the fracture occurs. The capture and analysis of the fracture lines in a posterior way may result in the bone arrangement not being exactly the same in all cases of study. Therefore, the best option for capture and analysis of the fracture area is at the time it oc-

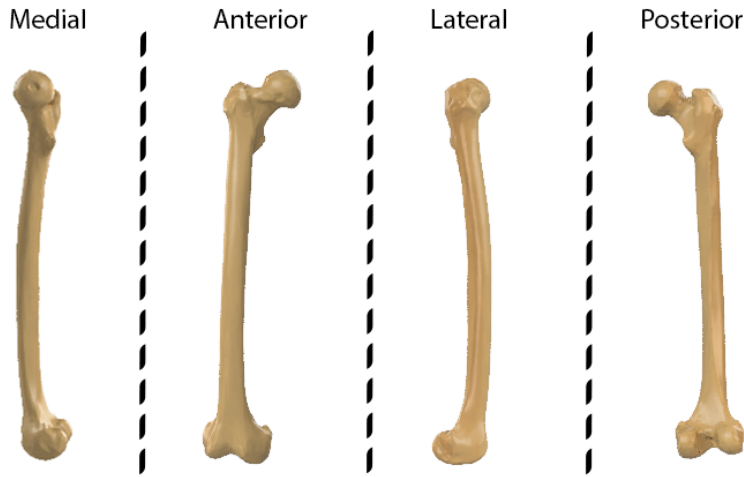


Figure 3.3: Representation of the four aspects of a femur.

curs and to carry out the complete experiment in a fixed device to preserve the position of the model. In the following chapters a setup for fracturing human bones by mechanical experimentation with a high-speed cameras system will be shown. Figure 3.4 shows an overview of the process to be followed to obtain the fracture pattern by manual analysis of the image after the fracture has occurred. To obtain the fracture lines, the frame where the fracture occurs is identified and the entire area is marked manually.

3.2.2 Map of heights

In this representation, a two-dimensional image composed of a range of colors between black and white is used. The colors closer to white are the points with the highest height while the colors closer to black are the points with the lowest height. Thus, this representation is more accurate as it contains 3D information about the fracture area.

The main problem with this representation relates both to the time required to obtain the fracture area information and to its adaptation to other models, since the dimensions vary according to the specimen and

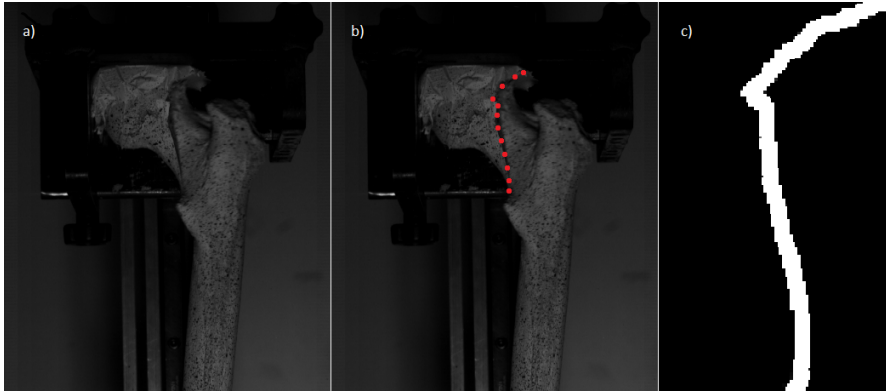


Figure 3.4: Fracture pattern obtained in a femur through mechanical experimentation. Figure a represents the instant at which the fracture occurs, b marks the line that delimits the fracture and c represents the fracture pattern obtained after manual analysis.

bone area [100]. In the case of the femur, the cortical area in the head zone is smaller than in other areas of the bone. Figure 3.5 shows an X-ray of the pelvis in which it can be seen how the size of the cortex of the femur, the cortical area, is wider in the area of the diaphysis while it is minimal in the area of the femoral neck.

In order to obtain the fracture pattern it is necessary to use a virtual bone model on which to perform the analysis. Previously described procedures can be followed to obtain the model. Once we have the model, the 3D models are processed to locate candidate points for fractured area identification. The algorithm developed is based on the method developed by Paulano and Jiménez [9]. This method use an oriented bounding box (OBB) encloses the model and it is discretized using a grid, being the direction of the OBB defined by the vector that joins the centroids of every pair of models (Fig. 3.6). Afterwards, the grid is traversed through the parallel columns to the sweep vector and the points that belong to the first populated voxel in each column are marked as candidate points. Finally, the candidate points are filtered based on their distance to the candidate points of the opposite fragment. The following subsections show the steps

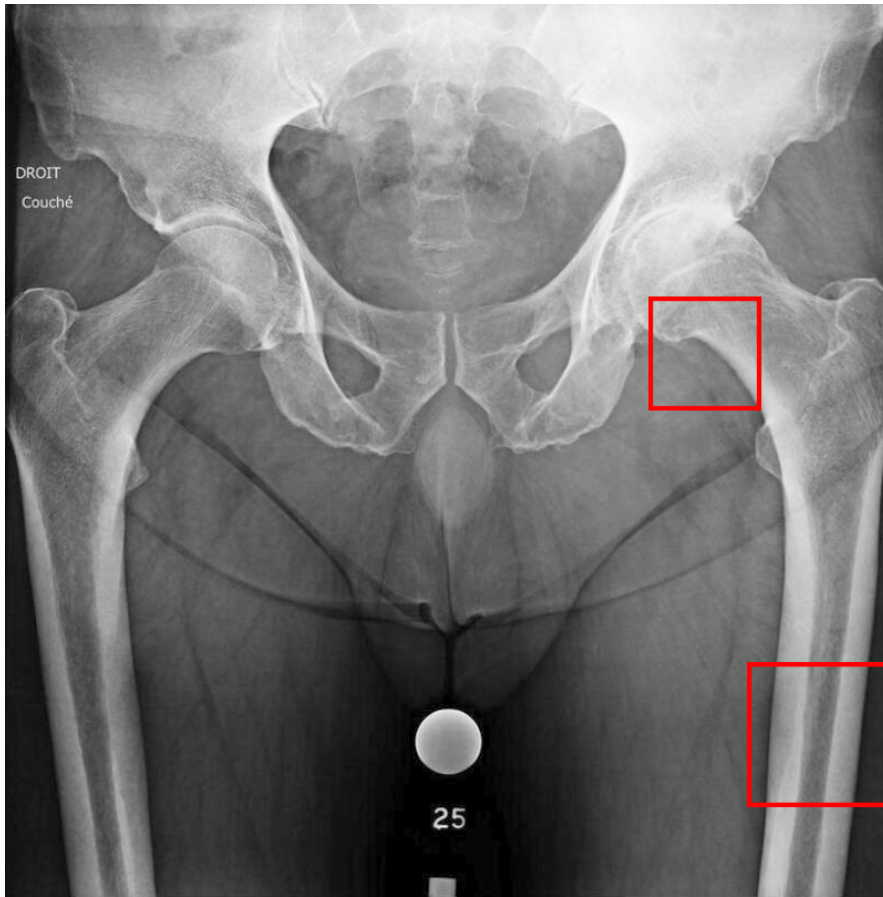


Figure 3.5: X-ray of the pelvis of a 78-year-old patient. Figure taken from [8]. The highlighted areas show the difference of the cortical area in the diaphysis and the head of a femur.

followed by our algorithm.

3.2.2.1 Candidate points

In our method [101], we only use one fragment. The OBB is aligned with the fracture. This coarse alignment is later refined when obtaining

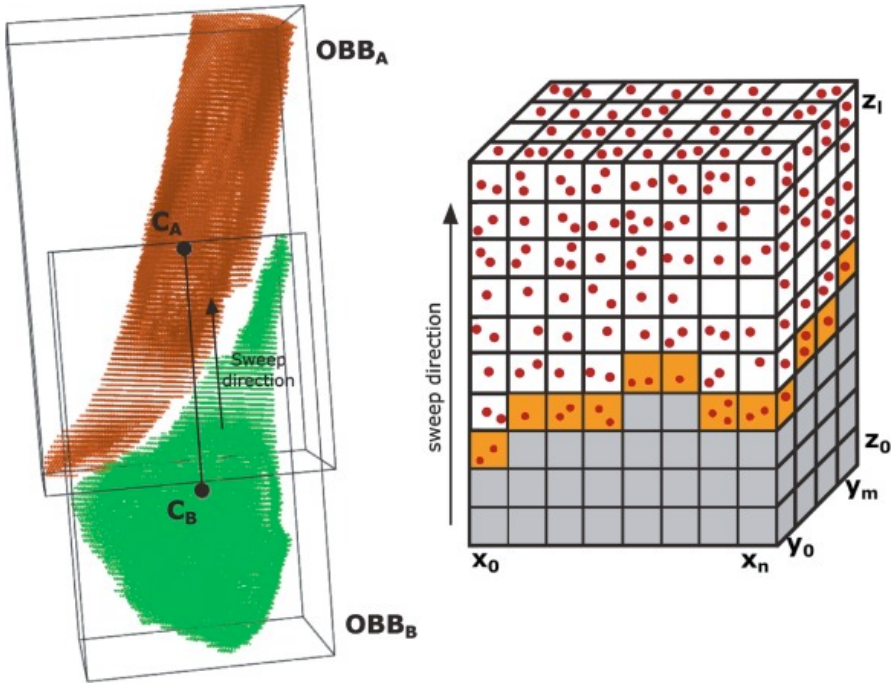


Figure 3.6: Left, OBBs and centroids associated with two fragments. Sweep direction used to calculate the fractured area of fragment A. Right, 3D representation of the sweeping procedure. Checked voxels that contain no points are displayed in grey. Checked voxels that contain candidate points (for belonging to the contact area) are displayed in orange. White cells are not checked. Taken from [9]

the points of the fracture area, before their projection to a fine oriented plane. Due to the diverse nature of each fracture, this coarse alignment is done by hand. Automatic algorithms for the initial alignment can be developed for specific fracture types by taking advantage of the previous knowledge. The used filters are based on the curvature, thus points with a curvature lower than a threshold are discarded. The angle between the normal of the point and the direction of the OBB are also used. The points

of the fracture area tend to have their normal oriented towards the opposite direction of the OBB. As seen in figure 3.7, the bottom plane of the OBB is oriented to the fractured zone. This arrangement provides more points that help to generate a smoother surface.

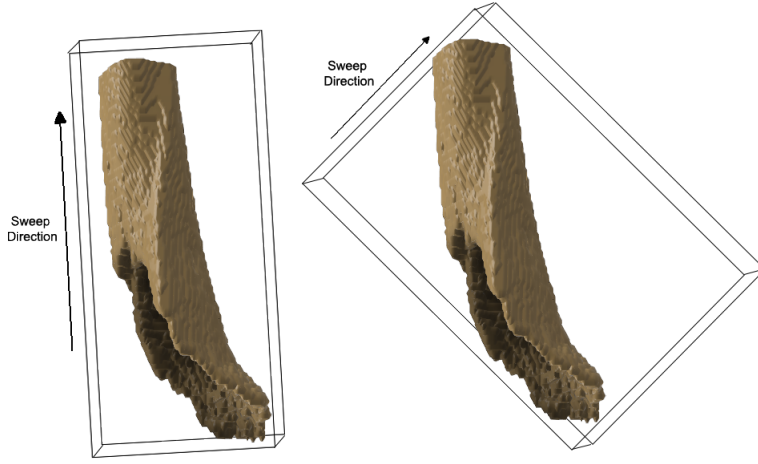


Figure 3.7: Left, OBB alignment realized by Paulando and Jiménez [9]. Right, our alignment.

3.2.2.2 Point cloud cleaning and plane fitting

Some of the points identified previously are false positives that would distort the pattern obtained. In order to delete those points, two automatic cleaning methods are implemented. The first method uses a statistical algorithm included in the Point Cloud Library [102] to detect outliers. It is based on discarding those points that are at a greater distance than a threshold to its neighbours. The threshold is based on the global average and the standard deviation of the distances between the points and its respective neighbours.

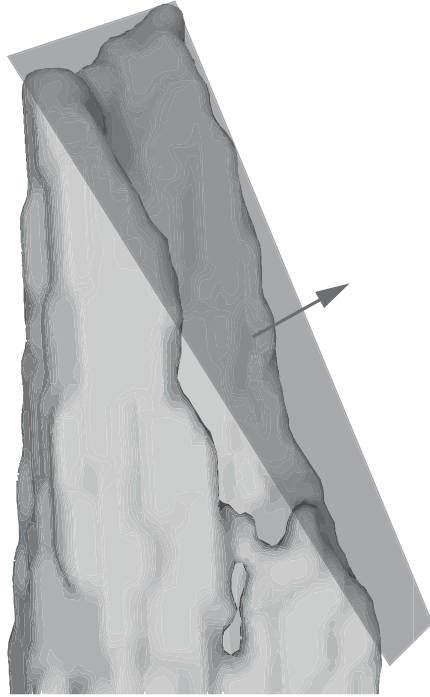


Figure 3.8: Fracture plane and normal vector

The second method takes advantage of a fitting plane. This plane is calculated close to the points that make up the fractured area, leaving the fragment to one side. The normal of the points that make up the fractured area tend to have the same direction as the plane (Fig. 3.8). The point of application of the plane is the center of mass of the candidate point cloud. This mathematical approximation returns the plane that minimizes the distance to the points of the cloud identified as candidates and defines a reference system for the following phases. So with this plane, we can remove the points located beyond the plane. The plane is calculated automatically using the principal component analysis (PCA) algorithm in some situations, but there is other situations in which it require a previous manual coarse alignment of the plane because the normals of the points

belong to the fracture area do not have an specific orientation.

It is difficult to automatically identify all the outliers near the surface of the bone fracture, so manual filtering is needed as the last task in this step. In [43], we add an additional filter using seeds to avoid or reduce the manual cleaning of the bone fracture surface. In each iteration, the neighborhood of the initial set is checked using several filters that determine the candidates to be considered as part of the fracture in the next iteration. Two filters were used for the expansion of the seeds: curvature (Eq. 3.1) and normal (Eq. 3.2). Curvature is measured as the average cosine between the normal of a point and the normal of its neighbours. Normal filter refers to the value of the angle formed by the normal of the point and the normal to the plane of the fragment fracture. The number of iterations can be automatized using as a stopping criterion the number of new points included from one iteration to another.

$$Curvature\ Value = \frac{\sum_0^N v_n \cdot v_{ni}}{N} \quad (3.1)$$

$$Normal\ Value = v_n \cdot v_f \quad (3.2)$$

N	number of neighbours
v_n	normal vector of the point
v_{ni}	normal vector of the i-neighbour
v_f	vector of the fracture plane

3.2.2.3 Fracture area identification

The cortical area identification is performed with a projection of the point cloud on the fitting plane calculated previously. The information obtained has been used to create different representation of the fracture (Fig. 3.9). The first two images in the figure represent the points in a range of colors from blue to green in which blue indicates the points farthest from the fitting plane while green indicates the points closest to the fitting plane. In figure 3.9a we have the points in their original position with the associated color meanwhile in figure b they are projected on a 2D plane, including

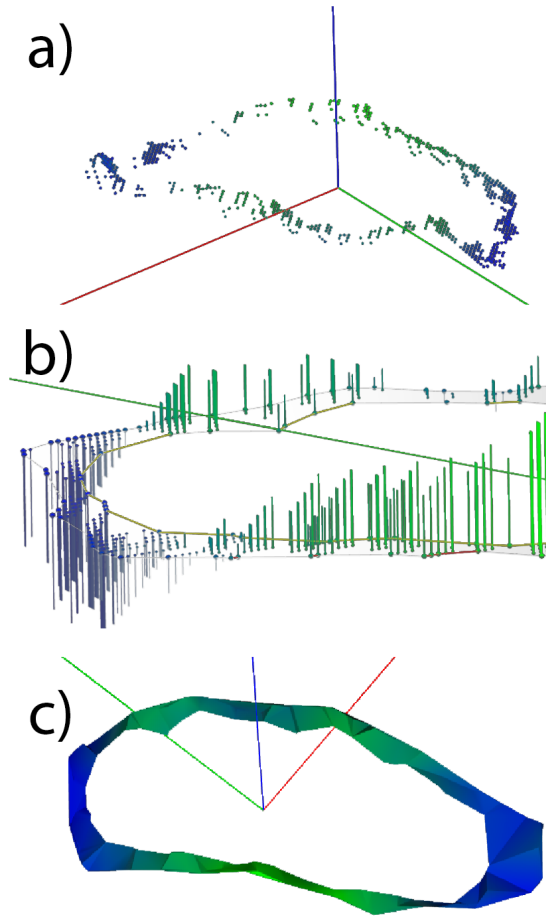


Figure 3.9: Figure a represents the fractured area (coloured). The lower the point in relation to the plane, the bluer the point, and the higher the point, the greener. Figure b contains the details of the points with the border of the fracture and lines that represent the projection of the points to the plane. The surface representation of the fracture pattern can be seen in figure c.

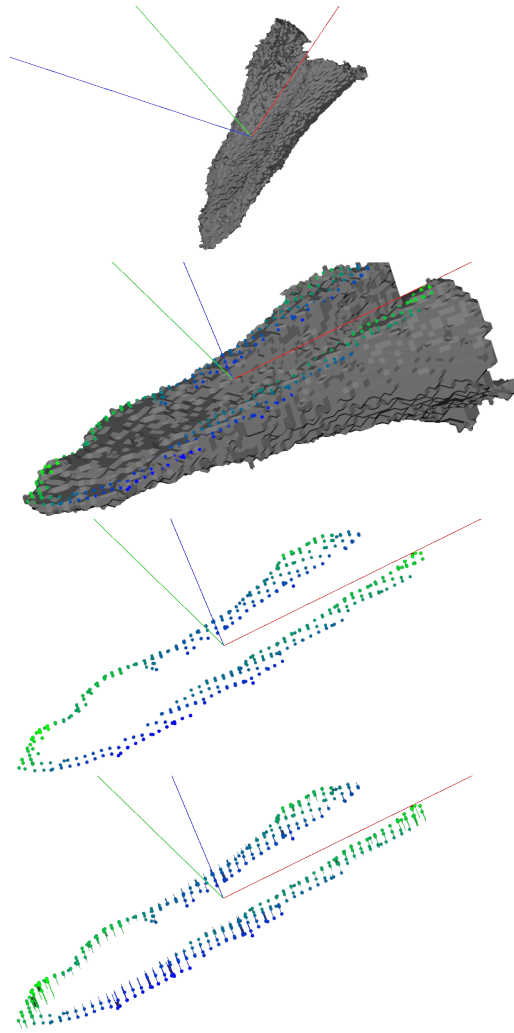


Figure 3.10: Fracture localized between the epiphysis and diaphysis of a humerus. From top to bottom: fragment overview, points of the fracture area overlapped on the fragment, points of the fracture after the filters and the projection of the points of the fracture area to the plane.

the border that delimits the fracture area, and a projection of the points on the plane representing the distance to it. These points are processed by a 2D alpha shape algorithm [103] that returns the cortical surface of the pattern (Fig. 3.9c). The alpha parameter is different for each point cloud.

Figure 3.10, present clean and straight fractures between the epiphysis and diaphysis, which allows a precise segmentation, due to the density of the cortical part of the bone. This figure presents a summary of the steps involved in obtaining the height map representing the fracture area.

3.2.2.4 Evaluation

The method has been applied to various clinical cases. The number of points representing each fragment is computed as well as those corresponding to the fracture area. These calculations have been carried out by our method and manually by specialists. The cleaning step has not been required in all the cases. Table 3.1 shows the results obtained. It can be observed that obtaining the fracture area significantly reduces the number of points in the representation, although the percentage is not entirely significant because it depends on the relationship between the size of the fragment and the size of the fracture area.

Results obtained with our method have been compared to the outcome of a complete manual selection of the fracture area. These experiments were conducted by the same specialists that carried out the manual cleaning step of the process. The number of points obtained is about 81% compared to the number of points delimited by specialists. This is due to several reasons; the first is that the manual selection has obtained the points selected by the automatic process and others that were not detected by the fracture area detection algorithm. The second is relative to a manual cleaning performed as the final step, in which those points that do not belong to the fracture area have been deleted. A subjective comparison between automatic and manual selection has been realized by specialists, indicating that the results obtained are valid for the cases showed. The fracture area detection algorithm works better in clean fractures. In the case of tibia 1, figure 6, the fracture is in the tibial pylon, a spongy

Table 3.1: Details of the bone fracture models used for the validation of the method presented in this paper. Including the number of points on the fragment, the number of points on the fracture area before cleaning, the ratio between points on the fragment and the fracture, points remaining after the cleaning process, the percentage of points removed from the fracture area, the number of points manually selected by specialists and the ratio between the number of points obtained with our process and the points which were extracted manually.

Fragment	# fragment points	# fracture points	% fracture points	# automatic points	% cleaned points	# manual points	Ratio auto/manual
Fibula 1 - 1	4917	481	10,84%	464	3,53%	554	83,75%
Fibula 1 - 2	6010	507	8,44%	507	0,00%	555	91,35%
Fibula 2 - 1	92656	4686	5,06%	3101	33,82%	3876	80,01%
Fibula 2 - 2	55626	1122	2,02%	998	11,05%	1209	82,55%
Fibula 2 - 3	22438	5249	23,39%	4284	18,38%	5711	75,01%
Humerus - 1	4716	195	4,13%	195	0,00%	208	93,75%
Humerus - 2	4660	485	10,41%	439	9,48%	497	88,33%
Tibia 1 - 1	11739	3026	25,78%	1566	48,25%	1800	87,00%
Tibia 1 - 2	6974	1376	19,73%	1193	13,30%	1432	83,31%
Tibia 1 - 3	6674	2247	33,67%	1346	40,10%	1521	88,49%
Tibia 2 - 1	41214	2307	5,60%	2013	12,74%	3519	57,20%
Tibia 2 - 2	69039	3398	4,92%	2954	13,07%	3641	81,13%
Tibia 2 - 3	33707	7322	21,72%	5419	25,99%	8031	67,48%
Tibia 2 - 4	11815	2737	23,17%	2378	13,12%	3160	75,25%

area with difficult segmentation, which complicates obtaining the fracture area. As a result, the greatest number of points were removed in that case.

The fracture area detection algorithm works best in clean since some segmentation contains information about the spongy area of the bone which difficult the process. There have also been cases where it was unnecessary to apply any of the cleaning processes. Figure 3.10, present a clean fracture, which allows a precise segmentation. This results in a more accurate calculation of the fracture area.

3.2.3 Spherical coordinates

Spherical coordinate systems are based on the same idea as polar coordinates and allow to represent a position in space. The use of spherical coordinates can be simplified by projecting them onto a 2D plane (Fig. 3.11). The fracture patterns found in the literature with this representation are formed by a projection on the plane divided into four parts [104, 105, 10] which coincide with the four aspects of the bones (Fig. 3.3).

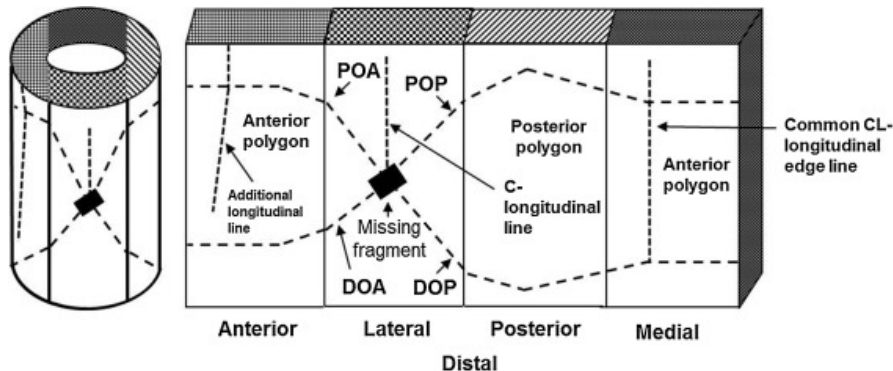


Figure 3.11: From spherical coordinates to a 2D representation [10].

The aspect on which the 2D representation starts is irrelevant since the order of the views is always the same and the last view connects with the first one when it is transferred to the 3D model. In addition, a forensic

analysis process is also necessary to determine the features of the fracture lines that make up a real bone fracture.

In the previous fracture representations we have discussed the procedures to identify a bone fracture and to carry out the representation. In this case, we could not use the bitmap information since there is only 2D information about the fracture, but we could start from the point cloud representing the fracture obtained in the previous section. The problem with this method is that it requires an exhaustive and precise analysis of the fracture area. Therefore, with the aim of minimizing the calculations to obtain a spherical representation of the fracture area with 3D information about the fracture, a system based on forensic analysis has been developed for the creation and validation of fracture patterns without the need to analyse the fractured area of a bone.

3.2.3.1 Fracture area representation

Forensic analysis studies aim to deduce the parameters of a certain injury based on fracture pattern analysis. Therefore, some parameters such as the impact direction, the force, the relative size and shape of the impact body or the axial loading can be identified. These data can be extracted from experiments performed by other authors [104, 105, 10] to validate the patterns generated with the tool. Cohen et al. [10] reveals that there is a relationship between the complexity of a fracture and the axial load on the bones. Moreover, the impacts on the lateral and anterior aspect of the bones produce more fracture lines than the other aspects. Bones subjected to axially loaded impact are significantly more fragmented. The longitudinal line that appears in fractures is longer in bones subjected to impacts with larger objects, having in most cases a size similar to that of the impacting body. The size of the impacting body also increases the area of branching and the size of the detached fragment, although if the impact occurs with a round object, no longitudinal line will be created and the oblique lines will be born at the point of impact. In addition, there are forensic studies demonstrating that the number, length and curvature of fracture lines created under impact depend on the energy used [104].

