3D Printing as a Way of Integrating Mathematical Models in Arthroscopic Knee Surgery

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Our objective is to develop a novel method of approaching the arthroscopic treatment of osteochondral lesions within the knee joint by using mathematics as a way of understanding the geometry involved in the knee, both in normal and degenerated knee joint surfaces. Bone and cartilage lesions are frequent, whether as a result of trauma, degenerative pathology, vascular pathology (osteocondritis dissecans) or tumoral. In all cases, a defect can be repaired arthroscopically, if it has manageable dimensions and if the surgeon has the technological means and the necessary skills, through the use of grafts (autografts or allografts). Alternatively, a lesion that may be approached arthroscopically initially could prove to be too great for repair and may need a second intervention for reconstruction with an endoprosthesis. We aim to further deepen the surgeon's understanding of this pathology, through the use of 3D technology as a way of representing the osteochondral defect. Thus, its dimensions and position may be better understood, and the surgical intervention may be better planned out, potentially resulting in a shorter operating time and an overall superior outcome for the patient, and even potentially diminishing the number of unnecessary surgeries performed.

Keywords: Knee, arthroscopy, geometrical models, 3D printing, osteochondral lesions

Arthroscopy is an important tool in the management of bone and osteochondral lesions within the knee joint, to a certain extent [1]. These lesions are often a result of trauma [2,3], degenerative pathology [4], vascular pathology (osteocondritis dissecans) [5-7] or tumoral [8]. In all cases, a defect can be repaired arthroscopically, if it has manageable dimensions and if the surgeon has the technological means and the necessary skills, through the use of grafts (autografts or allografts) [9-11]. Alternatively, a lesion that may be approached arthroscopically initially could prove to be too great for repair and may need a second intervention for reconstruction with the aid of a technique that requires an open/mini-open approach or with an endoprosthesis.

In planning a procedure, the surgical team will use all imaging data available in order to reconstruct a bony or osteochondral defect, which will have two defining characteristics: volume and shape. These may be summarily approximated on a AP and LL set of radiographs, and also evaluated through a CT study, or even an MRI, but at the moment the most commonly used technique for visualization of a bony defect, at least in trauma, is a 3D reconstruction from a CT [12]. In tumors of the bone, a CT scan will be the method of choice, while in osteochondritis dissecans the defect will most often be visualized on an MRI examination of the knee [13].

A novel method to approach the problem of visualizing the bony defects around the knee is to use the data obtained through an imagistic study (i.e. a CT of the knee) in order to create a file to be 3D printed, therefore offering the surgical team a direct and to scale representation of both the bony surfaces as well as a representation of the bony defect, either as a negative image (the absence of material in the printed bone) or a positive volumetric image. The latter may be done by creating a representation of the defect in itself, calculating as close as possible the volume and defining the overall shape (difficult because of the highly irregular shape of a bony defect) and 3D printing the resulting object.

Objective

The objective of this article is to explore the methodology and the concepts behind the use of 3D printing in order to give the surgical team a better understanding of the spatial characteristics (i.e. volume, shape) of a bony or osteochondral defect of the knee that has the potential to be treated arthroscopically.

Experimental part

Materials and methods

The knee joint surfaces can be modeled geometrically, and represented visually by using 3D printing. We looked at the fundamental mathematical models using three dimensional (3D) geometry to represent the joint surfaces in a computer model, as a base of programming the printing of 3D models of knees. We also looked at the feasibility of different ways of representing bony and osteochondral lesions affecting the knee joint surfaces. We used visual information in the form of DICOM file format CT and MRI scans of knees as a basis for our gathered data.

In order to 3D print or to compute the volume of a bony defect or that of a bone segment itself we need to undergo two phases: segmentation and 3D printing or volume computation. For segmentation we used the software packages *3D Slicer* and *Analyze 12.0*. For 3D printing we used the software *Meshmixer* and a 3D printer and for volume computation we used different software packages such as *3D Slicer*, *Analyze 12.0*, *Netfabb Studio Basic 4.9* and three different methods. *3D Slicer* and *Analyze 12.0* can perform both segmentation and volume computation.

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Netfabb Studio Basic 4.9 works by computing the volume using a STL file of the segmented volume and STL files that we used were generated in *3D Slicer*.

Segmentation

In order to obtain an accurate segmentation, the size of each individual three dimensional unit of measure - voxel - must be determined, which includes also the slice spacing or slice thickness. In *3D Slicer*, we can find this information in the Volumes module/ Volume information section / Image spacing field/third box. In Slice viewer toolbar we can set the slice spacing automatically or we can set it manually using the slice spacing information from Volumes module. In *Analyze 12.0* the slice spacing is automatically set to its value.