This study also suggests a relationship between velocity and the fracture pattern. Cohen et al. [105] also reveal the importance of the geometry of the impacting objects. Bones impacted by round objects produce fragments with the form of a false butterfly, but if the impact body is flat and wide, the fragments have the form of a double trapezoid.

If we focus on the fracture lines, it can be observed that there is two lines that completely surround the bone, one in distal direction and the other in the proximal direction. The shape of this lines is known as fracture polygons. The longitudinal lines are common in the representation of the aspects, especially on the contralateral and impact aspects. Moreover, oblique fracture lines may arise as branches of the main fracture lines. They generally extend from the proximal or distal region into the epiphysis and other aspects of the bone. However, transverse fracture lines arise from the impact area.

Based on the above observations, the factors which determine the bone pattern features are as follows:

- Position of impact: refers to the aspect in which the impact occurs.
- Chip fragment: bone detachment occurring on impact. Its presence and the length of the diameter in *mm* are considered.
- Fracture lines: fracture lines vary according to the direction in which they occur:
 - Longitudinal lines: extend proximally or distally parallel to the longitudinal axis of the bone. The metric used for this parameter is the presence or absence of these lines, the number and location.
 - Oblique lines: extend with an angular variation with respect to the long axis of the bone. As in the previous case, the metrics used are the presence or absence, the number and the location of these fracture lines.
 - Transverse lines: surround the diaphysis area, appearing as straight lines. The metric used for this parameter is the presence/absence of transverse lines.

- Polygon: is the area between two oblique lines that appear from the impact area. It can be also formed by a transverse and an oblique line.
- Partial polygon: is the one that is only generated by one fracture line.
- Location: indicates the aspect aspect of the bone in which the fracture line is found.
- Branch line: oblique line which starts from another fracture line.
- Branch points: correspond to the points along the fracture line in which new branches are generated.
- Shape of the fragment: this corresponds to the shape of the chip fragment detached from the bone. It can be circular, squared, rectangular, etc.

The tool developed consists of an editor that displays a plane with the four aspects of the bone in order to draw the fracture lines (3.12). Even though the editor allows to draw as several lines, the model goes through a self-validation process that discards the patterns that differ from the morphology they should have. In addition, it can also generate patterns automatically using the same rules it uses to validate the models made in the tool.

The steps to generate a spherical pattern using the aspects of the bones are as follows:

1. Determine the occurrence, shape and appearance of a chip fragment detachment.
2. Draw the oblique, transverse and longitudinal lines of the pattern (Fig. 3.12a).
3. Draw the branches that are generated through the fracture lines (Fig. 3.12b).
4. Automatic validation of the pattern.

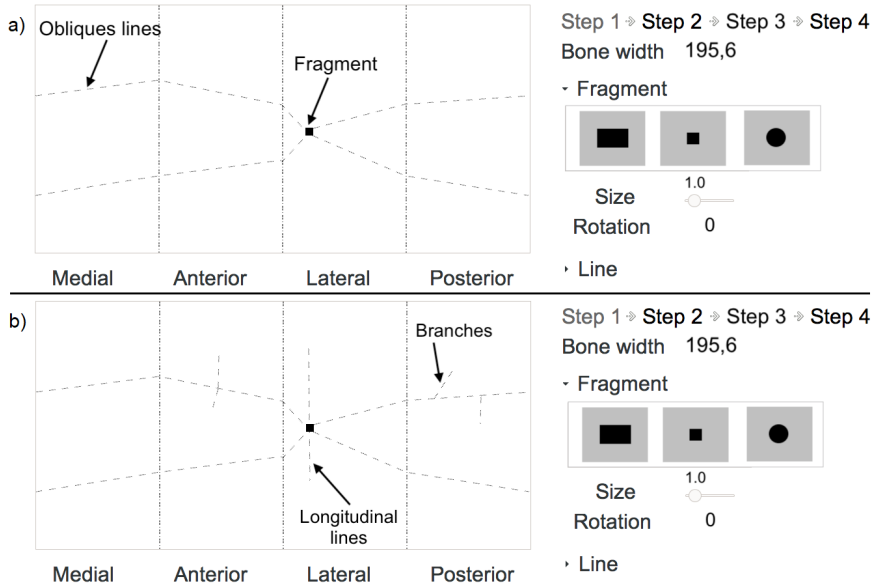


Figure 3.12: Editor developed to generate the representation of fracture patterns. a) Oblique lines drawn in the editor combined with the use of a chip detachment. b) Longitudinal lines and branches are added to the model.

3.2.3.2 Validation

The validation of the models generated with the tool involved two validation processes. The first process focuses on the measurement of the parameters of interest identified above while the second stage has focused on an expert assessment. For the validation process, a set of 64 fracture patterns have been created using the interactive tool, 16 fracture patterns for each impact aspect. Likewise, a set of 64 fracture patterns have been created automatically. As the automatic generation aims to generate valid models, it has been modified to force the generation of 4 erroneous patterns for each aspect. Figure 3.13 shows a set of cases employed in which there is two valid fracture patterns and one invalid for each aspect.

The first process focuses on performing an automatic validation by

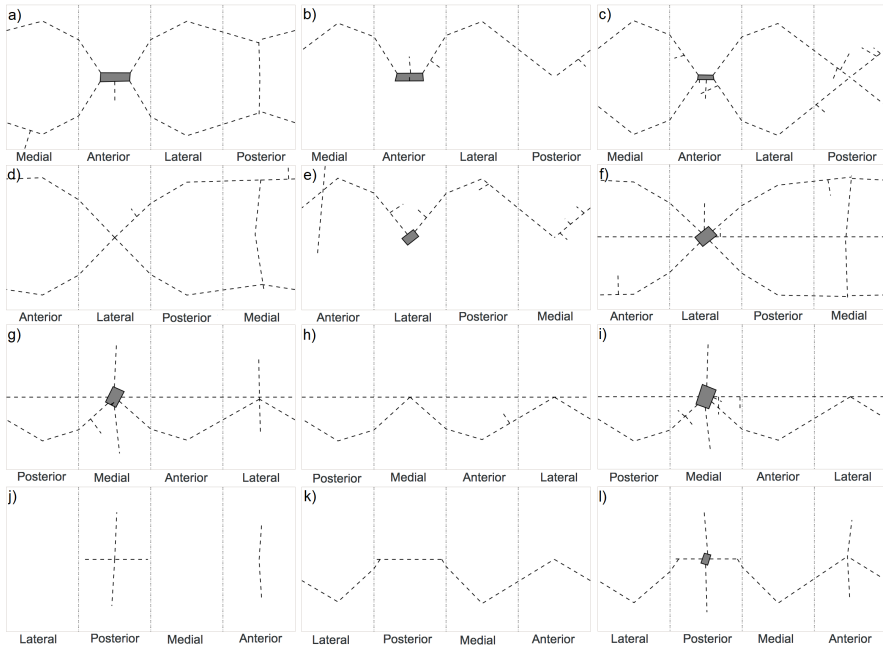


Figure 3.13: Parametric fracture patterns. The first three fracture patterns represent a selected subset of fractures with impact on the anterior (a to c), lateral (d to f), medial (g to i) and posterior aspects(j to l). There are two valid and one invalid case for each impact aspect.

the measurement of the features of the generated pattern. This process is based on the measurement of the number of lines of each type by aspect, their distribution, the length of the fracture lines, the total number of lines and the presence or absence of a chip fragment. In addition to extract the fracture pattern features in previous subsections, it was also possible to estimate a series of ranges in which these values should be found. Table 3.2 indicates the average and the standard derivation of some measurements. No relationship can be appreciated between the length of the fracture line and the resulting polygon since the size of the bone itself is involved. However, they have a relationship with the number of lines that are part of the fracture, so it can be helpful to discard a pattern. Concern-

Table 3.2: Statistics of the analysis of fracture metrics extracted from the study conducted by Cohen. [10].

Measurements	Direction of impact							
	Lateral		Posterior		Medial		Anterior	
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Number of fracture lines	4.5	1.3	2.9	1.7	3.8	1.3	3.6	0.9
Fracture line/polygon length (<i>mm</i>)	265.7	127.7	165.7	92.8	177.8	123.6	176.6	71.5
Chip size (<i>mm</i>)	33.5	13.8	0	0	33.9	16.3	48.9	7.7

Table 3.3: Statistics on the distribution of longitudinal lines by the aspect in which the impact is produced in the study conducted by Cohen [10].

Impact direction	Location of longitudinal lines (aspects)			
	Impact	Contra lateral	Impact + contra	Anterior
Lateral	25%	50%	0%	25%
Posterior	34%	0%	66%	0%
Medial	57.5%	14%	26.5%	0%
Anterior	72%	14%	14%	0%

ing the fragments, there are certain differences depending on whether or not they appear within the pattern.

Table 3.3 shows the distribution of longitudinal lines according to the point in which the impact is produced. Therefore, certain fracture lines can be discarded depending on the point at which impact occurs. In addition, the patterns can also be evaluated based on the number of fracture lines in the model using the values of table 3.4 as a reference.

A positive assessment of the above points results in a positive valuation by the automatic evaluation system. Some parameters are not decisive to identify an incorrect fracture pattern. In these cases, it is necessary to perform an overall evaluation. For example, in relation to the size of the fragment, there is a small difference according to the statistics that determine whether a fragment detachment should be produced. Thus, we consider it valid if the other criteria measured are valid.

The second step of validation completes the automatic validation of the previous section by an analysis of the results obtained from a group

Table 3.4: Statistics on the distribution of the average number of fracture lines according to the direction of impact in the study conducted by Cohen [10].

Impact direction	Bone aspect							
	Lateral		Anterior		Posterior		Medial	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Lateral	4.3	1.2	2.5	0.7	2.2	0.6	2.7	0.9
Anterior	1.8	0.8	4.2	0.8	1.9	0.6	2	0.7
Medial	2.3	0.7	2	0.7	1.3	0.5	2.9	1.5
Posterior	1.4	0.52	2.4	1.1	2	1	1.3	0.5

of experts. Two experts were consulted in the area of traumatology, one radiologist with experience in bone fracture interpretation and a surgeon with wide experience in fracture reduction interventions. The validation was performed independently. A survey was also carried out to improve the usability of the tool.

A study of the results obtained with both the experts and automatic validation, is provided for each of the 64 cases of interactive generation and for each of the 64 cases of parametric generation. In the case of discrepancy between the evaluation of the experts or dubs, it has been marked as “doubt”. In addition, the concordance between the experts and the generation is provided, as well as the discrepancy between the premise and the generation for the parametric generation cases.

For interactive patterns generated by users, the table 3.5 shows how the automatic validation evaluates 35 patterns as correct and 29 as incorrect. The experts considered 41 correct patterns and 23 incorrect patterns with doubts or discrepancies in 6 cases. 5 doubts correspond to correct cases and 1 doubt corresponds to an incorrect case according to the automatic validation. All the doubts concluded with a correct classification of the automatic validation, obtaining a total of 62 matches between the automatic validation and the experts conclusion.

In the case of the parametric generation of fracture patterns (Fig.

Table 3.5: Validation process for interactive generation.

Measurements	Total	Correct	Incorrect
Automatic	64	35	29
Experts	64	41	23
Concordance automatic and experts	56	34	22
Experts doubts	6	5	1
Experts correction	64	37	27
Final discrepancy automatic and experts	2	2	0

3.13), 48 cases have the premise of being valid, while 16 cases are considered as invalid due to the parametric generation performed. The automatic validation matches with the premise in 62 cases from the 64, it fails on one generated as a correct pattern and on one generated as an incorrect pattern. Experts agree with the majority of cases although it differs in 4 cases in which the automatic validation obtains a correct result and 3 cases evaluated as incorrect.

The interactive generator proposed allows to obtain fracture patterns with 3D information. In addition to drawing patterns manually, it is also possible to generate them automatically by setting some parameters. The tool has a very accurate self-assessment method that allows the generation of new patterns in a simple way and without the need to analyse the fracture area of a real bone. The above paragraphs show the high percentage of accuracy for both correct and incorrect cases evaluated in comparison with an expert analysis. A more extensive analysis of the training set is available at [106]. In this way, we can use these patterns to fracture the bone models and increase control over the fracture area of the bones.

3.3 Conclusions

The different methods of representing a bone virtually have been studied in this chapter. The most accurate representation of the bones is obtained

with means of a triangle mesh, since a volumetric representation of 3D voxels would require a very small size to achieve the same level of detail on the surface of the bone, resulting in an increase in the computational cost when performing simulations on the model. Considering the objectives of this dissertation, in which the cortical bone is not only analysed at the macroscopic level, it is also considered at the microscopic level, the best approach to obtain the representation of the bone is through CT scans, since they allow delimiting the internal limits that are not visible in a natural way.

In terms of fracture patterns to carry out simulations, several approaches have been shown. In this case there is no obvious argument for determining the best approach, as the cost and time involved vary considerably. The bitmap representation is the simplest. To obtain the pattern, it is sufficient to analyse images manually and define the fracture area. When carrying out a simulation using patterns, it is possible to adjust to one of the aspects of the bone and project the lines that make up the fracture. The degree of realism is lower due to limited 2D information of the fracture, but the time required to obtain the representation of the pattern and the fitting to the test samples is lower than in the other cases.

The representation by height mapping is the most accurate as it allows the fractured zone of the model to be represented in great detail. The problem with this approach is the time required to obtain a fracture pattern. Before a fracture area can be analysed, it is necessary to segment the images of the clinical case to obtain a representation of the fractured model. Once the model is obtained, the fracture area can be analysed. For this purpose, an algorithm has been developed to analyse the fracture area in detail and to select the points that make up the fracture area. In addition, several filters are applied to avoid the inclusion of outliers in the fracture zone.

Finally, a method for obtaining a spherical representation of the fracture coordinates has also been studied. To avoid the computational cost of the whole process of analysing a fracture as in the previous approach, a fracture editor based on forensic analysis has been developed. Although the user does not have to segment any model and perform an exhaustive

analysis of the fracture zone, the user is in charge of drawing the fracture pattern which is verified through an automatic process in which the characteristics of the drawn pattern are studied. A priori, it could be the best option since the time to obtain the pattern through the editor is low and a fracture with 3D information is obtained. The main problem of this approach, which also occurs in the representation based on height map, is the adaptation to the model when carrying out simulations. Each bone has different dimensions and an irregular surface. Therefore, the adjustment of the patterns to the dimensions of the model is not trivial as it happens in the bitmap representation where it is only necessary to project the pattern. The methods developed complement previous literature on pattern derivation.

The results obtained enable different ways of representing and obtaining the information of a bone fracture. The advantages and disadvantages of each method leave it up to the user to decide which representation best suits his study or simulation, since some reward the level of detail while others reward time. The next chapter focuses on describing an algorithm for fracturing macroscale bone models using one of the representations we have discussed throughout this chapter.

Chapter 4

MACROSCALE FRACTURING

This chapter describes the method that has been developed to fracture human bone models at macroscale level [107, 50]. To achieve this goal, there are different libraries with tools that help us with the fracturing of geometric models such as Blast[108], Bullet[109], LibMesh[110] or Vega[111]. Blast has a large number of tools for fracturing geometrical models and is the reference library for geometric destruction. This library has been developed by NVIDIA and is constantly updated, so we have decided to use it as the basis for our simulations.

4.1 Blast

Blast replaces the APEX destruction module and has been designed from the ground up, focusing on resolving performance, scalability and flexibility deficiencies. It consists of three layers: a low-level layer, a high-level layer and extensions that complete the functionality of the library. Even though it does not have a graphical interface, the library is integrated with Unreal Engine (UE) as a plugin. The library allows to fracture

models with the following methods:

- Voronoi fracture: this method is based on generating Voronoi cells from a cloud of internal points. It is composed of different variants to make a fracture. These variants range from specifying a number of pieces to be generated in the model to using a radial pattern.
- Uniform slicing fracture: this approach focuses on cuts chunk with grid like pattern. It is possible to adjust the number of slices along the axis and set angle variations. In addition, it can be activated a noise in the new faces that are generated when cutting the model.
- Cut fracture: the method consists in cutting the model with a specific plane.
- Cutout fracture: this approach use a Bitmap texture like fracture pattern. It is necessary to select the center of the clipping plane, the normal and the size.

These methods also allow to active a function of noise for the new faces generated while the fracture process. The utilities described above are constantly evolving and the latest fracturing methodology was not implemented Unreal Engine version 4.18, which was the latest version of the graphics engine with Blast integrated when the algorithm for fracturing was designed for this dissertation in 2019 [107, 50].

4.2 Fracture algorithm

As discussed in previous chapters, there are different methods for fracturing geometric models. Considering the importance of obtaining an accurate representation of the fracture area and the influence of the hierarchical structure of the bones on the fracture area, it is not clear which method is more appropriate for fracturing a bone model.

Therefore, taking advantage of the benefits of using a library as powerful as Blast together with extensions such as ExtPhysx or ExtAuthoring

that provide tools for the definition of physical properties in the models and manipulation of the mesh structure, it is possible to define an algorithm that combines methodologies based on the use of patterns and the use of physical properties. This makes it possible to obtain realistic-looking fractured bone models and to reproduce physical conditions that determine the final shape of the fracture. As mentioned above, the current versions have an implementation for fracturing using patterns, but UE version 4.18, on which all the experimentation was carried out, did not have this functionality, so it was decided to create a plugin to manage the entire fracturation process.

The fracture algorithm is divided into two stages: generate a prefRACTURED model through a pattern and the detachment of the pieces that make up the fractured model through the use of physics. The first step is based on the decomposition of the fractured model, described by Muller et al. [52] and Pacevi et al. [53] using patterns. To obtain the prefRACTURED model, the bone model is decomposed into 3D Voronoi regions to improve efficiency and delineate the regions forming each fracture slice after projecting the fracture pattern. The second step of the procedure focuses on establishing links between the pieces that make up a bone fracture of the fractured model with mechanical properties of real bones [51]. This stage begins by establishing a hierarchical structure between the different fragments generated in the fractured model which makes it possible to establish a relationship between the different fragments or sets of fragments. The links, with the properties of human bones, established between the fragments, determine when one piece or another becomes detached depending on the forces applied on the model.

4.2.1 PrefRACTURED model

This stage requires as a starting point a 3D bone model (Fig. 4.1) and a fracture pattern represented in a bitmap by the conclusions obtained in the previous chapter. At this point we are focusing on a macroscale simulation and we do not have to delimit the cortical area, as it happens in the microscopic studies, so we have used bone models that have been ob-

tained through a 3D scan and models that have been obtained after reconstruction from a stack of CT images. The advantages and disadvantages of each method have already been discussed in previous chapters, although at this moment it makes no difference which method is used because we only focus on the macroscale level. The bone models obtained using a manual 3D scanner have been obtained with the model Artec Eva with a point accuracy of 0.1mm and a 3d resolution of up to 0.5mm. This scanner allows to obtain a high precision through the use of structured light to obtain the points of the model. The use of Poisson surface reconstruction algorithm [112] was also necessary to close and smooth the mesh of the bone model.

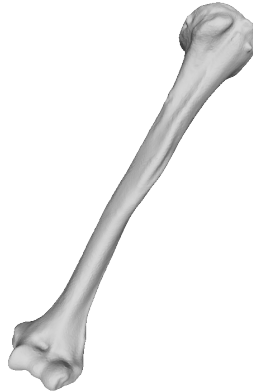


Figure 4.1: Humerus obtained from CT image segmentation.

In the previous chapter, the different approaches to represent a bone fracture pattern were described, as well as various techniques to obtain it. In this algorithm we are going to focus on the use of bitmaps because they are the simplest patterns. The projection of these patterns on the bone model is simple as it only consists of a projection on one of the aspects of the bone. However, the other representations contained 3D information

about the fracture area and the projection onto the model is not trivial and required further analysis. Even though they have not been considered in this algorithm, it will be extended in the future to include the rest of the representations. In addition, the final sections of this dissertation will also report the progress we have made in this issue.

The patterns have been obtained through a manual analysis of the fracture area after a process of mechanical experimentation with human bones described in the following chapter. Figure 4.2 summarizes the process for obtaining the bitmap representing a fracture. The first image shows a high-speed camera device for capturing the precise moment at which the fracture occurs. The second and third images in the figure represent the images captured by the cameras as well as the manual identification of the fracture area. In this way it is possible to obtain the bitmap that represents the fractured area from one of the aspects of the bone. The pattern is composed of a series of regions indicating the fracture limits seen from one of the different axes of the bone. The white region of the pattern indicates the limits of the fracture. The size of the pattern created manually must be adjusted to the size of the bone, since it is automatically adjusted to the model to be fractured when it is loaded, using the bounding box of the model, as if it is a texture. Once the pattern is loaded, the user must indicate the axis on which the pattern is to be projected and the level of detail with which the projection is to be made. The higher the level of detail set, the longer the plugin will take to generate the prefractured pattern. Since the number of patterns obtained with the simulations was limited, a few samples drawn by hand have also been used for testing.

The prefractured model is obtained via the subdivision into 3D Voronoi regions, providing a more efficient computation [52, 53], and the projection of the fracture pattern. The number of Voronoi regions generated can be parameterized as well as the pattern and allow a greater level of detail to be obtained when generating the fragments that make up the prefractured model. The algorithm is responsible for calculating all the regions that collide with the fracture pattern. In this way, we can find two types of regions, those that collide with the pattern and those that do not. The algorithm calculates the regions that collide with the fracture pattern. Thus,

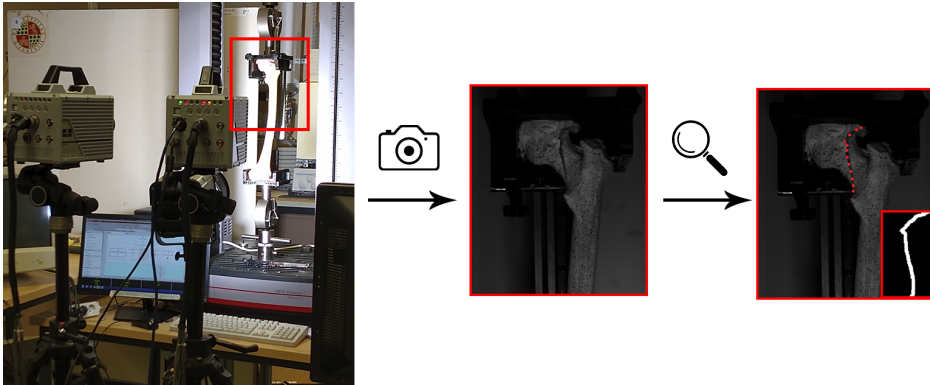


Figure 4.2: Overview of the process for obtaining a fracture pattern by mechanical experimentation. The first figure shows the camera system for capturing the fracture from one aspect of the bone. The second image represents the exact moment in which the fracture occurs while the last one represents the identification of the fracture in order to obtain the bitmap that represents it.

we can identify two types of regions: regions that collide with the pattern and regions that do not collide with the pattern. The next step is to identify which regions belong to each fragment. For this purpose, a region that makes up the input model and is not part of the fracture line is randomly selected. Each of its neighbours is studied recursively to determine the regions that make up a piece of the fracture. This process is repeated until all regions are part of a piece of the fracture. Finally, regions colliding with the fracture pattern are grouped with the nearest fracture slice using the center of the region as a reference. Therefore, a larger number of regions will result in smaller region sizes and thus a more accurate representation of the fracture area. In addition, the hierarchy between the pieces that make up the fracture and the relationships that they must have with each other at the time of detachment is also established through the study of the neighbourhood.

4.2.2 Detachment of fragments

The hierarchy between the pieces that make up the fracture is established in the last step of the previous section. The relationship between the pieces can be determined from the study of the neighbourhood of a region that coincides with the fracture pattern. Therefore, a series of properties can be established between the links of the pieces that make up the prefRACTURED model in order to detach only those that are affected by a force.

The generic features of the links established include the health of the link, which determines when a fragment is separated from another. When the health of the bonds of a fragment with its neighbours reaches a value of 0, the fragment is detached. As long as one of its neighbours maintains an unbroken link, the fragment will remain attached to the rest of the model. Figure 4.3 shows a scheme of the process of detachment of the fragments through the established links. The image on the left shows the three fragments of the prefRACTURED model linked with green lines representing link health. At the initial time, all links have full health. In the central image it can be seen how a load, a blow or a force has been produced on the original model causing a decrease in the health of the link that exists between the fragments of the neighbourhood. As the impact on the femoral head has not been strong enough, no detachment has occurred and therefore the model remains intact and united without any apparent fracture. Finally, the image on the right represents a second impact on the femoral head in which the bond is completely broken and fragment 3 is detached.

In order to determine the damage received by a link, it is necessary to establish a series of properties on the bone model to determine the resistance it opposes to the forces applied on the model as well as the way in which the forces affect the areas adjacent to the point where the impact occurs. The main parameters are the damage thresholds, which determine the detachment of a piece by the damage to the associated links, the hardness of the link against an impact, the maximum radius affected with all the damage from the point of impact and the percentage of propagation

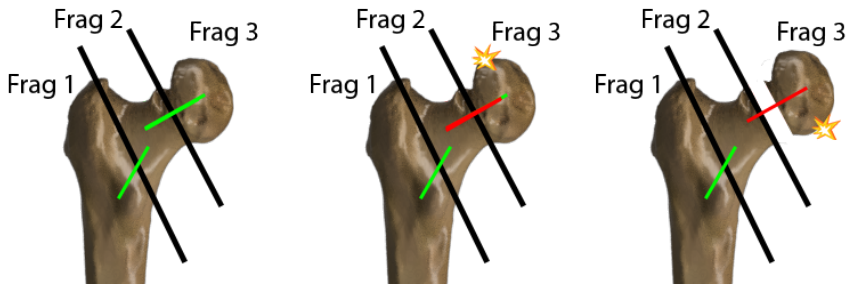


Figure 4.3: Scheme of the process in which the fragments are detached. The image on the left shows the prefractured model with the established links, the image in the center shows a collision that occurs in the femoral head and damages a link without breaking it completely and the image on the right shows a new collision with the femoral head that ends up breaking the link and producing the detachment.

according to the distance from the point of impact. The properties established are common for all the links that make up the prefractured model. All properties can be managed via the Blast extension called ExtPhysx. In the tool developed, a series of fields have been enabled so that the user can determine the value of all these parameters to adjust the tests to the case or simulation to be carried out.

The use of forces in specific areas causes damage to the links between the pieces that make up the prefractured model. When the health of the link is zero, the pieces that were linked are separated from each other. The force applied on the model is determined by the properties of the model colliding with the model to be fractured such as speed, size, collision point or direction using the UE physics system. The mitigation of impact damage to the links is managed in combination with the material properties assigned through Blast. Once a link is broken, the fragments that made up each part of the fracture break off independently and can be divided again according to the hierarchy of the prefractured model.

4.3 Results

The algorithm developed for UE 4.18 use the Blast editor and library as starting point (Fig. 4.4). The editor have a top menu with basic options related to the fracture which is common to all implemented algorithms in the Blast plugin. In this menu an option to apply basic transformations on the model to be fractured has been added that was not included in the default tool. On the left side there is a field which shows the hierarchy of the pieces that make up the fracture. Normally only one entry appears until it is prefractured. The menus on the right side contains the properties to customize for the fracturing process. These options are from general options, such as the material to be used for the new faces generated, to the properties needed for a specific method. The fracture method proposed contains the following input fields:

- A drop-down to select the axis on which the fracture must be projected.
- The pattern selector.
- A field to indicate the precision of the lines that are part of the pattern.
- A field to indicate the number of Voronoi regions to improve accuracy of the pieces that make up the fracture.

The algorithm focuses on the combination of a pattern-based and physics-based method for fracturing bone models. The examples below use two different patterns on the Y axis. Figures 4.5a and 4.5c show the projection of the fracture pattern. These patterns are projected on the Y axis of the model. As result, two fragments are obtained in each case. The use of Voronoi regions to delimit the fracture area also causes the fracture area to appear noisy and not completely flat, resulting in a much more realistic result. Figures 4.5b and 4.5d represent the prefractured model obtained with the application of the above patterns.

When the prefractured model is generated, the hierarchy between the fragments is established, as well as the assignment of properties to the

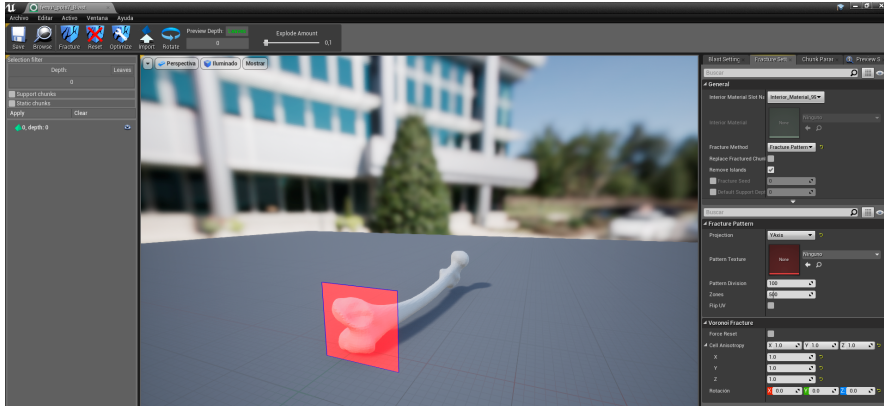


Figure 4.4: Blast editor with the algorithm integrated for the Unreal Engine.

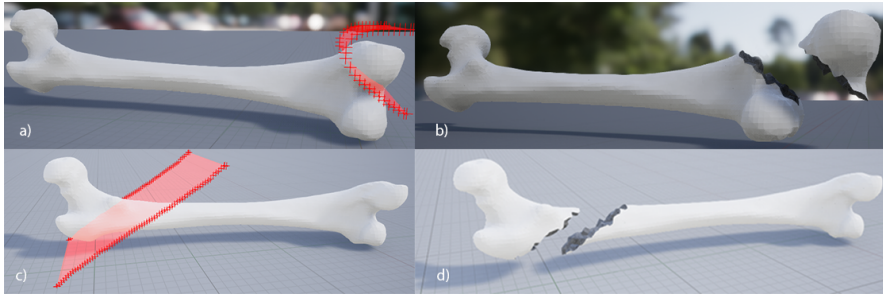


Figure 4.5: Figures a and c represent the bone prepared to be fractured with the fracture patterns already projected. Figure b and d represent the result obtained after being fractured.

links between the pieces. Figure 4.6 represents the complete process followed to fracture a bone model. Figure 4.6a shows the pattern used for the calculation of the prefactured model and establish the relationship between pieces. It is possible to identify how the prefactured model is composed of 3 pieces. Figure 4.6b shows the use of a laser that damages the links between the different fragments of the prefactured model while figure 4.6c shows the detachment of a piece. The damage used in

the simulation is constant, so depending on the health of the link and the properties set for the bonds between the fragments, a longer or shorter impact time will be required. As mentioned above, there is an associated feature that allows the propagation of the damage through the model taking as reference the point of impact. In this case, the damage has occurred in a the distal area of the bone, so only one of the links between the fragments has been broken, while the rest remain attached.

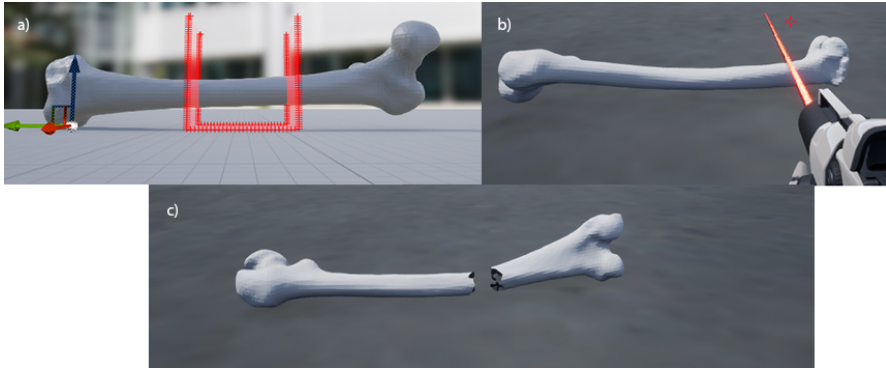


Figure 4.6: Figure a represents the projection of the fracture pattern on the model in order to obtain the prefractured model. Figure b shows the model to be fractured as well as a laser to break the links, while figure c represents the model already fractured in the area where the damage was received.

The tests have been carried out with different fracture patterns as well as manually designed with the objective of exploring the possibility of obtaining every different type of fracture that can be produced on a bone model.

4.4 Conclusions

The algorithm developed allow to obtain fractured bone model at macroscale level. The method combines the use of patterns and physics to obtain frag-

ments with a realistic appearance and to respect the process of fracture, taking into consideration the forces that are applied to the model.

The user has all the responsibility to establish adequate properties in the model as well as to use real patterns extracted through a process of experimentation.

The proposed approach projects the fracture pattern to obtain the prefractured model, but also avoids using the pattern lines as division lines between the fragments, since they would result in totally flat fracture regions by the projection on one of the aspects of bone. Thus, although they are used as a guide, the fracture area generated are not totally flat, increasing the degree of realism. The patterns employed without 3D information available on the fracture area make it impossible to obtain some types of fractures. The projection of the pattern along an axis of the model cannot reproduce the forceful rotation or twisting on a bone.

Although the patterns used are simple, several patterns could be combined into one and study how the physics affect the detachment of the fragments by comparing with real cases. The main drawback of this approach is that the bones are heterogeneous and that the distribution of the cortical and trabecular part of the bone varies from one area to another, so the properties in each area and between different bones are totally different. It would be interesting to update the algorithm so that the properties, established between the fragments of the prefractured model, are independent of each other.

In spite of not using patterns with 3D information on the fracture zone, the results look quite realistic and faithful to the patterns used. However, in the future we will work on the inclusion of the remaining representations of the patterns analysed in previous chapters and how to project them efficiently on the bone models to obtain a prefractured model with greater accuracy when representing a real case of fracture.

In the next chapter, the focus will be on showing the results of a collaborative study involving several areas of knowledge to study the repeatability of bone fractures in real human bones under similar conditions as those applied in simulations such as the one presented in this chapter.



Chapter 5

MECHANICAL EXPERIMENTATION ON BONE FRACTURING

In this chapter, an analysis of the most common fractures of the femur and a series of experiments in collaboration with members of other disciplines are carried out. The experiments performed have focused on the constitution of a process for fracturing human bones in a controlled environment through mechanical experimentation with the aim of studying the repeatability of a fracture using the whole bone. Thus, a direct relationship can be established between the way in which the fracture occurs and the type of fracture that occurs. Consequently, it can be tested whether pattern-based fracturing approaches are the most optimal in bone fracturing. Moreover, it is also expected to corroborate how the composition of the bone at the microscopic level affects during fracture growth with different fracture lines. To achieve these objectives, a precise measurement of the features of a human bone will be made, a system to perform

the fracture in a controlled environment will be defined, and the results obtained will be analysed.

5.1 Introduction

Each bone has its own characteristic areas that allow to distinguish them from each other, although they can be classified into long and short bones. As previously mentioned, we focus on long bones in this dissertation, with special emphasis on the femur, since it is the most frequently fractured bone. With the increase in life expectancy, it has become more common to find cases of hip fracture, since the slightest trauma can cause a fracture in fragile bones [20]. Over the years, bone wear and tear increases and a fracture of this type is an injury with serious consequences for the population. Smith et al. [16] analysed the factors which increase mortality after hip fracture surgery. The estimated mortality rate is between 5% and 10% in the first month and increases over the recovery period.

Even though the different types of fractures are known, the monitoring and conditions under which they occur cannot be determined with certainty. Fracturing experiments on human bones are unusual. The main handicap encountered in these studies is the difficulty to obtain human bones. Additionally, the equipment needed to perform the simulation as well as to collect the data is quite expensive. In this case, the device used for the experiment must allow the use of compressive forces on the model to simulate the weight and stress placed on the femur in a natural posture. Furthermore, an incremental load will be applied until fracture of the femur occurs.

Grassi et al. [113] focused on the measure of the strain of three femurs after being subjected to a physiological strain rate up to fracture in a configuration that simulated the natural posture of the femur. The experiments were not performed on the whole bone, in the experimental setup the bones were cut in the area of the diaphysis and placed in the fixture. Although the positioning was natural, the strength and thickness of the cortical zone of the bone varies from one part to another, so the omission

of the distal part of the bone in the experimentation increases the error of the results obtained. Feng et al. [27] concluded that bone geometry directly influences the stresses received by all parts of the bone model after performing a computational experiment with finite element analysis and tensile testing on porcine bones. Giordano et al. [114] used a similar device to study synthetic bone mechanics. These bones were fractured so the main object of study was the fixation of the bone for fracture reduction.

Bettamer [115] used a digital image correlation system to measure planar and volumetric fracture displacement. The research performed loads on eight human femurs simulating the load they receive from the weight of the body. As in the previous study, the entire bone is not employed, only the proximal end segment of the bone is used. Hambli and Allaoui [47] performed an identical experiment to compare the result obtained after the simulation of fractures in the proximal femur area with those obtained through the application of loads on 10 human bone specimens.

In addition to the problem of the difficulty in finding human bones to carry out simulations and the high cost of the devices for this purpose, the available studies are carried out only on a part of the bone without taking into consideration the complete bone specimen. Therefore, the distribution of forces and the resistance of the bone model varies from reality. In the studies previously analysed, the focus is on hip fractures, which occur in the proximal part of the femur without considering the distal part of the femur. The models used are cut in the distal area and are supported on a tool. Our simulations are performed on the entire bone.

In order to supervise a complete bone fracture in a controlled environment for future simulations, it has been carried out an original research in collaboration with the department of mechanical engineering of the University of Jaén and the Complejo Hospitalario de Jaén. Our work focuses on the study of femur fractures in the proximal end segment using the whole bone. Fractures in this area are the most typical since it is the area that connects with the pelvis and, consequently, it is the area most affected by the movements of daily life. The experiment involves several stages.

In the first stage, human bones are prepared for subsequent fracturing. The second stage consists of placing the bones in the universal material testing machine to apply a load to each femur until it fractures. Once the bone models have been fractured, the last stage begins with an analysis of the results obtained from a statistical and clinical point of view.

5.2 Fracture classification

Bone fractures follow a pattern that varies according to the conditions that produce them. AO Trauma International and Orthopaedic Trauma Association Representatives (AO/OTA) presented a compendium for the classification of fractures and dislocations [11]. Figure 5.1 represents the main types of fractures in the diaphysis of long bones. The number of pieces of bone detached, the angle and the shape of the fracture lines are the elements that allow differentiating the different types of fractures. Spiral fractures are more unusual as they are the result of a forceful rotation or twisting of the bone. Egol et al. [30] also performed a classification of fractures at the bone diaphysis area in 2010 following similar guidelines.

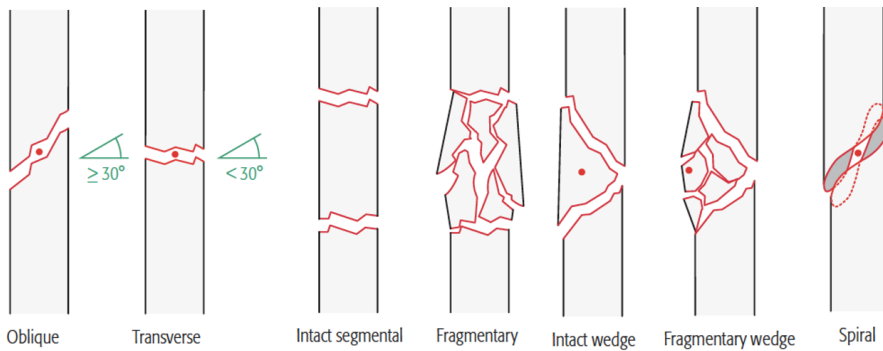


Figure 5.1: AO/OTA fracture and dislocation classification [11].

In the case of the proximal end segments, the classification of fractures depends on the bone because the morphology is different in each

one. AO/OTA describes the characteristic elements and landmarks that allow the classification of bone fractures for each bone [11]. As previously discussed, this dissertation focuses mainly on the femur so only the classification of this bone will be shown in this report. Fractures in the proximal end segment of femurs are the most typical since it is the area that connects with the pelvis and, consequently, it is the area most affected by the movements of daily life. Pauwels proposed a classification into three different types based on the angle formed by the fracture and the horizontal axis of the bone [116]. In 1961, Garden described a more comprehensive classification that incorporates displacement and fracture completeness [117]. AO/OTA [11] presented a classification in which three different regions where the fracture can occur: head, neck and trochanter (Fig. 5.2). In these regions, we can distinguish different subgroups of fractures according to the center of the fracture, the fragments that break off, the direction and the displacement. This classification is the most complete and is used as reference throughout this work. Furthermore, the physical characteristics of the proximal epiphysis of the femur allow to predict the risk for hip fractures in different populations [118]. Radiologists usually classify fractures into two major groups: intracapsular fractures and extracapsular fractures. Intracapsular fractures include the area of the neck and head of the femur while the remainder of the area is considered as extracapsular fracture.

The morphology of the long bones also varies in the distal end segment and each bone has its own landmarks [119]. However, the AO/OTA [11] establishes a unique classification in this area based on three different types: extraarticular fracture, partial articular fracture and complete articular fracture. The extraarticular fractures are those that occur in the area connecting the diaphysis with the distal end segment of the bone. The partial and complete articular fractures correspond to a detachment of a part, or complete detachment in the second case, of the bone in this area. Within these types, some subtypes are also described according to the number of fragments that are detached during the fracture and the way in which they are produced.

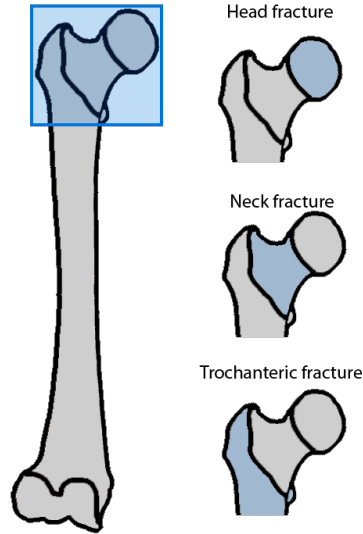


Figure 5.2: Areas of the proximal end segment where fractures result.

5.3 Bone specimens

The experiment was carried out using 8 dried human femurs obtained from the hospital of Jaén. Previous reports indicate the influence of bone geometry on the risk of fracture [27, 28, 29]. Therefore, all bones have been measured using as reference the standard anthropometry handbook definitions [120, 13] (Fig. 5.3):

1. Greatest femur length.
2. Femoral shaft length.
3. Superior transverse diameter.
4. Femoral head height.
5. Anterior femoral head and neck length.
6. Cervico-corporal angle.

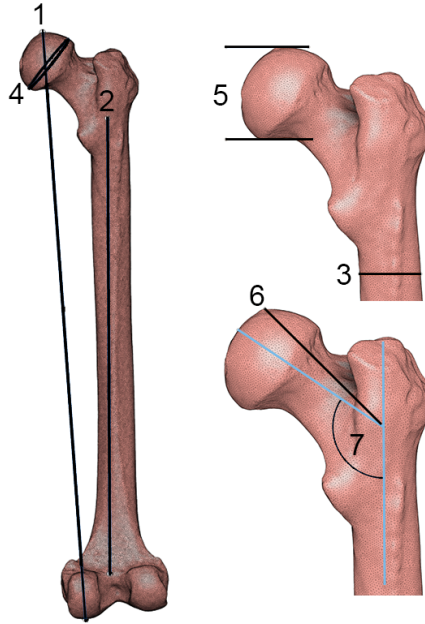


Figure 5.3: Standard measurements of the femur.

To determine the linear and angular dimensions of the parameter to be measured, it is necessary to choose some landmarks on the distal and proximal ends of each sample. Some authors have identified the landmarks for taking measurements on the bone, although they perform the measurements manually [121, 122, 13, 123]. Bone irregularities directly affect these manual measurements, so there is a slight error on them (Table 5.1). Some previous work, based on fracture reduction, also uses these landmarks to identify the different axes of the bone and align the fracture pieces [124].

Low bone mass is identified as the main cause of human bone fracture through the deterioration of the bone [125]. Traditionally, the bone mineral density (BMD) has been used to quantify the fracture risk. However, studies have shown that BMD is not the only factor contributing to bone fracture risk [1]. Burr et al. [126] divide these factors into three

Table 5.1: Comparison of manual measurements of the femurs in females and males carried out by Polguj et al. [13].

Measurements	Female			Male	
	Mean $\pm$ SD	Median	Min.-Max.	Mean $\pm$ SD	Median Min.-Max.
Greatest femur length (mm)	421,1 $\pm$ 33,7	421	359–508	456 $\pm$ 27,3	457 370–514
Femoral shaft length (mm)	328,3 $\pm$ 28,1	327	285–392	355,8 $\pm$ 26,7	352,5 289–422
Superior transverse diameter (mm)	32,5 $\pm$ 2,3	32,1	27,3–39	33,1 $\pm$ 1,9	32,7 29,4–37
Femoral head circumference (mm)	138,2 $\pm$ 10,2	140	118–156	149,3 $\pm$ 9,6	150,5 129–163
Femoral head height (mm)	40,9 $\pm$ 4,9	42,1	31–49,2	43,7 $\pm$ 4,1	44 37–51
Anterior femoral head and neck length (mm)	69,6 $\pm$ 4,1	69,1	53–78,9	71,4 $\pm$ 4,3	69,8 66,9–82
Cervico-corporal angle (°)	118,6 $\pm$ 2,9	119,5	109–126	130,3 $\pm$ 2,6	130 127–136

categories: load factors, changes in bone structure, and changes in material properties. All categories include anomalies as well as unexplained changes in properties. Therefore, all bones were also weighed using a high precision balance with an accuracy of one gram.

The measurements have been performed on a 3D representation of the models on which we carried out the mechanical experiments. For this purpose, all the bones were scanned using a high accuracy scanner (brand Artec model EVA). The accuracy of the points captured by the scanner is 0.01mm. Consequently, the measurements obtained are more accurate than the manual measurements obtained in the studies used as reference, since the irregularities of the bones do not affect the measurements. The measurements have been taken using the software Fusion 360 and following a methodology similar to the one used by Subburaj et al. [122] to determine the femur landmarks. In order to carry out the measurements, we use planes in different directions that allow us to align and measure the linear distance between the landmarks of the bone (Fig. 5.4). Table 5.2 represents all bone measurements obtained as well as bone weights measured on a high accuracy scale.

5.4 Experimental setup

The experimental phase was performed using an Instron universal materials testing machine with a load capacity of 30kN (Fig. 5.5). A square-shaped metal device has been used to hold the bone model in place on both the top and bottom of the model. The tool is indispensable as it supports us to keep the bone in a right position in which the mechanical axis of the bone is preserved, extending from the center of the femoral head to the center of the condyles that mark the direction of the body weight load of an individual in a standing position. In addition, this axis also forms an angle of 6 degrees in the proximal direction with the longitudinal axis of the diaphysis of the bone [127]. The bone placement has been supervised by experts in the field of traumatology. The device has dimensions of 9cm x 10.5cm and a depth that we have varied throughout the experimentation

Table 5.2: Measurements of the femurs on which the study was carried out.

Measurements	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 6	Femur 7	Femur 8
Greatest femur length (mm)	427,6	452,5	424,2	476,9	398	433,9	449,9	497
Femoral shaft length (mm)	333,1	354,8	335,7	367,6	322,4	330,3	357,4	395
Superior transverse diameter (mm)	27,4	28,8	27,2	31,6	24	29,1	29,3	32,6
Femoral head circumference (mm)	142,4	155,5	145,3	151	121	147,7	142	156,7
Femoral head height (mm)	41,4	43,7	40,9	44	38,4	44,5	43	42
Anterior femoral head and neck length (mm)	69	74,4	69,4	83,7	65,8	79	74,2	81,1
Cervico-corporal angle (°)	124	127,8	124,5	129,5	120,3	124,5	127,3	130,3
Weight (g)	336	384	327	325	188	303	330	392

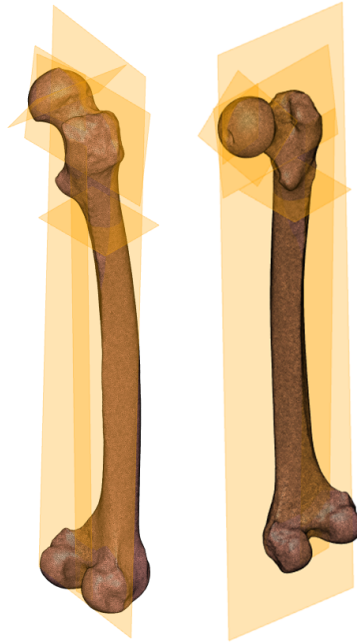


Figure 5.4: Planes to identify the landmarks for taking measurements on the bone.

between 2 and 4 centimeters to avoid the lateral contact with the bones, due to their irregularity and curvature, to be able to load the bone models in a realistic way.

Furthermore, Lucitone Fas For +, a resin for dental prostheses based on polymethyl methacrylate, has been used to prevent displacement of the bones when the load is applied and to ensure that it remains in the correct position. This resin has a greater resistance compared to other options such as bone cement or restorative putty. The resin is used on the base of the fixture and must touch the bone only in the parts in which it is in contact with other bones (pelvis in the proximal area and knee in the distal area). Figures 5.6 and 5.7 show how the resin is built up on the head of the femur just at the area where the bone connects to the hip so that the machine can simulate the weight load in the appropriate area.



Figure 5.5: Universal machine for testing materials used with the fixture in which the bone is placed in the experiment.

The resin used solidifies after a couple of minutes, so it is vital to keep the bone immobile, until the resin hardens. Therefore, we have designed and printed, using a 3D printer, a replica of the fixture we use in the materials testing machine, and a clamp arm to hold the bone in its right position (Fig. 5.7). This procedure has been supervised by a traumatologist.

In addition to the material testing machine, a 3D Digital Image Correlation system with two monochrome 5 megapixel CCD (Charge-Coupled Device) cameras (brand Allied Vision Technologies, model Stingray F-504 B/C) were employed. The cameras were synchronised and monitored



Figure 5.6: Proximal end segment of a femur with solidified resin in the femoral head.

from a laptop connected to a DAQ (Data Acquisition System) and a halogen light (brand Hedler, model DX15, 150W) to illuminate the specimen. The stereoscopic system was mounted on a tripod and subsequently calibrated. Finally, the displacement fields occurring at the specimen surface during loading and unloading stages were measured using the commercial software package VIC-3D, from Correlated Solutions Inc. [128, 129, 130]. In order to improve the visualization of the fracture as well as acquire better information about the growth of the fracture, white spray paint has been used on the area of the proximal epiphysis and distal epiphysis. At this point, we have all the components ready to carry out the loading on the bones and collect the data to analyse the fracture produced on the bones. Additional to monitoring the experiment, the system has also allow us to identify the exact moment of fracture to obtain the patterns described in previous chapters.



Figure 5.7: Femur placed on the 3D printing tool held by the clamp and resin in the areas that connect with the hip and knee.

To analyse the results of fractures, we used a scanner (brand GE Medical Systems model BrightSpeed) to scan the fragments generated and a combination of the Paulano et al. [4] algorithm and 3DSlicer [36] to segment the fragments and obtain a 3D digital representation of the bones. This scanner used has a higher resolution than the scanner used before fracturing the models. This is due to the need to capture the fracture area with the maximum level of detail. Finally, we also used the CAD soft-



Figure 5.8: Camera system designed to capture the displacements resulting from the load applied to the human bone.

ware developed by Autodesk, Fusion360, for taking take all the reference measurements for the study.

5.5 Results

In this section the results obtained after fracturing all the bones are shown and analysed. Seven bones were fractured in the device described in the previous section. Bone number 8 had very large longitudinal dimensions, making it impossible to place it in the device for fracturing. Table 5.3 shows shows the fractured area of the bone in each case.

The bone arrangement was natural and validated by an expert at the time the resin was used to fix the position of the bone. Once the resin had dried, the bones were placed in the device described above to apply compressive forces simulating the weight bearing of a person when standing upright. Once fractured, the results were analysed by a committee of experts and from a mechanical perspective.

Table 5.3: Measurements of the femurs on which the study was carried out.

Number of sample	Area of fracture
1	Neck
2	Distal
3	Neck
4	Trochanter
5	Neck
6	Neck
7	Neck
8	-

5.5.1 Expert analysis

Femur 1,3,5,6 and 7 were fractured in the neck area. The shape of the fracture is similar in all these experiments due to the fact that the fracture goes from the neck area, very close to the area in which the femoral head begins, to the area of the lesser trochanter. It is important to note that in all cases two fragments have been generated. One fragment is the head of the femur and the second fragment is smaller and formed by a small part of the femoral neck up to the area of the lower trochanter. On the other hand, femur number four was fractured in the trochanter area near the neck of the bone. In this experiment only one fragment was generated. Figure 5.9 represents the fracture of this bone in which figure 5.9.a shows a rendering of the bone before the fracture, figure 5.9.b shows a rendering of the fractured bone with the fragment that has been generated, with a high level of detail over the fracture zone, and figure 5.9.c shows a photograph of the fractured bone after the experiment was performed.

The experiment on femur 2 had different results from the previous ones. Figure 5.10 shows the fracture on the distal region. The fracture line begins at the distal bone and extends to near the medial condyle, the lower extremity of femur. Looking at the measurements taken on the bone, the bone (table 5.3) has very similar dimensions to those of specimen number 7. However, the circumference of the head circumference and the weight



Figure 5.9: Image a represents the render of a femur before the experiment, b the render of the fractured femur and c the fractured bone obtained after the experiment.

of the femur is considerably higher than the specimen number 7. In fact, these measurements are even higher than the other bones. Since we do not know the antecedents of the individuals to whom the bones belonged, we assume that the difference in weight is determined by a greater bone density, for being from a younger individual, as well as a better bone conservation. Thus, in the experiment, the bone fractured in the weakest area which corresponded to the distal area since the area of the epiphysis was in very good condition.

Femur number 4 has larger dimensions than the rest of the bones in all aspects. However, the weight is similar to most of the specimens, so we can deduce that the bone density of the bone is lower. Therefore, the fracture obtained as a result varies slightly in the area where it occurs, being in the area that connects the neck of the bone with the trochanter and generating a single fragment.

5.5.2 Mechanical analysis

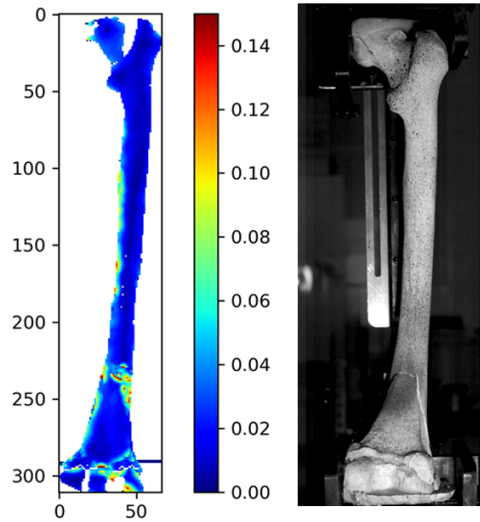
The previous assessment is consistent with several phenomena that we have found by analysing the results from a mechanical perspective. In order to analyse the results and evaluate the deformation under the forces, a series of heat maps have been generated showing the maximum unit



Figure 5.10: Femur fractured in the distal end segment.

deformation up to the moment of fracture. Figure 5.11 shows the deformation for bones 2 and 6. In bone 2, the only case where a fracture occurs in the distal end segment, it can be seen that the neck of the femur suffers a very slight deformation and that the area most affected by the load is the distal area and the condyles coinciding with the area where the fracture occurred (Fig. 5.10). However, bone 6 shows how the deformation occurs directly in the area of the femoral neck and trochanter resulting in two fragments at the time of fracture. Moreover, the figure also shows some deformation of the diaphysis of the bone. This occurs in all case studies confirming that the initial arrangement of the bone in the device was correct and how the bone was resisting the force applied by the device. The repeatability of the deformation of the bone models is also observed, since in most cases the maximum deformation is between 0.05 and 0.15 mm.

Bone 2



Bone 6

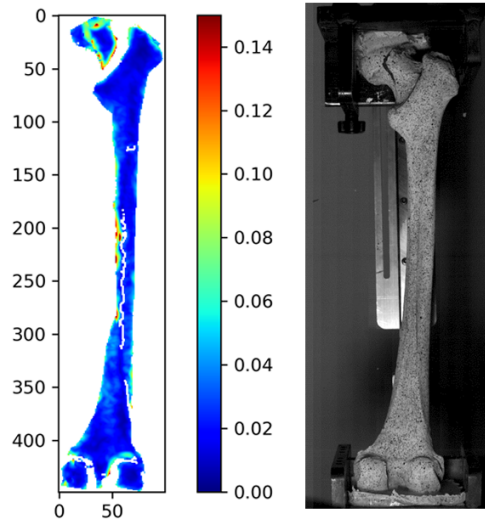


Figure 5.11: Heat map with maximum historical deformation.

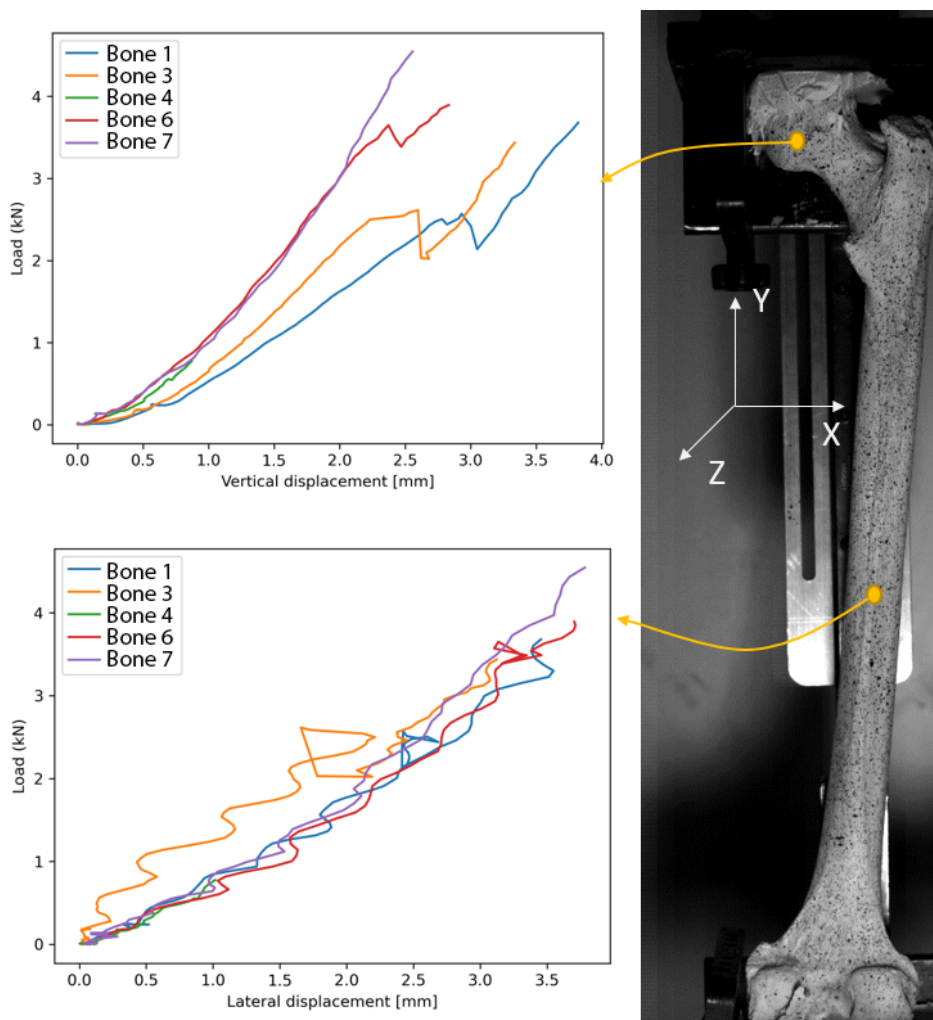


Figure 5.12: Load-displacement curves. The upper image shows the compressive stiffness in the Y axis while the lower figure shows the bending stiffness in the X and Z axes.

A study has also been carried out on the relationship between load and bone displacement in the head area and in the diaphysis area. Figure 5.12 shows the compressive stiffness in the Y axis and the bending stiffness in

the X and Z axes. As conclusions from the graphs, it can be determined that the compression on the Y-axis is not linear, at least initially. Although it has a tendency to become linear as the load increases. Most of the cases of fracture occur after applying a load greater than 2kN, although in the case of bone 4 it can be observed that the fracture occurs much earlier and with a smaller deformation (1kN and 1mm of displacement). This case was the only one that occurred directly over the trochanter area at the proximal end segment of the bone.

In terms of the flexion that is produced in the X and Z axes on the bones, a linear and similar flexion can be observed in all the cases. Moreover, certain perturbations appear which indicate that the model was not completely fixed and was subjected to a certain vibration. The force curve (Fig. 5.13) and the displacement curves (Fig. 5.14) individually show that the only axis on which the disturbances appear is the Z-axis, so it can be deduced that the disturbances in the load-displacement graph are due to vibrations of the device itself when the experiment is being carried out.

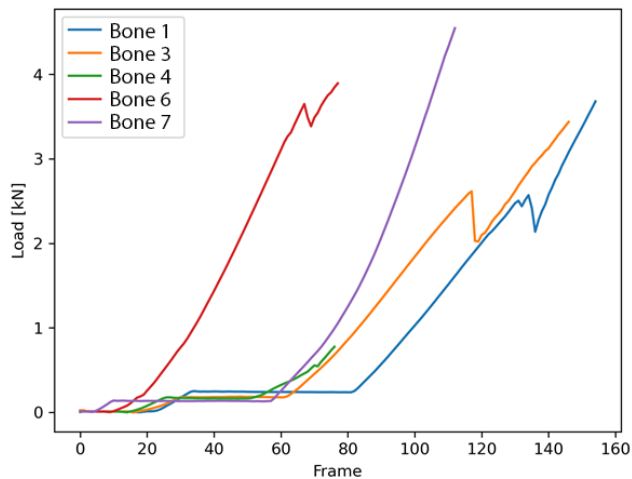


Figure 5.13: Load curves.

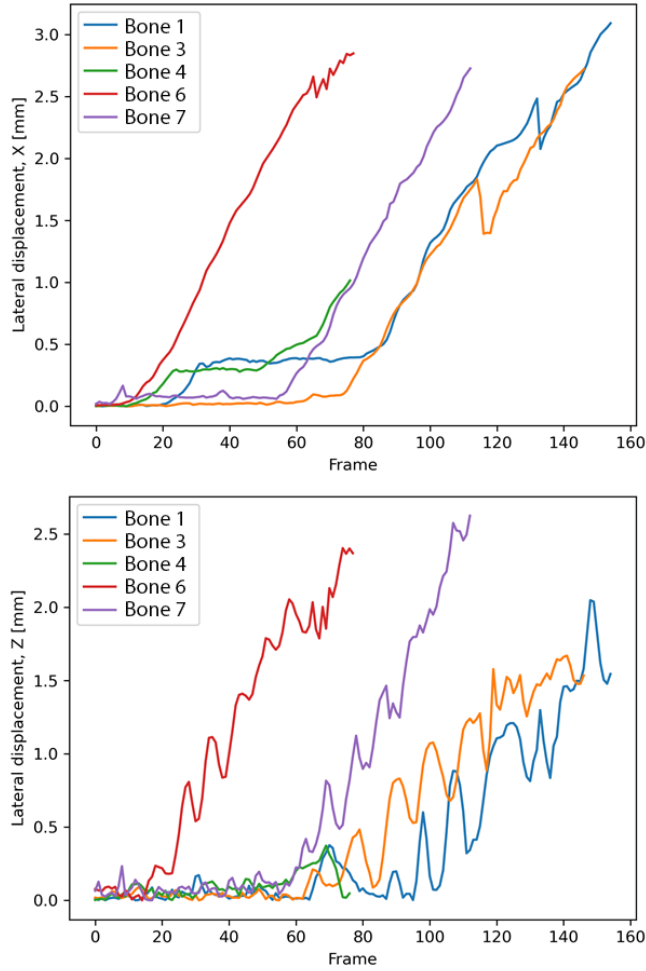


Figure 5.14: Displacement curves in the X and Z axes.

5.6 Conclusions

In 72% of the study cases, the fracture occurred in the femoral head while 14% occurred in the trochanter. All cases occurred in the proximal area of the bone except one case in which the fracture occurred in the distal area.

After analysing the results obtained in the experiment, it can be concluded that a fracture pattern can be repeated within a controlled environment as long as the characteristics and condition of the bones are similar as they have a direct influence on the results of the experiment.

Bone dimensions and bone density are the parameters that have had the greatest influence in determining the type of fracture, for its outliers, confirming the studies of other authors discussed above in which they indicate these parameters like the principal factors to determinate the risk of a fracture.

The use of fracture patterns as a means of obtaining fractured bone appearance is an area that can be further explored as it has been shown that in a controlled environment, where the conditions of a fracture are replicated, the area over which the fracture occurs is replicated. Therefore, although bones are heterogeneous with different properties and dimensions, it can be confirmed that patterns can be extrapolated between different bone models to perform simulations as long as they are applied or performed on the same area of the bone. Thus, a new avenue is opened to perform more in-depth studies on the fracture area and how to extrapolate these areas to new models.

The information obtained about the deformation of the bone models and the fracture lines (initiation, propagation, etc) allow us to perform more accurate simulations and improve the interaction of the algorithms proposed throughout this research as well as the detection of the key features in order to classify and compare the fractures with each other.

Moreover, the fracture lines have different shapes, although they occur over the same area, which reinforces the theory of previous microscopic studies concluding that the characteristics of the tissue over which a fracture propagates are fundamental in determining the path that a fracture follows in its growth.

At this point, the next chapters will focus on bone modelling and fracturing from a microscopic point of view.

BONE MODELLING AT MICROSCOPIC LEVEL

This chapter focus on the development of an algorithm for the representation of cortical bone tissue [131, 132]. The study performed and the model starts with the identification of the main structures that compose the bone tissue at the microscopic level. Once the characteristics have been analysed, the features to be considered are selected and used to carry out the representation. The representation is carried out using a procedural algorithm which includes the complete process from the representation of a complete bone to the representation of all the structures that make up the tissue at microscopic level.

6.1 Introduction

As we have seen in the previous chapters, there are several techniques that allow the representation of complete bone models at the macroscale level. These techniques are based on the use of 3D scanning and tomography

with subsequent segmentation. Regarding the techniques for bone tissue representation at the microscopic level, the only methods available are based on FEM in which manually segmented images of the bone tissue are used (Fig. 6.1). The main problems with these representations are that they are models representing a very small region of the tissue, so large variations are observed between the microstructures that make up the cortical bone, and the studies are performed on few images due to the difficulty in obtaining them. With an optical microscope, a large number of structures can be observed with a great variability in size from one to another (Fig. 6.2). Comparing figures 6.2a and 6.2b we can observe the variations in terms of number of microstructures and size when we focus on a small region of bone tissue, being x20 zoom more commonly used to obtain images of bone tissue for further study (Fig. 6.2b).

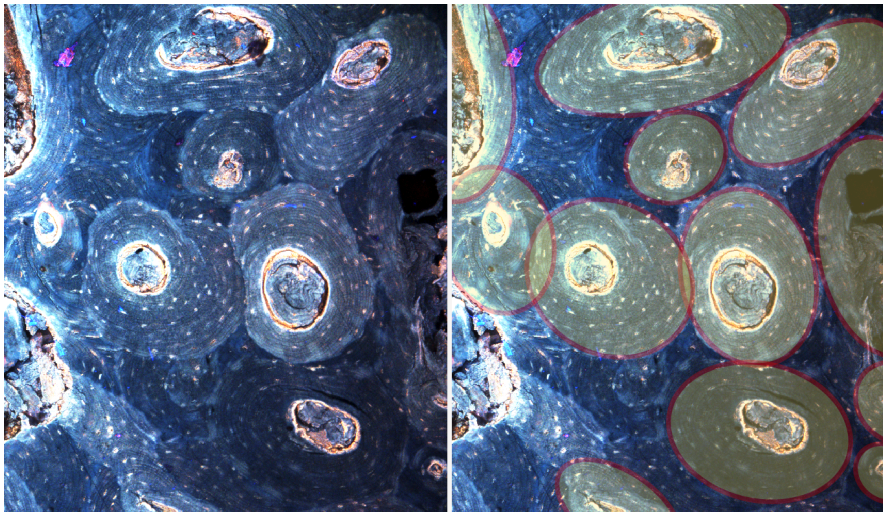


Figure 6.1: Manual segmentation of cortical tissue in which osteons are delimited.

The missing longitudinal information on the microstructures and the absence of mechanisms for their validation makes the proposal to be based on a 2D representation model. This does not imply that the model cannot be extended to obtain a three dimensional representation of the

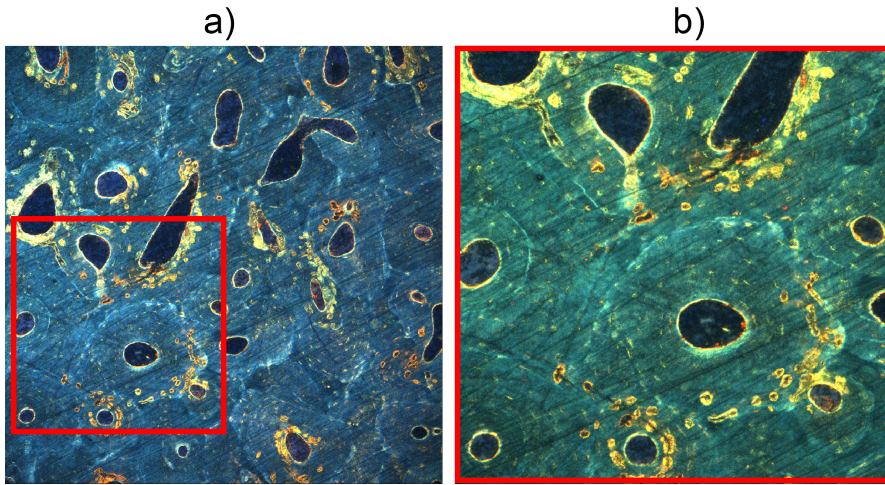


Figure 6.2: Images of cortical tissue of a bone using an optical microscope. Figure a shows the tissue at a zoom of x10 while figure b shows the more specific area at a zoom of x20.

cortical bone tissue in the future. The nomenclature, abbreviations and parameters follow the recommendations of the American Society for Bone and Mineral Research (ASBMR) [133].

As previously mentioned, this dissertation focuses on the study of the cortical bone, the compact bone. Figure 2.3 shows the main bone microstructures that make up the cortical tissue and have been taken into consideration in the modelling phase. The algorithm developed employs the tissue volume (TV), or area of interest, as a baseline. This area represents the region cortical of the bone in which the different microstructures are to be generated. Figure 6.5 represents the selection of a specific area of the cortical bone through a plane simulating a flat cut on a real bone (Fig. 6.3a).

Analysing the cortical tissue with an optical microscope (Fig. 6.3b and Fig. 6.3c), a large number of osteons (N.On) can be observed (Fig. 6.2). Osteons are the main structures that form the cortical bone. The density of the osteons (On.Dn) represents a relationship between the mass and

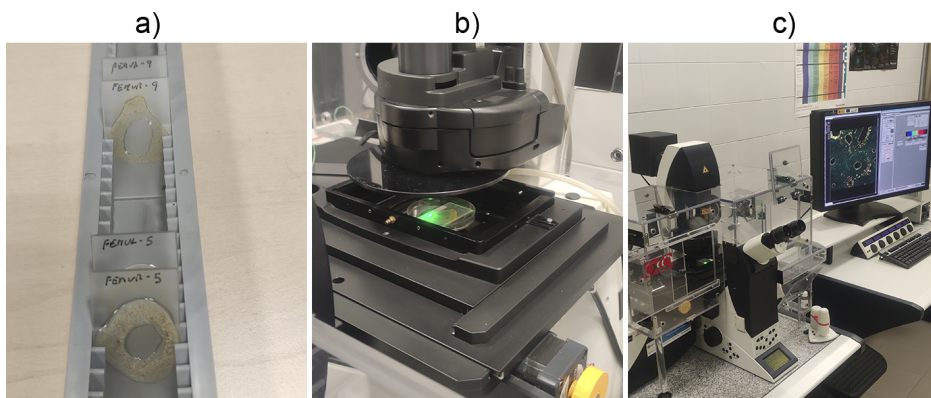


Figure 6.3: Stages for microscope imaging of cortical bone. Image a represents horizontal slices of the cortical area of a bone, b shows the laser light illuminating a small area of the bone and the lens which captures the image and c shows a general view of the optical microscope with the computer that renders the image.

volume of all osteons in a region of interest. The values of the area that a single osteon occupies (s.On.Ar) is mainly delimited by the maximum (Max.On.Dm) and minimum (Min.On.Dm) diameter while the osteonal area (On.Ar) is made up of the sum of the areas of all the osteons in a specific area. The osteons are separated from each other and are delimited through the cement line. This line coincides with the last of the concentric layers that surround a central cavity of an osteon. The central cavity is known as the Haversian Canal and its area (s.H.Ar) is taken into consideration to measure the porosity (Po). The number of smaller pores (N.Po) also need to be considered to measure the porosity. Lacunae are small cavities that are found mainly between the lamellae that form the osteon and their area can also be measured (s.Lc.Ar).

There are some parameters of general character in the zone evaluated like the bone volume (BV) which represents the density of the cortical volume, that is, the difference between the total volume of the zone evaluated and the volume that the pores occupy in this area. The bone volume fraction (BV/TV) indicates the fraction of a volume of interest that is oc-

cupied by mineralized bone.

As discussed above, these parameters are usually measured on 2D images and are determined by absolute measurements. The procedural algorithm proposed in this dissertation use some of these measures as input for the cortical bone modelling algorithm and deducts other absolute measures based on these inputs. Figure 6.4 represents a scheme of the procedure for the modelling of the cortical tissue.

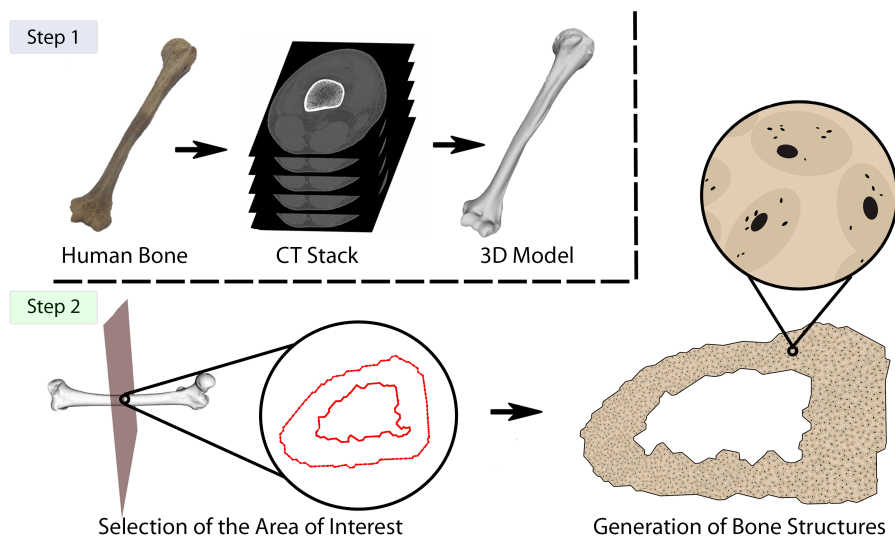


Figure 6.4: Scheme for the representation of cortical tissue at the microscopic level. The first stage focuses on the preparation of the 3D bone model while the second stage focuses on the selection of a specific area and the procedural generation of the microstructures.

6.2 Area of interest

The proposed model has two different input methods for determining the TV parameter: manually or selecting a region of a bone model. The first

option consist of generating a square with the specified area. The boundaries of the square delimit the area in which the microstructures are generated in a procedural approach, controlling the quantity and dimensions of the structures in order to ensure that all the parameters previously mentioned are consistent. The second method involves the segmentation of a bone through a stack of CT images to obtain the geometric model and the selection of a specific area of a bone through a freely oriented cutting plane. This option, although it is more expensive in terms of time, allows us to delimit an area of interest of a real bone through a plane with a high level of detail, preserving the irregularities of the inner and outer perimeter that make up the cortical area. The other options to obtain a 3D model of the bone cannot be performed since we need to delimit the internal area of the bone to have the representation of the cortical area of the whole model [131]. In the following subsection a method is defined for obtaining the area of interest of a bone model.

6.2.1 Model segmentation

As a starting point it is necessary to obtain a virtual representation of a bone model. The techniques discussed in previous chapters can be used for this purpose. In this case, a triangle mesh representation of the model will be used and the mesh will be obtained from CT scanner images. In contrast to simulations performed at the macroscale level, to represent and cortical tissue it is necessary to delimit the cortical area. Therefore, models reconstructed using traditional 3D scanning techniques cannot be used because they do not allow to delimit the inner border of the cortical bone.

The CT scans used have been obtained from the Complejo Hospitalario de Jaén. The condition of the original bone conditions the algorithm used to reconstruct it. Most algorithms can reconstruct bones made up of a single fragment using a simple procedure. 3D Slicer [36] has been used in these cases as it is the most powerful platform for the analysis and visualization of medical images and includes several algorithms for image segmentation. However, it is not always possible to have a complete bone

to scan, it is easier to obtain medical images of clinical cases in which a bone fracture, with several fragments, is usually present. In these reconstruction cases, the previous tool does not work as well, so it is better to use other techniques such as the one proposed by Paulano et al. [4]. Figure 3.2 shows an overview of the segmentation process from real bone to the 3D model in which the reconstruction of a complete humerus and a fibula composed of two fragments is shown.

6.2.2 Area selection

The geometrical model obtained after segmentation allows us to select the area of interest of the bone using a plane. The area of contact between the plane and the mesh of the bone model delimits the cortical bone (Fig. 6.6). This process makes it possible to go from a 3D model to operating in two dimensions, allowing subsequent comparison with the studies of the specialists who work in the same dimension. The plane can be adjusted manually, allowing displacement along the longitudinal axis of the bone. The longitudinal axis of the bone is obtained through the calculation of the center of mass of the model at different points along the entire model. Bones have a certain curvature so only considering any two points in the model can cause some imprecision and considerable variation for the other two points. The longitudinal axis is determined using the centre of mass of the whole model as the first point and the average value of the centre of mass calculated at the other points along the model (Fig. 6.5). A higher number of measured values for the calculation of the longitudinal axis will result in a more accurate estimate. As it is not a 3D representation, and an approximation is enough to move the plane through the model, four cuts have been made along the model: one at each end and another two between the ends and the centre of the model. Alternative methods can be used, but in order to use it only to move the cutting plane, it provides us with speed in its calculation.

An algorithm of the VTK library [134] was used to obtain the point cloud representing the collision between the bone model and the plane. This algorithm trims a geometric model using the implicit function of a

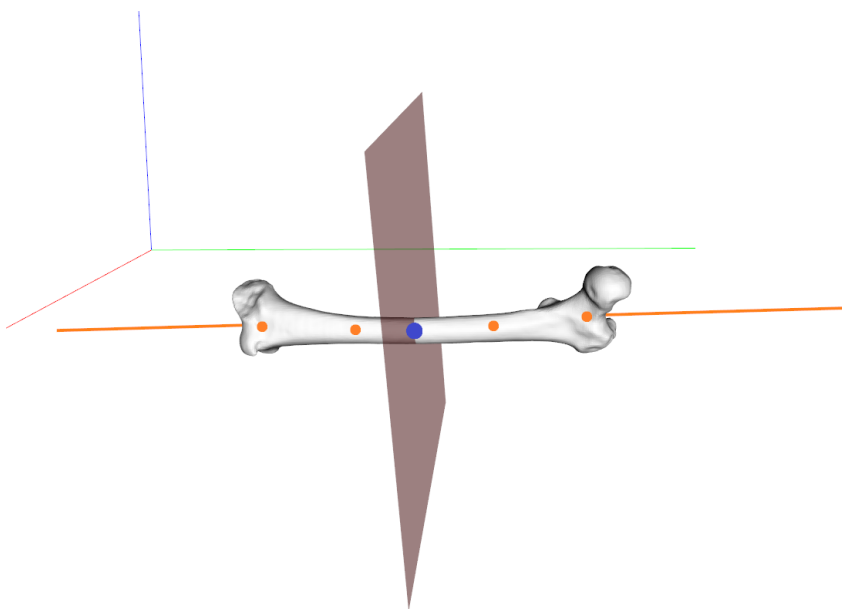


Figure 6.5: Bone model with the longitudinal axis calculated through the intermediate points.

plane. The algorithm reduces the dimension from 3D to 2D when trimming the faces of the models. The point cloud obtained represents the intersection zone between the plane and the triangle mesh representing the bone model. Thus, the cloud obtained can be analysed to establish the internal and external perimeter of the cortical part of the bone for the generation of the microstructures.

6.2.3 Boundaries

This subsection focuses on the classification of the cloud points obtained in the previous subsection to delimit the internal and external perimeter of the cortical bone. As mentioned above, it is necessary to consider the condition of the bone and the area when delimiting the cortical zone. Although the input models come from already fractured models, the areas

that have not been affected by the fracture are delimited like any healthy bone. If the area selected for generation corresponded to a fractured region, it must be taken into consideration that the cloud of points generated in the previous step would form part of a single line to delimit the cortical zone (Fig. 6.6b).

In a previous study [131] an algorithm for the selection of the cortical zone through a 3D model was described. This algorithm used the alpha shapes algorithm to establish the internal and external boundaries of the cortical bone. This algorithm is a generalization of the convex envelope and can be derived from the Delaunay triangulation. A parameter called alpha is used to determine the level of detail. Multiple regions can be determined by varying the alpha. Therefore, the algorithm starts from the average distance between the points and reduces the value of the alpha through continuous iterations. When the algorithm detects multiple regions, the points that generated the region of the previous iteration together with the values close to those points form the outer part of the bone while the rest form the inner boundary of the bone. Once it is known which part of the points cloud belongs to each boundary, the contour is generated by joining the points closest to each other and avoiding possible crossing between the different edges that form it (Fig. 6.6). In the case of fractured areas, the entire cloud is considered as part of the contour that delimits the cortical bone and the proximity between the points that form it is used as a criterion.

The internal and external boundaries of the cortical bone allows us to calculate the TV parameter through Gauss's area formula [135], which calculates the area of irregular polygons. Therefore, the outer and inner area of the cortical part of the bone is calculated and subtracted to determine the area between both limits. In fractured zones, no subtraction is necessary as there is only one region. The Gauss's area formula is as follows:

$$A = \frac{1}{2} \left| \sum_{i=1}^n \det \begin{bmatrix} x_i & x_{i+1} \\ y_i & y_{i+1} \end{bmatrix} \right|$$

The formula consists of the following elements:

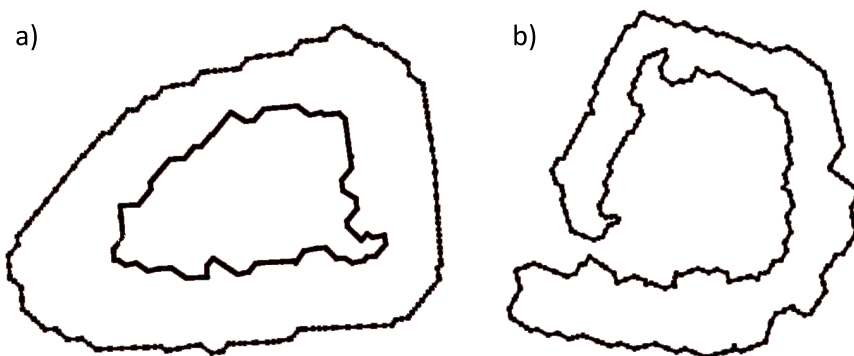


Figure 6.6: Area of interest obtained after the intersection between a plane and a bone model. Figure a represents the area in a healthy bone while figure b shows the result of performing it on an area in which there is a fracture.

- A is the area of the polygon,
- n is the number of vertices of the polygon,
- $x_i, y_i, i = 1, 2, \text{etc}, n$ are the Cartesian coordinates of vertices, and +1 or -1 define next or previous vertex from i vertex.

6.3 Estimated and input parameters

In addition to the cortical area of the bone, it is necessary to use some estimated parameters obtained from the literature. These parameters have been determined from studies which analyse the microstructural characteristics of the bones. Although this chapter focuses on cortical tissue modelling, it is possible to add new parameters and expand it. In this section the dimensions of osteons and cavities of the tissue are analysed, while the shape and arrangement of these microstructures will be analysed in the following sections.

Osteons are the main microstructures that make up the cortical bone. The acceptance that osteons have a circular shape is well known in the

scientific community. There are several studies that focus on the influence of different parameters on osteon geometry, such as the sex or the age, and determines that the average diameter of an osteon (On.Dm) is around $220\mu m$ with a standard deviation of $16.171\mu m$ [71, 25, 136]. These studies also reveal a minimum and maximum diameter On.Dm ranged from $155\mu m$ to $325\mu m$. With this data and the premise that the osteons are round, the area of an osteon can be determined. In the center of the osteons there are cavities known as Haversian canals, with a diameter between $30\mu m$ and $50\mu m$ [137, 84], and some transverse canals which connect the Haversian canals among them known as Volkmann canals. Lacunae are cavities of a smaller size with a diameter ranged from $5.16\mu m$ to $12.82\mu m$ that are connected through small canals called canaliculi [25, 26, 137]. As in the above case, knowing its diameter and that its circular shape is accepted by the community, the area of these cavities can also be obtained. There is a certain division in the studies about the porosity studies in determining whether to consider the lacunae and canaliculi for measurements. Thus, the canaliculi have not been taken into account in the model generated because they are too small.

The model generator sets constant parameters for the diameter of these microstructures, based on the average measures and the standard deviation obtained from the literature. The resulting values of the generator are random and determined by the mean value and a normal distribution over a range of values with maximum and minimum value restrictions.

The input parameters combined with the estimated parameters enable us to complete the data required to calculate the remaining parameters of interest for the generation of the microstructures that make up the cortical tissue. The osteonal density is the main input parameter. This parameter establishes a relationship between the mass and volume of all osteons in the area in which the bone structure will be generated. The porosity percentage is another necessary parameter for the generator and it is used as an input for the porosity representation of the model. Porosity is an optional input parameter since the computation time for model generation increases and in fracturing studies it would be further increased by the increase of the generated geometry and the higher number of calculations

to fracture the model.

Studies such as that conducted by Demirtas et al. [5, 6] serve as reference to introduce these parameters and compare the results obtained through image analysis and the features calculated from our simulated models. The model generator could be modified to include a larger number of input parameters or turn the estimated parameters into inputs, to expand the versatility of the model generated.

6.4 Computed parameters

In this section we analyse the calculated parameters for the generated model obtained through the input and estimated parameters described in the previous sections. The main characteristic parameters of cortical bone tissue have been identified, after analysing the studies of the reference experts in the area, such as Gibson or Ural [138, 139]. These parameters allow to represent the bony microstructures on the chosen area preserving the real properties of the cortical bone. Table 6.1 contains the calculated parameters that the bone tissue generator must consider, as well as the formulas to calculate them.

Table 6.1: Calculated parameters.

Parameter	Formula
Number of Osteons (#)	$On.Dn = N.On/TV \rightarrow N.On = On.Dn \cdot TV$
Area of a osteon ($mm^2 \cdot 10^{-3}$)	$s.On.Ar = \pi \cdot (On.Dm/2)^2$
Area of a Haversian canal ($mm^2 \cdot 10^{-3}$)	$s.H.Ar = \pi \cdot (H.Dm/2)^2$
Area of a lacuna ($mm^2 \cdot 10^{-6}$)	$s.Lc.Ar = \pi \cdot (Lc.Dm/2)^2$
Bone volume (mm^2)	$BV = TV - (\sum s.H.Ar + \sum s.Lc.Ar)$
Porosity (%)	$Po = (\sum s.H.Ar + \sum s.Lc.Ar)/TV$
Bone volume fraction (%)	BV/TV
Osteonal area (%)	$\sum s.On.Ar/TV$

The parameters listed in the previous sections enable the calculation of all the characteristics listed in the table (Table 6.1). The number of osteons to be generated in the model generator can be determined by isolating the variable in the osteonal density formula. The area of the osteons

is determined by the formula of the circle because the generator is based on the premise, accepted by the scientific community, that the osteons have a round shape. The model use a random value of diameter, following a normal distribution, within the ranges seen in previous sections. The Haversian canals area and lacunae area are calculated in the same way. Bone volume refers to the cortical volume density without taking into account the porosity. Therefore, it is calculated using the area of interest and discounts the area of the pores. Porosity is calculated as the proportion of the area of all pores to the area of interest. The bone volume fraction formula indicates the proportion of volume of interest that is occupied by mineralized bone. The sum of the area of all the osteons in the model forms to the osteonal area. Although the model is based on these calculations, new parameters could be included or those proposed could be reformulated in order to be improved in the future.

6.5 Geometric representation and distribution

The area of interest or TV is represented by two polylines that conform the outer and inner boundaries of the cortical bone (Fig. 6.6). This lines delimit the area in which the microstructures are generated. The geometrical shape of the microstructures follows the guidelines of the literature reviewed in the last sections while their arrangement along the cortical area has been represented using a grid. The grid divides the area of interest into a set of cells in order to speed up access to the information by storing the information about the microstructures. These cells are also divided into a smaller subset of cells which allows a more precise representation of the limits of the generated bone structures in order to avoid unwanted overlapping between them. Before the generation of the osseous microstructures, the cells are classified according to whether they are completely inside the area of interest or are boundary. The larger grid stores the osteons and pores while the smaller grid is used primarily to handle intersections and limits. Thus, the combination of both data structures provides fast access to information and improved accuracy of repre-

sentation. The algorithm allows small intersections between osteons, simulating the remodelling process in which the old osteons partially overlap with the new ones [140, 141, 142, 143], although this process is not taken into consideration when the osteons are distributed in the model. Through the calculated parameters the number of osteons and pores in the model can be deducted. The generator distributes the osteons randomly in the area of interest following the pattern achieved by Gao et al. [7]. Every single osteon is generated, its Haversian canal and lacunae are generated. In a subsequent step, the remaining pores outside these microstructures are generated given rise to the porosity of the interstitial bone which are cortical bone areas without osteons.

Some authors assume that osteons have a perfectly circular shape [144, 145]. Britz et al. [71] suggest that osteons are elliptical in shape, but smaller and more circular in cross section as the bone ages without distinction of gender. However, the study conducted by Henning et al. [72] shows that if osteons become smaller and more circular with age, their orientation should also change and become more longitudinal in cross section, so there is no significant relationship between age and orientation. Thus, it is not appropriate to use the cylinder representation for the osteons because the shape of them are more closely related to the shape of an ellipse. It should also be noted that some osteons have a certain irregular shape. This implies that some of the measurements have a small margin of error. Thus, in order to approach a realistic representation it has been considered that osteons tend to have an elliptical rather than circular shape. Although the use of the average radius of an osteon is not entirely correct, it is the most common data in the literature and the one we have used as reference for the generation of the osteons. The radius of the osteons is established through a random value, following a normal distribution, within the limits of the articles used as reference. Once the osteon is created with a circular shape and a determined radius, it is transformed into an ellipse. The circularity of the osteons is defined by a random variation (v) between 150% and 200% into the major (a) and minor (b) radius forming the ellipse. The following formulas have been used to generate the points(x, y) of the ellipse that make up the cement

line, the outer boundary, of an osteon:

$$s.On.Ar \text{ with circular shape} = \pi \cdot (On.Dm/2)^2$$

$$s.On.Ar \text{ with elliptical shape} = \pi \cdot a \cdot b$$

$$s.On.Ar/\pi = a \cdot b$$

$$a = v \cdot b$$

$$b = \sqrt{s.On.Ar/\pi^2}$$

$$x = center.x + a \cdot \cos(\alpha); y = center.y + b \cdot \sin(\alpha)$$

The Haversian Canals are in the center of the osteons. The size of these cavities varies greatly according to different aspects such as age or sex, although what causes the greatest difference in the sizes of the cavities is the remodelling process [142, 143]. The proposed model of representation does not consider it and the size of these microstructures has been established according to the literature reviewed in previous sections. The size of the canal is proportional to the size of the osteon. About its distribution, Morales et al. [146] performed an analysis of the Haversian canals that concluded that the canals are located in the central zone of the osteons and have an oval shape. The proposed model represents them as ellipses and takes, as the central point of the channel, a random point near the center of the osteon with a maximum distance of 35% with respect to the minimum distance between the center of the osteon and the cement line. This is due to the fact that canals are in the central area but not necessarily in the center of the osteon.

When measuring porosity, in addition to the Haversian canals, it is also necessary to take into account the lacunae and the canaliculi. The lacunae inside the osteons are located between the lamellae and are elliptical in shape with a diameter between $5.16\mu m$ and $12.82\mu m$ [147, 137]. The canaliculi that connect the lacunae are very small, around $10nm$ of diameter, so they have not been taken into consideration to represent the cortical bone. The size and circularity of the lacunae is defined randomly in the same way as the osteons. It is important to highlight that an osteon

is a structure which is composed of a series of 20 to 30 concentric lamellae [148] that surround the Haversian canal. The lacunae generated within the osteons are created in the limits of the lamellae so they are always between two lamellae, as the morphology of an osteon indicates. Although the lamellas are not represented, an approximation of the limits of each one is calculated using the projection of the boundaries of the Haversian canals as reference and a random number of lamellae using the boundaries mentioned above. Once all the osteons and their pores have been generated, without exceeding the percentage established as input, lacunae are generated in the interstitial area of the cortical bone until the sum of all their areas corresponds to the value established as input.

6.6 Results

The experimentation was based on the use of several human long bones, both healthy and fractured models are included, which have been scanned for subsequent digitization following the process described previously. Two fibulas, two humerus and two tibias have been used. For each of the bones, a cortical area near the mean diaphysis has been selected in order to carry out the generation of microstructures. In addition to the tests performed with the bone models in which an area of interest was selected, some tests were also performed by introducing the TV parameter manually.

Several experiments are included in the articles used as reference. Each value of these articles corresponds to a single experiment, although the average values of all the experiments are also compiled. The table 6.2 reflects the results obtained in each individual study, as well as the average values. These values were obtained from the results of the analysis, at microscopic levels, of human bones conducted by Demirtas [5, 6] (S-Demirtas16₁, S-Demirtas16₂, S-Demirtas18) and Yeni [14] (S-Yeni00). In the last study (S-Yeni00), the author takes into account the deviation in each sample because the study was based on average parameters according to the sex of the subjects studied. This section shows the results

obtained after using these input parameters with the 6 human long bones described above.

In order to validate the accuracy of the algorithm for the modelling of bone at microscopic level, a two-step validation procedure has been carried out: expert analysis and statistical analysis. During the first step, a group of specialists was selected. This group was composed of three experts with experience in fracture reduction at different scales and two radiologists expert in the analysis of traumatology images. The specialists evaluated a set of images of the models generated. The second step was a comparison between the parameters of the models generated and the values of the reference studies. It should be noted that the search for experts in the medical community, with enough knowledge to evaluate the models generated, has been more costly than expected.

6.6.1 Expert analysis

Based on the data presented previously, different models have been generated. Each model, provides a representation and an analysis of the characteristics of the tissue generated, allowing its subsequent comparison with the studies used as reference. The models generated are always different from each other, even if the same input parameters are used, due the randomness of some estimated parameters that determine the shape and size of the microstructures. Figure 6.7 represents the model generated by entering the TV parameter manually, while figure 6.8 refers to the result after selecting an area near to the diaphysis of a fibula with a plane.

At a similar levels of zoom to the images of the reference studies, it can be appreciated similarities in terms of shape and size of the microstructures (Fig. 6.9). In addition, the features of the microstructures described in previous sections can be appreciated. Several samples also have been sent to experts in the field in relation to the analysis of the microstructures that compose the bone tissue and have obtained satisfactory results about the similarity between the proposed model generator and the results obtained with other tools that identify the osteons through image analysis tools.

Table 6.2: Measurements obtained from the baseline studies and the total average of the study conducted. Columns S-Demirtas16₁ and S-Demirtas16₂ correspond to the study carried out by Demirtas et al. [5]. Column S-Demirtas18 corresponds to one study by Demirtas and Ural [6]. The last study (S-Yeni00) was conducted by Yeni and Norman [14].

Parameter	S-Demirtas16 ₁	S-Demirtas16 ₂	S-Demirtas16 _{Avg}	S-Demirtas18	S-Demirtas18 _{Avg}	S-Yeni00	S-Yeni00i _{Avg}
On.Ar (%)	53.5	64.6	58.5 ± 10.9	72.8	59.3 ± 14.1	48.17 ± 14.57	48.95 ± 11.83
On.Dn (mm ²)	15.5	20.3	17.3 ± 3.7	19.3	17.1 ± 4.8	15.78 ± 4.77	14.06 ± 4.33
Po (%)	4.46	5.02	5.2 ± 2.3	10.15	6 ± 3.7	6.752 ± 62	7.68 ± 3.27
s.On.Ar (mm ² · 10 ⁻³)	32	28	32.4 ± 11.4	38	37.3 ± 15	31.76 ± 9.34	36.93 ± 11.46
s.Po.Ar (mm ² · 10 ⁻³)	3	3	3.6 ± 2.1	8	4.7 ± 3.1	4.77 ± 2.63	6.33 ± 4.04

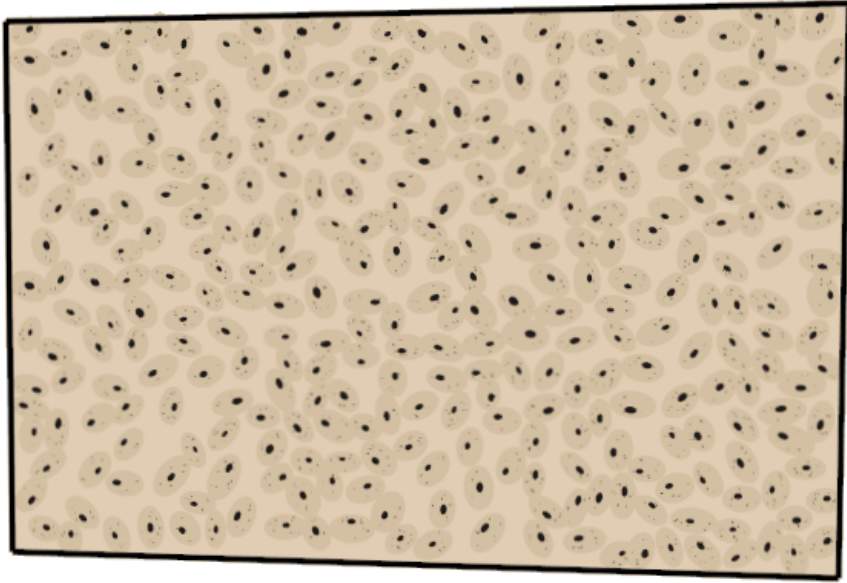


Figure 6.7: Representation of a whole model using the model generator by introducing the size of a specific area manually.

In this stage, the committee of experts was able to corroborate the good results obtained with the model generator. The experts evaluated a set of images and answered a questionnaire designed using five level Likert responses, in which 1 point was the lowest score and 5 was the highest. The set of images was composed of samples obtained from the proposed model generator (Fig. 6.10a), fake images of osteons and images extracted from representation in FEM (Fig. 6.10b). FEM generate a representation of the bone structures through the analysis of bone images, so it is not a real or random representation generated automatically, it is an approximation through the analysis of real images. To avoid the association of the images to a specific tool, different filters were applied to blur the lines of the models as well as to invert the tonalities of the different structures represented, preserving the use of the gray scale as a ref-

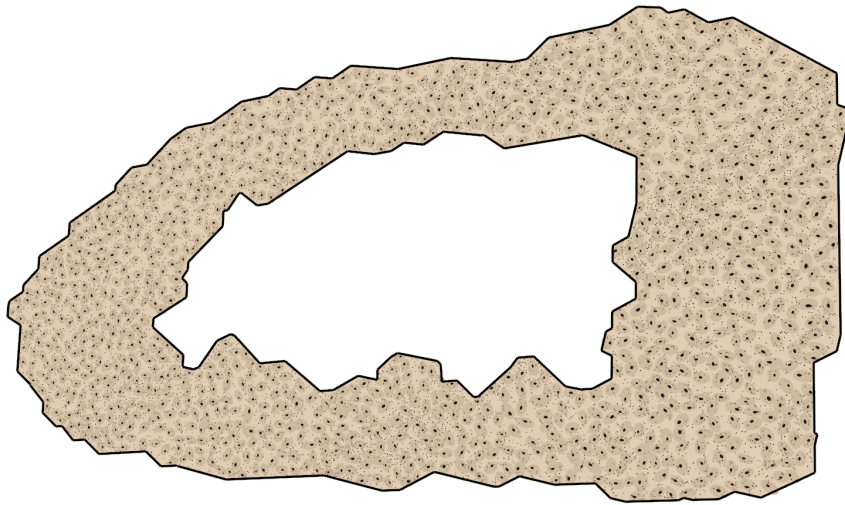


Figure 6.8: Representation obtained using the model generator after the selection of a specific area through a bone model and a plane.

erence (Fig. 6.10). The questionnaire focused on determining the degree in which a representation of the cortical area corresponds to a manual approximation similar to that made by traditional methods. Since the FEM representations do not take into consideration the porosity and only represent the osteons with the Haversian canals, most of the images provided to the experts did not contain the representation of the smaller pores. 90% of the images evaluated, created by the algorithm, have been rated with 4 or 5 points. Therefore, it can be affirmed that the experts consider that the generated random models obtained are susceptible to being identified as the results of a traditional tool in which images of the cortical bone tissue at microscale are analysed manually.

The model proposed also includes the possibility of generating a representation of porosity and the generation of osteons along a whole slice of a bone model and not just in a determined area. It is necessary to emphasize the facility of obtaining all the characteristics of the tissue generated as well as the information concerning of all the microstructures that



Figure 6.9: Representation obtained using the model generator after zooming.

compose it. The inclusion of the lacunae provides more detail than other representations but it is possible that the greater detail also increases the time necessary to make simulations by the increased amount of geometry. Thus, the user can use the most suitable representation for the study or research being carried out.

6.6.2 Statistical analysis

The second step of the evaluation process of the generated models shows that the morphology of the models are similar to the real cortical bone. The accuracy of the representation of a bone model must not only be visual. It is also necessary to check that the characteristics of the model are similar to the characteristics of the cortical tissue of human bones. Table 6.3 shows the microstructural and geometric parameters calculated

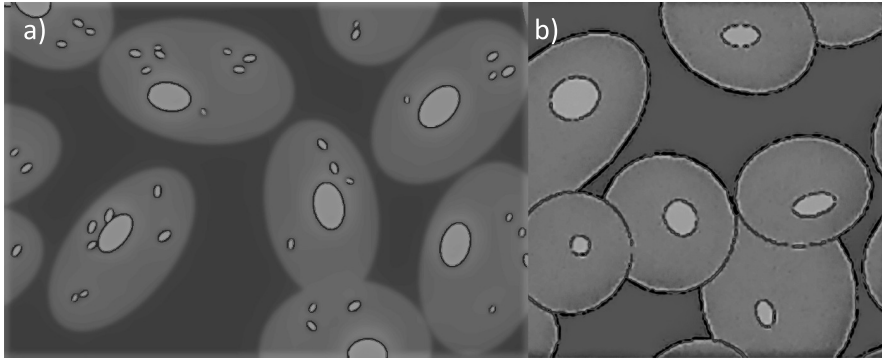


Figure 6.10: Comparison between an image obtained with the algorithm developed (a) and an image obtained from a manual segmentation extracted from the study of Demirtas et al. [5] using traditional methods (b).

on the model generated. These values are obtained as the average of five generations with the same configuration in the same area of interest. The configuration follows the reference data of the articles indicated previously (Table 6.2), as well as the average of all these experiments. The use of some of this parameters as input allows the comparison of the rest of the parameters with the results obtained using the model generator. Table 6.3 show the results of the parameters obtained with the model generator while table 6.2 contains the data used as reference.

A comparison of the results obtained with the results obtained by Demirtas [5, 6], Tong [149, 78, 150] and Yeni [14] has been performed. The first conclusion extracted is a clear trend towards the average values of the reference studies. To analyse the variation of the osteonal area in greater depth, a scatter plot has been used. This graph allow to analyse the relationship between the osteonal area obtained and the values of each experiment take as reference (Fig. 6.11). In this figure, the dark blue points represent the result obtained in the individually-referenced experiments and the dashed line the trend line of the reference set. The trend line allows us to highlight the intermediate zone between the different experiments of reference. Moreover, the average value of the parameter, on the

Table 6.3: Results obtained after using the input data (On.Ar and On.Dn) of the experiments indicated above (Table 6.2).

		TV(mm^2)	On.Ar(%)	On.Dn(mm^2)	Po(%)	s.On.Ar($mm^2 \cdot 10^{-3}$)	s.H.Ar($mm^2 \cdot 10^{-3}$)	s.Lc.Ar(μm^2)	Min.On.Dn(μm)	Max.On.Dn(μm)	N.On(#)	BV/TV (%)
Fibula 1	S-Demirias 16 ₁	57.12	57.38	15.05	4.46	36.99	1.92	66.70	172.98	268.60	886.00	97.02
	S-Demirias 16 ₂	57.12	65.02	20.30	5.02	32.75	1.69	65.70	157.02	270.01	1134.00	96.64
	S-Demirias 18	57.12	64.46	19.30	10.15	34.25	1.77	65.60	162.41	263.66	1075.00	96.67
	S-Yeni00	57.12	58.42	15.78	6.75	37.00	1.91	66.80	161.97	281.93	902.00	96.98
	Avg	57.12	61.32	17.72	6.60	35.25	1.82	66.20	163.60	271.05	999.25	96.83
Fibula 2	S-Demirias 16 ₁	59.34	57.90	15.50	4.46	37.35	1.92	66.80	166.04	274.45	920.00	97.02
	S-Demirias 16 ₂	59.34	65.38	20.30	5.02	32.99	1.69	65.90	155.53	257.97	1176.00	96.64
	S-Demirias 18	59.34	64.90	19.30	10.15	34.14	1.74	66.10	161.61	264.69	1128.00	96.68
	S-Yeni00	59.34	58.20	15.78	6.75	36.86	1.89	67.10	157.25	273.55	937.00	97.01
	Avg	59.34	61.60	17.72	6.60	35.34	1.81	66.48	160.11	267.67	1040.25	96.84
Humerus 1	S-Demirias 16 ₁	139.04	57.69	15.50	4.46	37.20	1.91	66.70	170.77	277.76	2156.00	97.03
	S-Demirias 16 ₂	139.04	63.94	20.30	5.02	33.07	1.68	66.80	156.58	258.39	2688.00	96.74
	S-Demirias 18	139.04	62.49	19.30	10.15	34.46	1.77	66.20	159.20	271.23	2521.00	96.78
	S-Yeni00	139.04	58.87	15.78	6.75	37.29	1.92	66.70	160.33	266.98	2195.00	96.97
	Avg	139.04	60.75	17.72	6.60	35.51	1.82	66.60	161.72	268.59	2390.00	96.88
Humerus 2	S-Demirias 16 ₁	137.84	57.61	15.50	4.46	37.16	1.92	65.90	163.25	268.80	2137.00	97.03
	S-Demirias 16 ₂	137.84	63.95	20.30	5.02	33.10	1.69	66.4	155.61	264.09	2663.00	96.72
	S-Demirias 18	137.84	62.98	19.30	10.15	34.26	1.76	66.20	155.76	264.57	2584.00	96.76
	S-Yeni00	137.84	58.45	15.78	6.75	37.03	1.91	66.80	166.60	286.33	2176.00	96.98
	Avg	137.84	60.75	17.72	6.60	35.39	1.82	66.33	160.31	270.95	2390.00	96.87
Tibia 1	S-Demirias 16 ₁	270.96	56.60	15.50	4.46	36.51	1.87	66.70	161	268.57	4200.00	97.10
	S-Demirias 16 ₂	270.96	65.97	20.30	5.02	32.49	1.67	66.10	155.27	264.05	5501.00	96.60
	S-Demirias 18	270.96	65.38	19.30	10.15	33.87	1.74	66.50	155.09	267.73	5230.00	96.63
	S-Yeni00	270.96	57.37	15.78	6.75	36.35	1.87	67.00	156.29	268.30	4276.00	97.05
	Avg	270.96	61.33	17.72	6.60	34.81	1.79	66.58	156.95	267.16	4801.75	96.85
Tibia 2	S-Demirias 16 ₁	277.56	56.62	15.50	4.46	36.53	1.88	66.60	155.30	280.29	4303.00	97.09
	S-Demirias 16 ₂	277.56	65.91	20.30	5.02	32.47	1.67	66.30	155.37	259.33	5635.00	96.61
	S-Demirias 18	277.56	65.11	19.30	10.15	33.73	1.73	65.80	155.69	268.12	5357.00	96.65
	S-Yeni00	277.56	57.34	15.78	6.75	36.34	1.86	66.20	158.97	278.62	4380.00	97.06
	Avg	277.56	61.25	17.72	6.60	34.77	1.79	66.23	156.33	271.59	4918.75	96.85

study under consideration, is shown in red. The scatter plot, showing the osteonal area, shows that the results of the models generated are generally closer to the trend line than the results obtained in the reference experiments. However, the averages of the reference studies are much closer to the trend line.

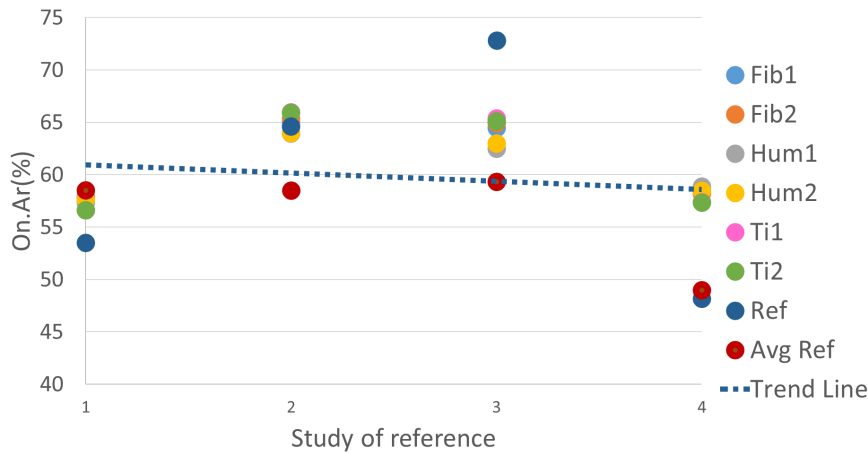


Figure 6.11: The graph shows the variation of the osteonal area for each experiment. The discontinued line marks the trend of the results of the values used as reference. The numbers on the lower chart correspond to the studies used as reference: S-Demirtas16₁ (1), S-Demirtas16₂(2), S-Demirtas18(3) and S-Yeni00(4).

This is due to the fact that, although microstructural elements are generated in a random way, the parameters used to generate the bone model are based on the average values determined by the literature. Even though the maximum and minimum values are considered, the function that generates the random values to determine the size of the osteons follows a normal distribution because there is no analysis in the literature of a function to determine a set of rules for determining the size in a precise way, causing the deviation generated to be very small. In addition, parameters such as age or sex do not take into account that they could have effects on the characteristics of the model. It should also be considered

that most of the reference studies correspond to small regions in which the set of osteons is tiny, so they are not too representative and may even contain irregular cases as reflected in the box and whiskers diagram used to compare the mean area of the osteons (Fig. 6.12). The green bar corresponds to the experiments carried out with the cortical tissue generator while the blue bar contains the values of the reference studies. The results obtained with the generator are around the mean of the reference results and the average value in both cases is very similar, $35.17mm^2 \cdot 10^{-3}$ in our model and $34.22mm^2 \cdot 10^{-3}$ for the reference studies. Furthermore, it can also be observed how the reference studies contain atypical cases that are quite far from the mean and come considerably closer to the minimum and maximum size of an osteon. The maximum and minimum values for the diameter of the osteons in the upper tables reflect the randomness to generating the microstructures that make up the bone tissue, always complying with the limits established by experts in the literature reviewed previously.

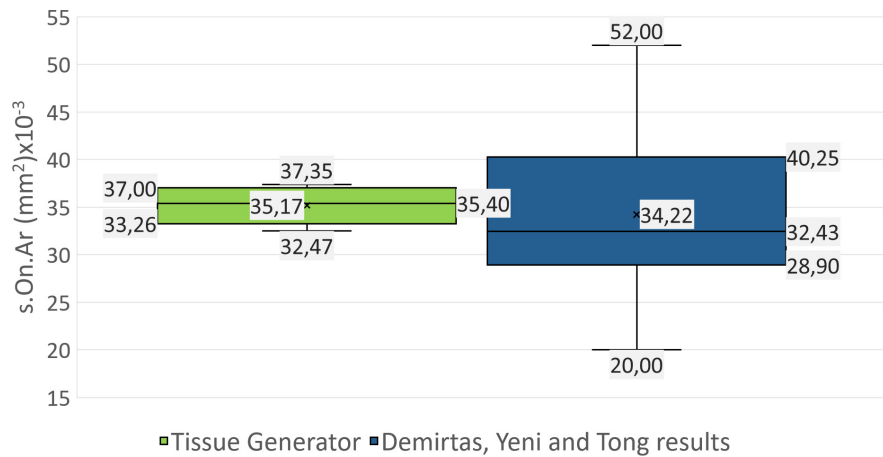


Figure 6.12: The graph represents the data concerning the average area occupied by a single osteon. The left side represents the values of the models generated with the algorithm described while the right side shows the values of the reference studies.

The evaluation of the parameters related to porosity has been more complicated because the articles of reference present data related to the porosity and size of Haversian canals but they do not determine which elements are considered when carrying out the measurements or how these data are obtained. Moreover, as previously described, there are certain discrepancies in the measurement of porosity since some authors consider lacunae when performing the calculations while others do not.

The algorithm described considered the lacunae and the Haversian canals as part of the porosity. Comparing the dimensions obtained with the values obtained in studies of reference authors in the field of porosity, such as Cummaudo et al. [147] or Prendergast and Huijkes [137], it is possible to reach the same conclusion as in the case of osteons, that the results obtained with the generator are around the mean. In these studies the maximum area of the lacunae was $126.91\mu m^2$ while the smallest was $14.12\mu m^2$. Furthermore, they establish that the average size of the lacunae is $61.14(\pm 15.24)\mu m^2$, which is very close to the values obtained in our generator, in which the average area of the lacunae is around $66\mu m^2$. Concerning the Haversian canals, the specialists who focused on the study of this microstructure [71, 25, 136] have determined that the diameters of the canals are around $30\mu m$ and $50\mu m$. This, added to their circular shape, like osteons, produces similar results to those obtained in the table of parameters obtained through the model generator (Table 6.3). However, in the studies used as reference based on FEM, it is observed that the value of the porosity obtained is higher than that of the Haversian canals and lacunae. Not having any reference to the measurements and observing that the values they present are higher than those in the data obtained by other authors whose study was exclusive to these bone microstructures, it can be deduced that the parameter they estimate is the sum of all the pores within an osteon, that is, the Haversian canals, lacunae and canaliculi. On the other hand, the representation of the cortical tissue of Demirtas [5, 6] (Fig. 6.10b), shows that the model resulting from using traditional methods only detected the Haversian canals, and the resulting mean pore area (s.Po.Ar) is far from what specialists in the field of porosity obtain as a result. Therefore, in the tables of results the size of the pores has been

separated according to the type and the comparison has been made with specific studies on the microstructures.

6.7 Conclusions

The main motivation for the development of the tool has been the need to obtain data sets for further analysis. The algorithm proposed allow to obtain the representation of the cortical bone at a microscopic level without the need for a large set of microscope images. The generation of the procedure is faster than traditional methods in which the researcher has to segment the bone tissue images manually. The data sets generated are similar to the segmentation of cortical tissue performed by the researchers in which they perform fracture simulations, physical simulations and measurements.

The results show that the proposed model obtains values close to the mean of the studies that focus on the measurements of the properties of the bone tissue. If the values are compared with the experiments carried out individually, certain variations can be seen because the different samples used are not very representative, even have some outliers, and individually they also differ from the average values of the complete studies. The reason for this is that the average values and the standard deviation of the literature are used as a reference to generate the representation of the microstructures through the use of a normal function.

The tool has been developed considering the future incorporation of other parameters. Another possible use would be to increase the number of input parameters in order to replicate the conditions of an existing study, with the aim of carrying out additional tests. In addition, the proposed model is not closed to the incorporation of new aspects of relevance that could be easily incorporated. Analysis of the roughness of the osteons could be an important aspect that could be included in order to, aside from granting a greater realism to the representation of the model, obtain more precise data of the model.

At first the possibility of carrying out a 3D representation of cortical

bone was studied but it was discarded because there were not enough data available to compare the results obtained. Therefore, in the future the possibility remains open to extend this model to a 3D representation, which includes the difficulty of determining the length of the structures as well as their distribution within the area represented. The models generated could be extruded to obtain a 3D approximation. Extrusion would not be an appropriate solution due to the fact that many other aspects such as orientation and length of microstructures have to be taken into consideration.

The use of deep learning on bone tissue images is an interesting line of future work in which progress can be made if the input data set is improved. As the time for the development of this dissertation is limited and it is a work line that requires greater depth, it has been postponed for the future.

In the next chapter, the representations obtained in this chapter will be used to carry out fracturing simulations at the microscopic level.

BONE FRACTURE AT MICROSCOPIC LEVEL

The aim of this chapter is to provide a tool for the simulation of fractures at the microscopic level over the entire cortical zone without using the traditional method. All the studies reviewed in the chapter 2 are based on the use of FEM method. The models used in these studies represent small area of the cortical bone, so the number of bone microstructures are significantly less. The images of bone tissue obtained through the microscope, reported in previous chapters (Fig. 6.1, 8.3 and 6.2), show significantly more structures than those used in most of these studies. One of the key points of the FEM method for fracture simulation of materials is the influence of the elements surrounding the fracture area in the model. Therefore, the results obtained are affected when using tiny representations of the cortical part of the bone. This explains the difference between the studies in terms of the forces to be used to simulate a fracture.

The representations used are approximations of microscopic images that represent specific points of the cortical area due to the complexity

of the bone structure. The fact that cortical tissue is not homogeneous is compounded. The modelling of a complete section of cortical tissue in FEM is unfeasible due to the number of elements to be represented and the computational time required to perform a simulation. The algorithm described in this section focuses on the modelling of a 2D graph-based fracture using the representation made in previous chapters as a reference. Figure 7.1 shows an overview of the steps involved in fracturing the model. The initial stage establishes a starting point and a direction in which the fracture propagates. In the second stage, the algorithm determines the path of the fracture based on the elements in its path. This stage does not end until one of the stop criteria is satisfied, resulting in the final fracture. The objective of this method is not to study the influence of microstructures on fracture growth, as in the articles reviewed in the literature, it is to simulate a fracture over the entire cortical area with a realistic appearance.

7.1 Model

In previous chapters a process for the representation of cortical bone tissue at the microscopic level was proposed. The method involved two stages. The first phase was the segmentation of images of real bones in order to obtain a 3D model on which to perform the modelling. It is important that the images used include information to delimit the internal boundary of the cortical area of the bone. Therefore, CT images were used. The second step starts with the selection of a bone area through a plane. This enables the delimitation of the inner and outer boundary of the area in which the microstructures of the bone tissue will be procedurally generated. The features and distribution of the osteons and other microstructures generated are based on scientific literature. This tool also allows the representation of the pores that make up the bone tissue, but they are not used in the fractured models due to the increased computational cost involved.

One of the key points to consider for fracturing is the way in which

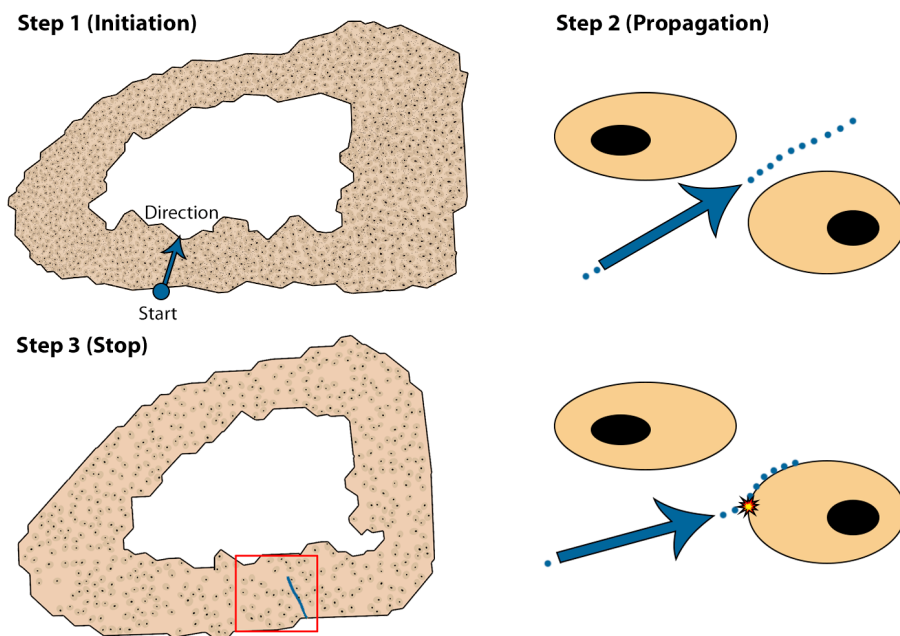


Figure 7.1: Overview of the steps involved in the fracturing algorithm.

the information is structured. Two grids are generated, adjusted to the boundaries of the area in which the bone microstructures are generated (Fig. 7.2). The first one is a large grid that is responsible for storing the information of all the bone microstructures that are found within each of the quadrants. The second grid has a larger number of divisions and is used to distribute the bone microstructures on the model. Grid cells can be divided into boundary cells, free cells or occupied cells. Thus, the distribution of the bone microstructures can be managed with precision. The larger grid is mainly involved in the distribution of osteons and the prevention of unwanted overlaps. Moreover, it stores the information concerning all osteons whose center is within the grid cell. The small grid is responsible for refining the representation of the bone structures to avoid that the limits of the cortical zone are overstepped. In addition, this grid

check the overlaps to discard those that are undesirable. Therefore, the information from both will be used to minimize the computations time when the fracturing process begins.

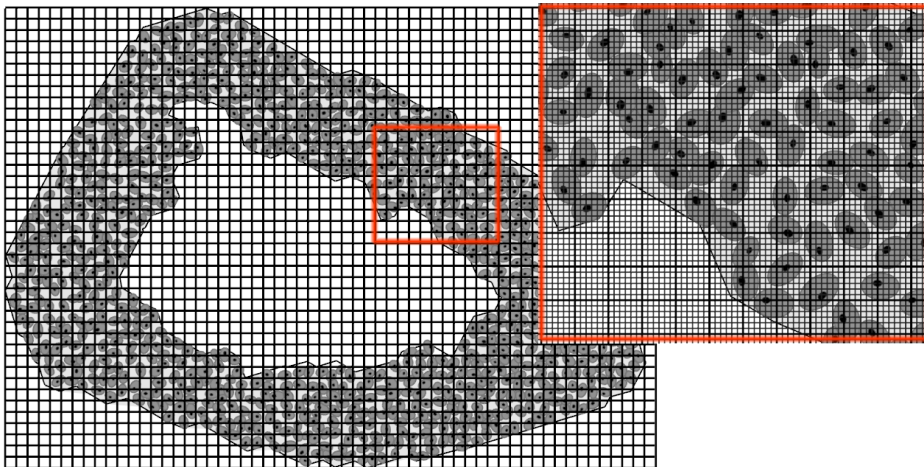


Figure 7.2: Grids that manage the distribution of bone microstructures.

7.2 Fracture initiation

The fracture starts with the selection of any point that constitutes the outer boundary of the base model (Fig. 7.3). The simulator also needs a direction in which the fracture will start to propagate as well as the input of parameters relating to the crack conditions that occur (Fig. 7.4). Before starting propagation, a ray is projected to a position far away that provides the number of collisions with the edges of the cortical area so that the algorithm only begins the propagation if a valid direction is chosen that travels towards the boundaries of the cortical area.

As mentioned above, the objective of this tool is to simulate a realistic looking fracture of the entire cortical area at the microscopic level. Therefore the only parameters that are taken into consideration to set the fracture are the force applied to the model as well as the maximum force

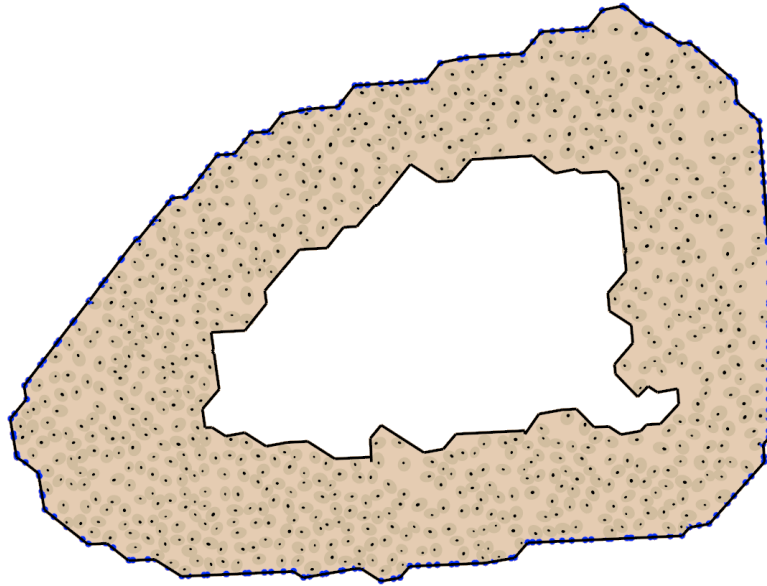


Figure 7.3: Selection of a fracture starting point. The blue dots are the candidates.

it is able to resist before a fracture. Factors such as modulus of elasticity, toughness, absorption capacity and other mechanical properties have not been taken into consideration since some are unknown and others have been previously studied using the FEM method, which is the most appropriate method to study the mechanical behaviour of the bone tissue. Once these values have been provided the algorithm starts to propagate the fracture in the indicated direction.

7.3 Propagation criteria

In terms of fracture propagation, many studies report the influence of osteons and the heterogeneous characteristics of the tissue during fracture growth [91, 89, 151, 87, 90, 83, 92, 5, 6]. Tang et al. [12] performed a

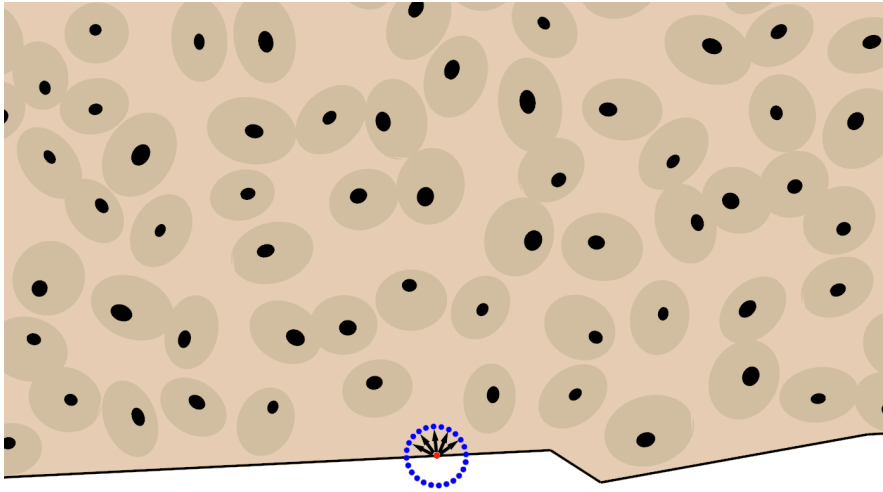


Figure 7.4: Selection of a fracture direction. The blue dots determine the possible directions that the algorithm can use to advance on the model.

microscopic study about the mechanical properties of the cortical tissue. In this study they applied forces on cortical tissue samples analysing the fractures produced at both macroscopic and microscopic levels. They report that three situations can occur when a fracture line reaches an osteon:

1. Be deflected by the cement line and went around the osteon (Fig. 7.5a).
2. Propagate into the osteon and then being deflected by the lamellar structure without arrive to the Haversian canal (Fig. 7.5b).
3. Pass through the Haversian canal without being deflected (Fig. 7.5c).

The algorithm considers these three cases when propagating the fracture in the indicated direction. The fracture does not propagate completely in a straight line, it has a margin of ± 15 degrees with respect to the initial direction. The algorithm is cyclic until it reaches a stop condition. Therefore, in each cycle the fracture advances to a adjacent cell. If this cell is free, there is no osteon in it, the algorithm continues. In case the

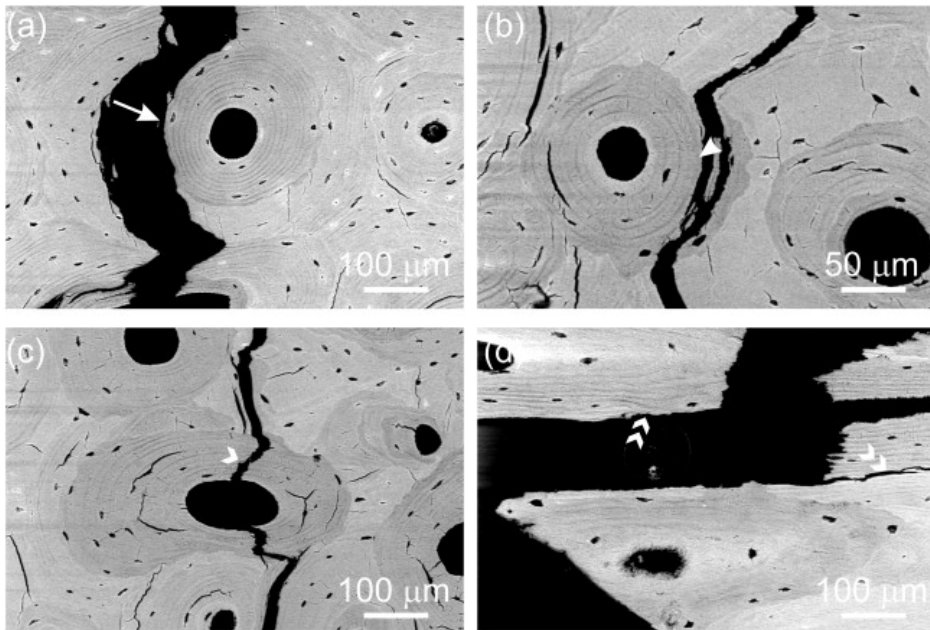


Figure 7.5: Interaction of a fracture with an osteon during its growth from the study conducted by Tang [12]. Figure a represents a crack deflected by the cement line, b shows a crack deflected by the lamellae that surround the Haversian canal and c a crack through the Haversian canal. Figure d shows a crack deflected along the cement line.

grid cell is occupied or partially occupied (the cement line of an osteon crosses the cell, but it is not fully inside of an osteon), the osteons that are in the area are identified using the grid of greater size and it is studied if there is a collision. The edge or cement line of an osteon is determined by a polyline while the growth of the fracture line is determined by another polyline. Therefore, an intersection between two segments is performed to determine whether a collision with the cement line of the osteon occurs as well as the point in which it occurs. In addition, the angle at which the collision is produced is also analysed. Without any collision with the osteon, the fracture line will continue its path as it implies that it has passed very close to the border, but has not collided with the osteon. Figure 7.6

represents the different types of cells. The green cells are empty so the fracture line can be propagated through them without any additional calculation. However, in the yellow areas that coincide with the cement lines of the osteons additional checks have to be performed to determine how the fracture growth continues.

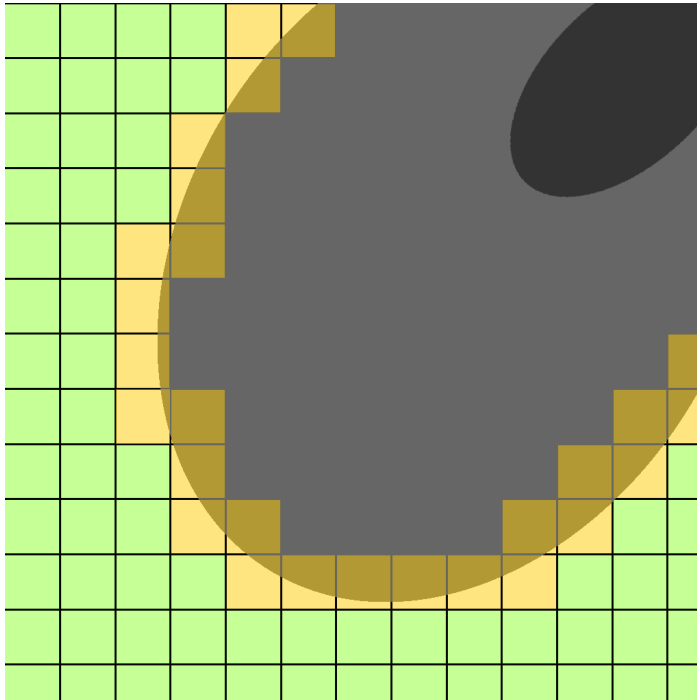


Figure 7.6: It represents the different types of cells that a fracture may encounter in its path. The green cells are the empty ones, the yellow ones are the ones that are part of the cement line of the osteons and the gray part represents the interior of an osteon.

The study carried out by Tang et al. [12] analysed the frequency at which the situations occurred when a fracture line collided with an osteon. In 50% of the collision cases, the fractures propagated into the osteon and were deflected by the concentric layers that surround the Haversian canal, but did not reach into it. Moreover, only 12% of the cases reported the

first situation in which the cement line deflected the fracture line. The remaining percentage is understood to correspond to cases corresponding to the third situation in which the fracture line penetrated the osteons and reached the Haversian canals. These values show that the first osteons encountered by a fracture line are traversed regardless of the angle at which it collides. That is due to the fact that they are close to the point of impact and the force applied to the model is sufficient to allow the growth of the fracture line. We can also identify that the further the line advances, the greater is the resistance of the osteons to fracture. The percentages associated with reaching the Haversian canal once a fracture line has penetrated an osteon are very similar. It is probably the direction in which the fracture advances is the most important factor to determine whether a fracture crosses it or not. The first chapters of this thesis showed that the cement line is the main barrier and that once penetrated, the resistance to fracture growth is much lower.

The algorithm developed considers the aspects mentioned in the previous paragraphs. The input parameters are used to determine the maximum length of a fracture line. This formula is detailed in the following section. The algorithm advances regardless of the osteons it encounters up to 50% of the maximum distance expected for a fracture line. There will be cases in which it will penetrate the Haversian canals and cases in which it will not, according to the direction of the fracture. Once 50% of the maximum length of the fracture line is covered, collisions and the angle at which they occur are considered. If the angle of the collision formed by the fracture line with the polyline formed by the cement line is between 70 and 110 degrees, the line penetrates the osteon, giving rise to situations 2 and 3 (Fig. 7.7a). However, if the angle is above or below these values, the cement line will act as a barrier and the fracture will advance along its edge (Fig. 7.7b and 7.7c). This process will be repeated until a stop condition is reached. As mentioned above, all these parameters can be customized to adapt them to the fracturing simulation.

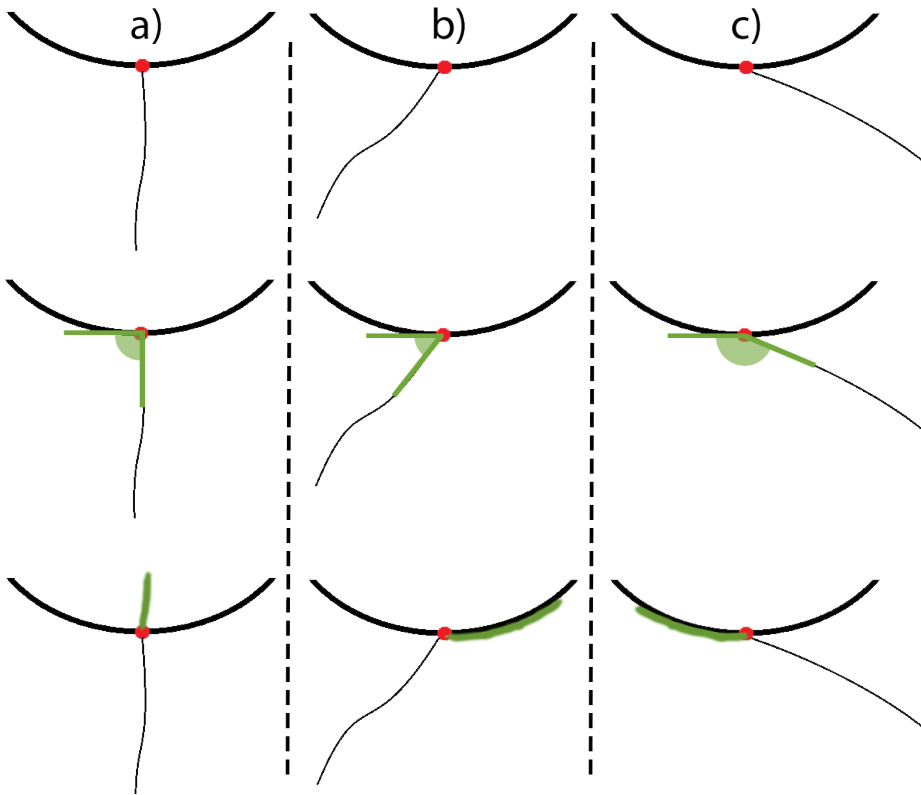


Figure 7.7: Interaction of fracture growth upon collision with an osteon. Figure a represents a collision at an angle close to 90 degrees causing the line to penetrate the osteon. Figure b and c represent collisions outside the range between 70 and 110 degrees causing the cement line to act as a barrier and deflect the fracture line.

7.4 Stop criteria

The propagation of a fracture line at the microscope level can end in two ways: fracturing the model or not. A model is considered to be fractured when the fracture propagation line crosses the bone boundaries twice, while a fracture line that only crosses the bone boundaries once (initial point of fracture) will be called a crack. It is not necessary that the line

crosses the outer and inner limit to refer to a fracture; it could cross the outer limit twice, causing a detachment of a part of the cortical zone without reaching the center of the cortical area. Likewise, it would be not representative the simulation of a fracture starting at the inner edge of the bone, so in no case will it cross it twice. The fracture line will advance until the model is fractured or until it reaches the maximum distance with the established configuration.

The main elements involved in determining the growth arrest of a fracture line are the force applied to the model, the maximum force the model can resist before being fractured, the covered distance by the fracture line and the number of osteons found in its path. The first step consists of calculating the average distance between the points which constitute the boundaries of the cortical area. Thus we can determine the average width of the cortical area. In a second stage, the maximum distance the fracture line can extend is calculated. This distance will be the equivalent to the distance that the fracture line can be traversed if the maximum force that the model can resist is applied as input. The width of the area is variable, so a factor customizable has been established to facilitate the fracturing of the wider areas. However, if the area is considerably wider than average, it is possible that the algorithm would stop the propagation of the fracture before crossing the boundary of the cortical area, so that it would be considered a crack rather than a fracture of the bone. These rules also limit the growth of fractures with a lateral direction that would cross most of the model. Therefore, the maximum length of a fracture line is calculated through the force introduced in proportion to the distance that the fracture line could extend taking as a reference the average width of the cortical zone when the force introduced coincides with the maximum force that the model can resist and multiplying this value by a factor. The default value of this factor is 1.25. This value has been obtained after several simulations on a model, although it can be adjusted manually.

Finally, the fracture line also considers the osteons that are found in its path once the line has advanced. Studies have shown how osteons act as barriers to fracture growth and their ability to absorb part of the energy. In the absence of information on the absorption capacity of osteons, the

fracture line considers the encounters with them after growth of 70% of the maximum length. Each time the fracture line collides with a new osteon at an angle between 70 and 110 degrees, the maximum length it can propagate is reduced by 10%. All these values can be customized to adapt them to the circumstances of the fracture to be simulated.

7.5 Results

The developed algorithm focuses on cortical bone fracturing at the microscopic level. The main objective is to obtain a realistic-looking fracture that is determined by the structure of the tissue in which it is produced. The output does not consider the mechanical properties of the bone tissue since the studies based on the FEM method described above focus on this topic. For this purpose, the previous sections have established the necessary parameters and the criteria that fractures follow as they propagate through the tissue.

The developed algorithm generates fractures along the model until it reaches a stop condition. These conditions are the fracturing of the model, when the fracture line crosses twice the boundaries of the cortical area, and the stop without completely fracturing the model, known as crack, as the force applied on the model was not enough to fracture it. Fracture propagation occurs in a specific direction, although it has a random variable which allows to slightly vary the direction in which it is propagating. Thus, the resulting fractures are prevented from being lineal. In addition, a number of rules that determine how fracture lines behave when they encounter an osteon in their path have been indicated above.

Figure 7.8 shows the fracturing of the entire model. Figures 7.8a, 7.8b and 7.8c show the advance of a fracture line through the model. All these figures share the starting point, the initial direction and the parameters in which a force greater than the model can resist has been indicated to ensure the complete fracture. Thus, it is possible to check the effect of the random variable and the encounters with the bone structures in the growth of the fracture line. Figures show the three situations identified in

the study conducted by Tang [12]. As in their study, collisions predominate in which penetration occurs in the internal part of the osteon, and as the distance traveled increases, the possibility of these acting as barriers and deflecting the fracture increases. Figures 7.8d and 7.8e highlight the different situations that can occur when a collision occurs. Figure 7.9 represents a fracture in which the force introduced was less than that required to fracture the model so that the growth of the fracture line stops before crossing the entire cortical area.

7.6 Evaluation

As the rules followed by the fracturing algorithm have been extracted from the literature, the validation process has been carried out by consulting three experts in the field. Two of them had expertise in bone fracturing at the macroscale level mainly while the other expert had experience in simulation using the FEM method in other disciplines.

To evaluate the results, they have been provided with a set of 15 images and asked to evaluate the results obtained through a questionnaire using the Likert scale. In the questionnaire, they were asked about the variability of situations seen in fractures at the microscopic level and about the degree of realism of the simulation. As for the evaluation of the variability of situations in the face of fracture growth, the three experts gave an average score of 4.6 out of 5. However, the average score obtained for the degree of realism of the simulation was 3.33 out of 5. In the comments of the experts we can identify how the lack of physical parameters on the simulation has caused the feeling of realism to be inferior. The lack of information from these data and the large variability among the reference studies led to the decision to use a graph-based approach instead of performing a physics simulation on the model.

There is no limitation with the values, so the user can adjust them to his needs, although a series of values based on previous literature are proposed. The fracture result obtained after the simulation is determined by the configuration established by the user. Graph-based algorithm allows

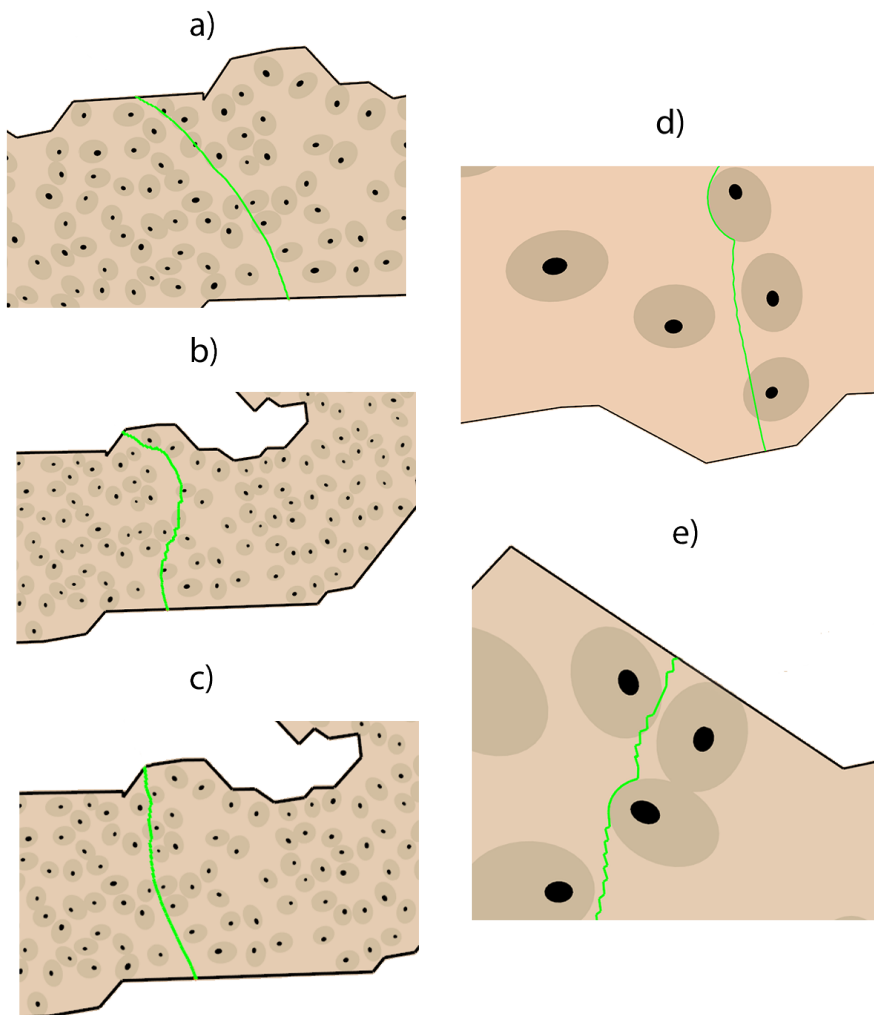


Figure 7.8: Figures a, b and c represent the fracture of the complete model. Figures d and e show a more detailed view of the area in which a fracture line collides with an osteon.

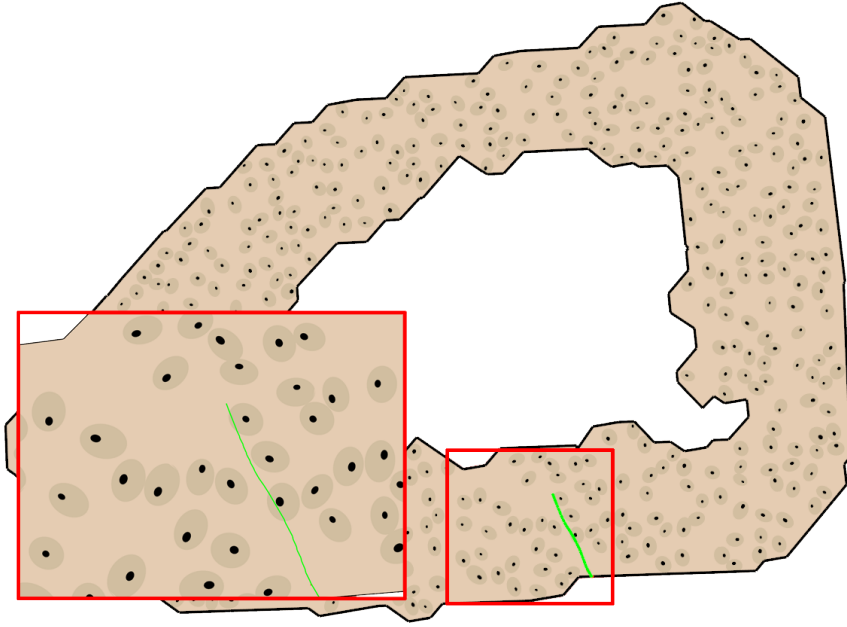


Figure 7.9: Fracture that does not fracture the entire model due to the input parameters.

for accurate guidance of fracture growth. As we have seen above, the results obtained with the default values have been positively evaluated by the experts. From a statistical point of view, in the case of altering the default values proposed in this work, the user must ensure that the parameters introduced are within the ranges established in the literature in order to ensure the correct performance of the simulation.

Considering all of the above, we can consider the validation of the results as positive, although we should try to improve the simulation by increasing the number of physical parameters taken into account during the simulation. In addition, it could be interesting to include as input different directions of growth so that the path of the fracture line can be monitored more accurately. In the visual aspect, some improvements could be made to improve the perception of the experts about the tool. Textures obtained

from microscope images could be used to increase the degree of realism as well as to add some roughness to the borders of the osteons so that the propagation through them, when they act as a barrier, is not linear.

7.7 Conclusions

In this chapter, an algorithm for fracturing bone tissue representations at the microscopic level has been developed. All previous methods are based on the FEM method. This method uses all the elements surrounding the fracture in question to determine its growth. In these studies, the representations used are based on small models in which only a few microstructures are visible. Therefore, the simulations that are carried out are inaccurate because many of the structures that make up the cortical tissue and should affect its growth are ignored.

The algorithm developed aims to provide an response to this problem by allowing the fracturing of the entire cortical tissue using the models generated in the previous chapter. The method is based on graphs since extrapolating the whole representation obtained previously to a tool with the FEM method to perform simulations is a practically unfeasible process. In a cut of the diaphysis area of a femur there may be more than 1000 osteons when in studies no more than ten are usually seen.

The evaluation of the results demonstrates the variability of the cases in fracture growth although it also shows that the degree of realism obtained can be improved increasing the number of physical parameters or enhance the visual appearance by using textures. It would also be interesting to adapt the system for the inclusion of traditionally segmented images in order to make accurate comparisons with traditional methods, despite the limitations discussed throughout the chapter.

In the following chapter we will analyse some of the lines of future work that have been opened up during this thesis as well as some proposals that we have recently begun to work on.



FUTURE WORK

This chapter discusses some of the open lines of research that have been left open for the future as they are currently being worked on. These lines will be divided into the two large blocks of work carried out throughout this thesis in a multilevel approach: modelling and fracturing. In addition, a brief overview of the use of deep learning to improve the models and algorithms proposed throughout the work will also be presented.

8.1 Bone modelling

The techniques for macroscale level representation satisfy the needs of the studies so that all improvements and future work can be associated with microscopic level representations of bone tissue.

The algorithm developed allows the automatic representation of the microstructures that make up the cortical tissue. The representations obtained are similar to the manual segmentations, in which a real image is used as a starting point and circular shapes are used to identify the osteons manually. This section presents some variants and alternatives that have

been studied and can be implemented in the future.

To increase the variability in a given area, a different function could be used to determine the size and shape of the bone structures. The problem is the great difference between two different images obtained from a microscope in assessing structural properties, so finding a function to determine this variability is a major challenge.

Another extension could be the conversion of some of the estimated and calculated parameters into input parameters. Therefore, the user could define the conditions in which the tissue representation is generated. This extension could replicate representations used by other studies in an accurate way, although the distribution of the structures would still be random and differ from the original.

Absence of information on the microstructures in the longitudinal axis of the bone also limits the 3-dimensional representation and validation. Although it has not been possible to include such information at this time, the design was carefully designed to be able to include this representation. Thus, the data structure used would change from a 2D grid to a 3D grid or octree, the estimated longitudinal values would only have to be added along with the other parameters and the area of interest over which the generation is carried out could be determined by two planes, to determine the beginning and end of the bone section. Moreover, with this 3D representation, a multilevel representation of the entire cortical area could be performed by joining the information of the macroscale representation of the bone with the microscopic representation of the cortical tissue.

8.2 Bone fracturation

This section shows some of the lines of work that have been opened during the course of this doctoral thesis regarding bone fracture at the macroscopic and microscopic level.

In the previous chapters, we have seen how to represent the fractured area of a bone in different ways in order to extrapolate them to a fracture simulator to use them as a reference. The fracture editor developed has the

limitation that the fracture patterns used only included information about one of the faces of the bone fractured by mechanical experimentation. These patterns were projected on one axis with a consequent loss of detail in the resulting model. The main reason why patterns with 3D information of the fracture zone have not been used is because of the difficulty in projecting this information on the bones, since the dimensions vary from one to another and the surface is irregular.

In the case of projecting height maps on a bone model, the best solution is to transform this information into spherical coordinates. In such a way that the cloud of points that delimits the fracture in the internal part of the bone is stored on one side and the cloud that delimits the fracture on the surface of the bone on the other side. As proposed for the spherical representation through the editor, these coordinates can be projected onto a 2D plane to facilitate their projection. At this point, the two representations with 3D information about the fracture zone would be projected following the same algorithm. The potential solution for this problem is described as below.

The first step of the algorithm consists of selecting the part of the triangle mesh of the bone model on which the fracture pattern is to be applied and transforming it into a perfect cylinder projecting the vertices up to the distance of the vertex farthest from the central axis of the selected area 8.1.

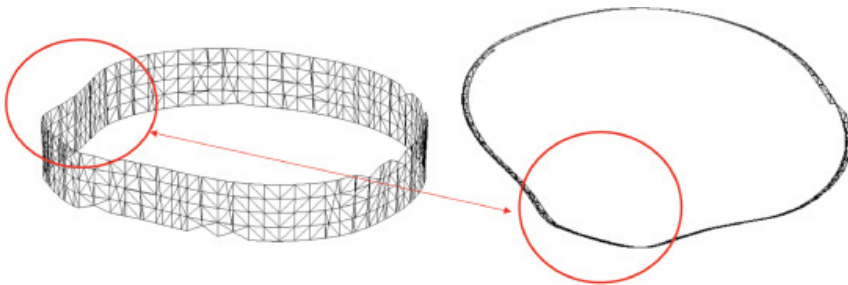


Figure 8.1: Adaptation of the original triangle mesh to a cylindrical shape.

Once adapted, the geometry is projected onto a plane to obtain a rep-

resentation of the mesh in the same dimension as the fracture pattern. Finally, the fracture pattern is overlaid on the 2D geometric representation of the model. As bone models have irregularities, it is highly probable that the width of the pattern does not match with the width of the fracture area after projecting its geometry on a plane, so it is necessary to fit the width of the pattern. Therefore, the pattern can be overlapped in a correct way on the geometry and the cut points between the fracture lines and the edges of the triangles that represent the area to be fractured can be identified (Fig. 8.2). The computation of the fracture can be optimized by approximating these cut points to the closest vertices of the triangles that compose the bone model. Thereby, the model could be separated directly without having to cutout the mesh in a subsequent process. Once the cut points are obtained, the opposite process is performed to identify the cut points on the 3D model.

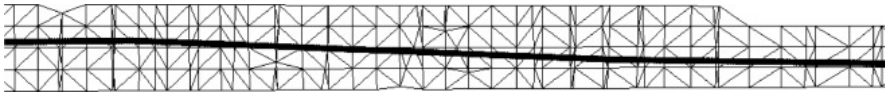


Figure 8.2: Fracture pattern overlapping on the selected geometry.

Although the representation of fractures at the microscopic level can be improved, the lack of information to validate the models considerably limits the simulations that can be made at that level. Some improvements that can be applied are the extension of the model to include more physical parameters for the fracturing simulation of the cortical tissue as well as improvements in the visual aspects, since it is the worst evaluated by the experts during the evaluation. For this purpose, textures can be used to increase the degree of realism as well as the improvements discussed in the modelling section to add some roughness to the borders of the osteons. In these simulations it does not have much impact to store or use fracture patterns, since as it has been shown throughout this work, the distribution and density of the bone structures that act as barriers to fracture growth are different between specimens and the selected area of the bone. Another possible future improvement would be to adapt the model to include hand-

segmented images using traditional methods to more accurately fit the model using FEM simulations.

8.3 Deep learning

As for the use of deep learning in the clinical setting, much progress has been made in recent years. The most common techniques are focused on classification using convolutional neural networks (CNN). Tanzi et al. [152] employed a CNN as support for segmentation and identification of landmarks during the intra-operative surgery for the subsequent use of augmented reality as assistance. Tanzi also uses CNNs to classify bone fractures through X-ray images that are in a grayscale [153, 154]. Lee et al. [155] employed a CNN, based on a pre-trained ImageNet model, to assess bone age through radiographs. This study uses images of the hand of patients and attempts to evaluate age by progression in the width of the epiphysis in relation to the metaphysis in different phalanges, carpal bone appearance and the radial or ulnar epiphyseal fusion.

Generative adversarial networks (GANs) are algorithmic architectures that generate synthetic instances of data that can be passed off as real data. They are used widely in image generation, video generation and voice generation. It is not common to find literature on medical imaging with these networks. Xiong et al. [156] trained GANs to reconstruct artificial defects of the bone midface using CT images of the skull. Su et al. [157] use it to obtain increased data based on radiographs of hands for use in age assessment studies.

Although no models are presented in this dissertation as a result of these techniques, several experiments have been performed with the aim of generating cortical tissue representations using GANs. The objective has been to use cortical tissue images from the microscope to train the neural network in order to obtain more representative images of the tissue, since the model generated in this chapter is more consistent with the result of segmenting an image of bone tissue. During the experimentation, different networks already constructed have been used as a reference

and tests have been carried out with previously trained models obtaining similar results. The main drawbacks encountered in obtaining the results are detailed below:

- Complexity to obtain images of bone tissue.
- The images are not uniform, mainly in color.
- Complexity to configure the network.

To obtain microscope images of human cortical bone tissue, the first drawback lies in obtaining human bones as well as permits for handling and transporting them to the workstation. Once obtained, the next step consists of collecting a sample, so we have contacted an expert in mineral cutting from the Department of Geology of the University of Jaén. For the samples to be visible through the microscope, they had to be a couple of millimeters thick, so the approach was to cut off one end of the sample, attach it to the sample holder and then file the sample until the thickness of the sample allowed the light of the microscope to pass through. Once the sample was obtained, a x10 magnification lens was placed on the microscope and a x2 optical zoom was used. In this way, we could already see the cortical zone. To obtain each of the tissue images, a test was launched with the RGB lasers of the microscope and an interpolation was made of the color channels obtained at different heights. Normally between 10 and 15 layers were made for each image, although this varied depending on the thickness of the sample in the area. Each test took more than a minute to run and was carried out in the facilities of the central research support services of the University of Jaén with the help of a laboratory technician. Figure 6.3 summarizes the process described in this paragraph.

The second drawback we found is that the images obtained are not uniform. Figure 8.3 depicts an image of bone tissue obtained from the microscope. The image shows even the direction in which the sample has been filed. In this way, it is possible to observe different disturbances on the image in an area that for our eye is a point. In addition, when working at such a small scale, the difference in height in the cortical zone is notorious. At the same point, different levels of height can be distinguished so

that the light crossing the sample is seen with different intensities depending on the area. Therefore, there is no common pattern that determines the boundaries of the microstructures that make up the cortical tissue and, combined with the above, makes it difficult to extract features from the images used as input. Both this issue and the previous one give rise to the third drawback, since they make it difficult to configure the neural network.

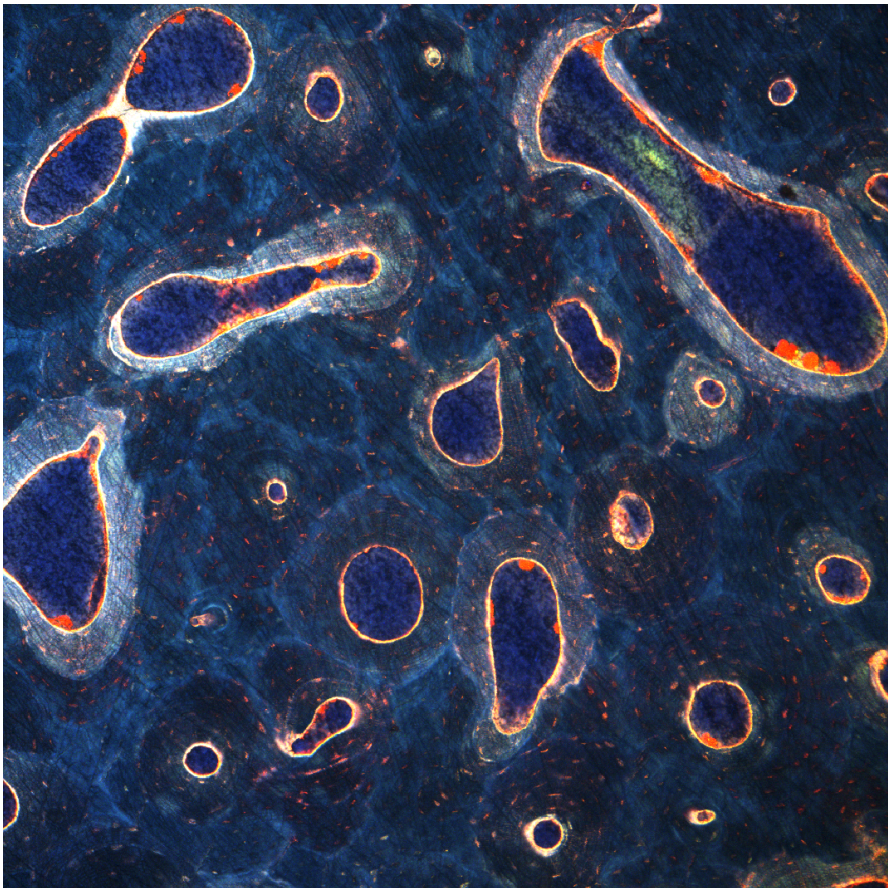


Figure 8.3: Image of cortical tissue obtained from the microscope at x10 magnification.

The best approach for further progress along this path would be to find some alternative method to obtain the sample avoiding height differences and detachments of the cortical zone when preparing the sample of training. In the same way, these networks can also be trained using point clouds and geometric models, which opens a new path not only to obtain replicas of medical images of cortical tissue, but also to obtain fracture models using as training the models generated with the macroscale fracture simulator and real clinical cases.

Chapter 9

CONCLUSIONS

Fracture of bone models is a field of great interest due to the increase in the number of cases associated with the increase in life expectancy and the consequences it has on the population. This thesis has reviewed the existing techniques and approaches on fracture representation and simulation. These studies have been classified and their advantages and shortcomings have been analysed. The review carried out has highlighted the need to consider the hierarchical structure of bones in the representation and simulation of fracturing. For example, fracture reduction at the macroscopic level involves an internal regeneration process in which bone microstructures are directly involved. Moreover, they also act as barriers to fracture growth by determining the route and expansion of the fracture. Therefore, it is vital that studies do not only focus on the bone at a macroscopic level, it is also necessary to represent and study the behaviour of the bone at the microscopic level.

The literature review has allowed us to identify the existing bone representation techniques at the macroscale level. However, it is the purpose of the study in question to determine the best approach to representing

the bone model. Therefore, virtual bone models have been represented through 3D scanning and medical image segmentation techniques according to the suitability of the study. The principal difference is that the models reconstructed from 3D scanning only have information of the outer surface of the bone while the reconstructions through CT images allow us to delimit also the inner edge of the cortical area, thus separating it from the trabecular area of the bone.

The algorithm developed for fracturing is based on bone models using the techniques described above. Previous studies have been based on concrete fracturing approaches, while the approach developed here allows the combination of a geometry-based approach through the use of patterns and a physics-based approach. Thus the results obtained present a realistic aspect, through the use of patterns, and simulate a mechanical behaviour when forces are applied on the model. This contribution opens a line to be exploited in the future using the best part of the approaches used.

Concerning the patterns used in the developed tool, the different approaches to carrying out the representation have been studied. In addition, different methods have been proposed to obtain information about the fracture area of a bone, in order to extrapolate it to other models through the patterns. Even though only one of the proposed patterns has been used to perform fracture simulations, in the future it is expected to extend the scope of the tool to include the rest of the representations, solving the pitfalls encountered when adjusting these patterns to the bone models.

In order to support the previous simulations and to verify that the simulations are repeatable under a controlled environment, a study has also been carried out in collaboration with several areas of knowledge in which a process for the arrangement of human bones in a device for their fracturing by means of compression loads has been established. As a result, we have been able to observe the effect of the bone features throughout the fracture process. In addition, as a conclusion of this study we have been able to determine that the repeatability of an experiment can be confirmed as long as the conditions of the bones are similar. In contrast to previous studies where only the proximal zone of the bone has been tested, the ex-

periment has been carried out on the entire bone. In fact, the only test model that did not fracture in the same area as the rest, fractured in the distal part of the bone, which is the one omitted in previous studies.

The bone models obtained are also used as a basis for the rest of the studies carried out. The representation at the microscopic level can be based on the whole bone model in which a specific area of the bone or a predetermined size is selected. In the first case, the bone model used as a reference must come from CT images, as this is the only method that allows the inner border of the cortical area of the bone to be delimited. Once delimited, the algorithm developed distributes bone microstructures throughout the entire area according to the input parameters. This representation resolves one of the main shortcomings of microscopic studies, since all the representations and simulations in the literature are based on manual segmentations of very specific areas of the bone, in which a very small number of bone structures appear. In addition, the process for obtaining a microscope image, as well as the manual segmentation of the image, is very slow.

In relation to the microscopic representation, an algorithm for the fracturing of the cortical area at this level has also been performed following a graph-based approach. In previous literature it is observed how cortical tissue structures are essential in determining the path that a fracture follows. All simulations reviewed at the microscopic level were based on the FEM method. The finite element method allows us to represent numerical models and to generate approximations of very complex solutions to physical problems such as fracturing models. The finite element method takes into consideration all the elements surrounding the object of study, i.e., if we are studying the growth of a fracture all the cortical tissue surrounding the fracture is taken into consideration. The models used in these simulations come from manual segmentations and focus on very specific areas. Therefore, the representations they use are very biased because they focus on a very small region of the bone, leading to inaccuracies. The representation of the cortical tissue proposed in this thesis is so large that it is almost unfeasible, and very inefficient, to transfer it to a tool for FEM simulations. Therefore, the algorithm developed

follows a graph-based approach.



INTRODUCCIÓN (SPANISH VERSION)

El incremento de la esperanza de vida está provocando un aumento de los casos de fracturas de cadera en los adultos mayores, pues con el paso de los años los huesos se desgastan y se vuelven más débiles. En este sentido, existen estudios recientes que documentan que la cantidad de fracturas se está multiplicando de forma considerable con el paso de los años a nivel mundial, pasando desde los 1.26 millones de casos en el año 1990 a los 4.5 millones en 2050 [15]. Las consecuencias para los pacientes van más allá de la afectación a nivel físico y mental, se ha registrado que la tasa de mortalidad tras una operación de cadera se encuentra entre el 5% y el 10% durante el primer mes y se incrementa de forma considerablemente con el paso del tiempo durante el primer año [16].

Ante esta situación, la informática gráfica aplicada a la medicina ha pasado a adquirir un fuerte protagonismo. Se trata de un campo de investigación que tiene numerosas líneas abiertas y que sigue en auge debido

al progreso de las nuevas tecnologías. Esta evolución ha permitido que en el ámbito de la traumatología y las fracturas óseas se creen técnicas asistidas por computador que, por una parte, facilitan a los especialistas médicos la reducción del tiempo de intervención y, por otra, minimizan el riesgo de error gracias al estudio previo de las fracturas.

La realización de estos estudios encuentran como uno de sus primeros escollos la dificultad para conseguir huesos humanos para realizar estudios, por lo que es habitual encontrar trabajos que se basan en el uso de huesos de animales. Precisamente, este es el gran inconveniente que plantean estos trabajos ya que los modelos óseos de animales presentan unas propiedades, forma y dimensiones que varían respecto a los de los humanos [17].

La literatura previa muestra una clara tendencia a realizar estudios sobre los huesos a nivel macroscópico sin tener en consideración la estructura jerárquica del mismo. Sin embargo, está demostrada la influencia directa que tienen las estructuras óseas que componen el hueso a nivel microscópico sobre los diferentes fenómenos que afectan a los huesos [18].

En este marco se encuadra la presente tesis doctoral que tiene por objeto el estudio de la estructura jerárquica de los huesos para llevar a cabo simulaciones desde un punto de vista macroscópico y microscópico. Para ello, se analizan las propiedades del hueso y se hacen representaciones multinivel del hueso. Por último, se identifican las características de las fracturas para terminar con simulaciones de fracturación sobre las representaciones multinivel del tejido cortical óseo obtenidas a lo largo del trabajo.

A.1 Propósitos y objetivos

Atendiendo a los problemas que se acaban de identificar en el apartado anterior, como se ha tenido ocasión de adelantar, el objetivo principal de esta tesis es investigar y desarrollar técnicas para la representación de los huesos a diferentes niveles de forma virtual para llevar a cabo simulaciones

de fracturación. Dado que existen varias técnicas para la reconstrucción de modelos óseos de forma completa, el esfuerzo principal se concentra en la representación del tejido cortical del hueso humano a nivel de microscopio. Además, se investigan y desarrollan nuevos métodos para la fracturación de los modelos generados anteriormente. Los objetivos perseguidos son:

- Identificar y aplicar las principales metodologías para la reconstrucción de huesos desde un punto de vista macroscópico.
- Investigar y desarrollar nuevos algoritmos para la representación del hueso cortical a nivel microscópico.
- Investigar y desarrollar técnicas que permitan la identificación y representación de la zona fracturada de un hueso.
- Investigar y desarrollar nuevos métodos que permitan la fracturación de los huesos a nivel macroscópico.
- Investigar y desarrollar nuevos métodos que permitan la fracturación del hueso cortical desde un punto de vista microscópico.
- Analizar y evaluar los resultados obtenidos por los métodos propuestos.

A.2 Organización de esta tesis

Esta tesis está organizada en torno a los propósitos y objetivos descritos en el apartado anterior. Se distinguen dos grandes bloques: el primero versa sobre los estudios realizados sobre el hueso completo (capítulos 3-5) y en el segundo se estudia el tejido óseo a nivel microscópico (capítulos 6-7).

En el capítulo 2 se realiza una revisión de los trabajos actualmente propuestos en la literatura relacionados con las técnicas de representación de los huesos y fracturación. Esta revisión se hace desde un punto de vista

macroscópico y microscópico. Además, se define la estructura jerárquica de los huesos y las partes más características. Durante todo el trabajo se hace especial énfasis en el fémur ya que es uno de los huesos más fracturados y el principal involucrado en los casos de fractura de cadera.

El capítulo 3 hace un análisis de las diferentes técnicas para la representación de un hueso de forma virtual y de las diferentes formas en las que se puede representar una zona fracturada. Cada representación de la zona de fractura lleva asociada un método con el cual se puede obtener dicha representación, así como el proceso de validación que se ha seguido para evaluar los resultados obtenidos.

El capítulo 4 se centra en la simulación de fracturación a nivel de macroescala. Este nivel de la estructura jerárquica del hueso es el que representa el hueso de forma completa. Dentro de este capítulo se analizan las características de Blast, la herramienta utilizada para llevar a cabo la simulación. El algoritmo que se propone en este capítulo mezcla un enfoque basado en los patrones obtenidos en el capítulo anterior con un enfoque basado en físicas. Para ello, se obtiene un modelo prefracturado mediante los patrones de fractura y se separan solo aquellos fragmentos que son dañados por algún componente físico durante una simulación. Para determinar los elementos del modelo prefractuado que deben separarse, se utilizan una serie de propiedades mecánicas y físicas preestablecidas. Por último, se muestran los resultados y se evalúan.

El capítulo 5, que cierra el primer bloque, presenta un estudio en el que se han involucrado diferentes áreas del conocimiento. En este caso, el estudio se centra en la fracturación de huesos mediante experimentación mecánica. Todos los huesos fracturados durante la experimentación, así como los resultados obtenidos han sido evaluados desde un punto de vista computacional con el que se han tomado medidas precisas de todas las zonas características del hueso, desde un punto de vista mecánico mediante un análisis del comportamiento del hueso en el momento de la fractura y desde un punto de vista clínico realizado por expertos.

Como ya se ha adelantado, en el segundo bloque se produce un cambio en la línea expositiva al centrarse en el nivel de microscopio. Este bloque se centra en la vista de los huesos a nivel de microscopio. Así, en

el capítulo 6, a diferencia de los métodos tradicionales donde se realizan segmentaciones manuales sobre imágenes de microscopio, se propone un algoritmo procedural que se encarga de generar una representación de todas las estructuras óseas en una zona determinada del hueso, siendo solo visibles desde un microscopio. La validación de los modelos generados se hace desde un punto de vista estadístico y mediante un análisis realizado por expertos en el área de estudio.

El capítulo 7 muestra un estudio original en el que se desarrolla un algoritmo para la simulación de fracturas en el modelo generado durante el capítulo anterior. En este caso, al obtener una representación de todo el tejido cortical y no una sola parte del mismo como en los casos estudiados, el algoritmo se expande hasta fracturar el hueso por completo. Las características del tejido óseo determinan el crecimiento de la fractura hasta que se llega a una condición de parada. Además, también incluye el proceso para la evaluación del mismo.

Por último, los últimos capítulos muestran las conclusiones generales obtenidas tras el trabajo realizado, así como nuevas líneas de trabajo que se han abierto tras los avances obtenidos a lo largo de esta tesis doctoral.



CONCLUSIONES (SPANISH VERSION)

La fracturación de modelos óseos es un campo de gran interés por el aumento de los casos asociado al incremento de la esperanza de vida y a las consecuencias que tiene sobre la población. Como se ha tenido ocasión de comprobar, en esta tesis se han revisado las técnicas y enfoques existentes sobre representación y simulación de fracturación. Estos trabajos han sido clasificados y analizando sus ventajas y carencias. La revisión llevada a cabo ha puesto de manifiesto la necesidad de considerar la estructura jerárquica de los huesos en la representación y simulación de fracturación. Por ejemplo, la reducción de una fractura a nivel macroscópico conlleva un proceso interno de regeneración en el que se ven involucradas de forma directa las microestructuras óseas. Además, también ejercen de barreras ante el crecimiento de una fractura determinando el camino y la expansión de la misma. Por ello, es vital que los estudios no solo se centren en el hueso a nivel macroscópico sino que también es necesario representar

y estudiar el comportamiento del hueso a un nivel microscópico.

La estudio bibliográfico realizado ha permitido identificar las técnicas de representación ósea a nivel macroescala existentes. Sin embargo, la finalidad del estudio en cuestión es la que determina la mejor forma de representar el modelo. Con este fin, se han representado modelos óseos virtuales a través de técnicas de escaneo 3D y de segmentación de imágenes médicas según la conveniencia del estudio. La principal diferencia es que los modelos reconstruidos a partir del escaneo 3D solo tienen información de la superficie exterior del hueso mientras que las reconstrucciones a través de imágenes CT permiten delimitar también el borde interior de la zona cortical, separándolo así de la zona trabecular del hueso.

El algoritmo desarrollado para la fracturación parte de los modelos óseos a través de las técnicas descritas anteriormente. Los trabajos previos se basan en enfoques concretos de fracturación mientras que el enfoque desarrollado permite la combinación de un enfoque basado en geometría mediante el uso de patrones y un enfoque basado en físicas. De esta forma, los resultados obtenidos presentan un aspecto realista, mediante el uso de patrones, y simulan un comportamiento mecánico ante la aplicación de fuerzas sobre el modelo. Esta contribución abre una línea que explotar en el futuro utilizando la mejor parte de los enfoques utilizados.

En cuanto a los patrones utilizados en la herramienta desarrollada, se han estudiado las diferentes formas de llevar a cabo la representación. Además, se han propuesto diferentes métodos que permiten obtener información sobre la zona de fractura de un hueso para extrapolarla a otros modelos a través de los patrones. Aunque sólo se ha utilizado uno de los patrones propuestos para hacer simulaciones de fracturación, en un futuro se espera ampliar el ámbito de la herramienta para incluir el resto de representaciones resolviendo los escollos encontrados a la hora de ajustar estos patrones a los modelos óseos.

Con objeto de dar soporte a las simulaciones anteriores y comprobar que las simulaciones son repetibles bajo un entorno controlado, también se ha realizado un estudio en colaboración con diversas áreas del conocimiento en el que se ha establecido un proceso para la disposición de huesos humanos en un dispositivo para su fracturación mediante cargas

de compresión. Como resultado, hemos podido observar el efecto de las características y dimensiones del hueso a lo largo del proceso de fractura. Además, como conclusión de este trabajo hemos podido determinar que se puede confirmar la repetitividad de un experimento siempre y cuando las condiciones de los huesos sean similares. A diferencia de los estudios previos dónde sólo se han hecho prueba sobre la zona proximal del hueso, el experimento se ha llevado a cabo sobre el fémur completo. De hecho, el único modelo de prueba que no se ha fracturado por la misma zona que el resto, se ha fracturado por la zona distal del hueso que es la que se omite en los trabajos previos.

Los modelos óseos obtenidos también sirven de base para el resto de estudios realizados. La representación a nivel de microscopio puede partir de un modelo óseo completo en el que se selecciona una zona concreta del hueso o de un tamaño predeterminado. En el primer caso, el modelo óseo utilizado como referencia tiene que provenir de imágenes CT, pues es el único método que permite delimitar el borde interior de la zona cortical del hueso. Una vez delimitado, el algoritmo desarrollado se encarga de distribuir microestructuras óseas a través de toda la zona atendiendo a los parámetros de entrada. Esta representación resuelve una de las principales carencias de los estudios a nivel de microscopio ya que todas las representaciones y simulaciones de la literatura se basan en segmentaciones manuales de zonas muy concretas del hueso, donde aparecen un número muy pequeño de estructuras óseas. Además, el proceso para la obtención de una imagen de un microscopio, así como la segmentación manual de la imagen, es muy lento.

En relación la representación de microscopio, también se ha realizado un algoritmo para la fracturación de la zona cortical a este nivel siguiendo un enfoque basado en grafos. En la literatura previa, se observa como las estructuras del tejido cortical son esenciales a la hora de determinar el camino que sigue una fractura. Todas las simulaciones revisadas, a nivel de microscopio, se basaban en el método FEM. El método de los elementos finitos es una herramienta muy potente que permite representar modelos numéricos y generar aproximación de soluciones muy complejas a problemas físicos como la fracturación de modelos. El método de los

elementos finitos tiene en consideración todos los elementos que rodean al objeto de estudio, es decir, si estamos estudiando el crecimiento de una fractura, se tiene en consideración todas las estructuras óseas que componen el tejido cortical que rodea a la zona de fractura. Los modelos que se utilizan en las simulaciones provienen de segmentaciones manuales y se centran en zonas muy concretas. Por lo tanto, las representaciones que utilizan están muy sesgadas porque se centran en una parte muy pequeña del modelo y no se puede tener en consideración toda la zona cortical, dando lugar a imprecisiones. La representación del tejido cortical propuesta en esta tesis es tan amplia que es casi inviable, y muy ineficiente, trasladarla a una herramienta para realizar simulaciones mediante FEM. Por lo tanto, el algoritmo desarrollado sigue un enfoque basado en grafos.

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