Segmentation for bony defects can be done automatically or manually. Thresholding segmentation is one of the automated segmentation methods, but it is not very reliable for MRI data sets due to dramatically changes in intensities within a bony defect and due to other tissues intensities common with bony defect intensities. According to in-hospital generally accepted data acquiring protocols, we used MRI data sets for bone cysts and osteochondral lesions, while for tibial plateau fractures we used a CT data set.

For all our examples, with the exception of the normal knee bone segments, we have done manual segmentation.

Volume computation

The first method we used was the *3D Slicer* protocol. We obtained a segmentation of the bony defect using Segment Editor Module and Editor Module, alternatively. We then used Segment Statistics Module for volume computation. The second method we used was the *Analyze 12.0* protocol for segmentation and volume computation while the third method used the STL file of the segmented volume generated in *3D Slicer* and computed the volume in *Netfabb Studio Basic 4.9*.

Results and discussions

1. Segmentation of normal knee bones for 3D printing

We used a CT scan data set in DICOM format, axial section. The slice spacing was 0.7 mm and we had 286 images to work with. We introduced the CT images in DICOM format in the software *3DSlicer* version 4.8.1 for segmentation and volume rendering. We performed bone segmentation using threshold based automated segmentation technique embedded in *3D Slicer* (fig. 1).

2. Segmentation and volume computation of a tibial plateau fracture

In order to perform the segmentation and volume computation of a lateral tibial plateau fracture we used CT scan data set in DICOM format, coronal section (fig. 2). The slice spacing was 4 mm and we had 5 images of the

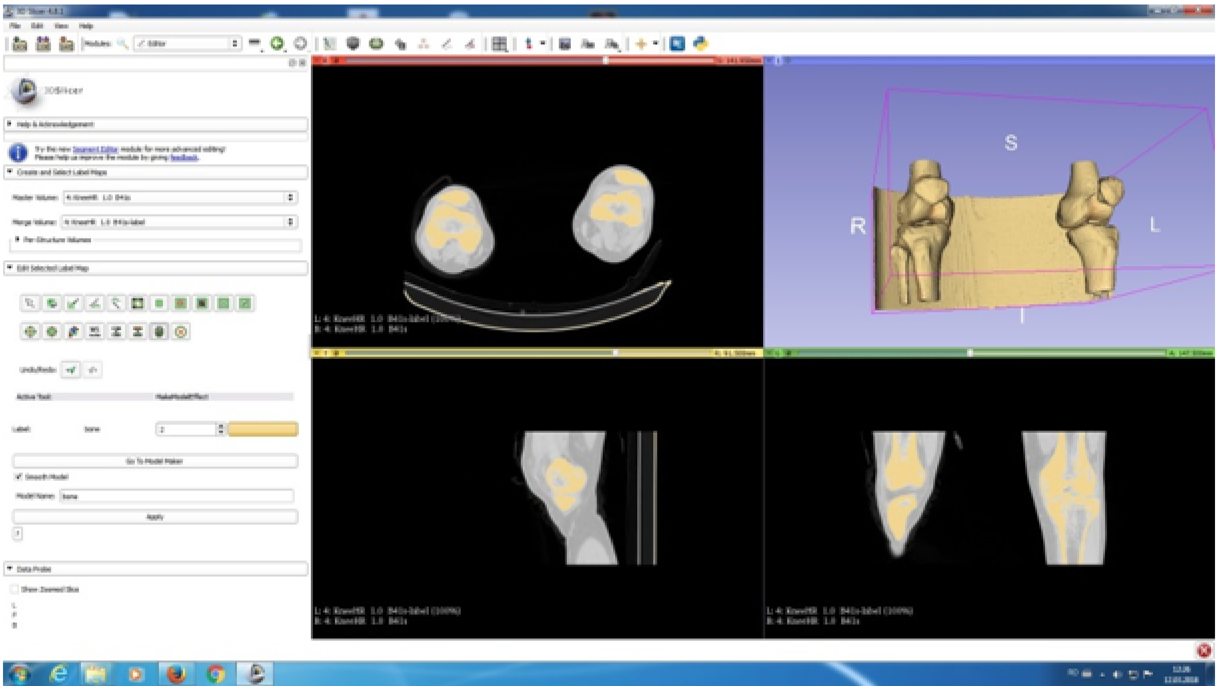


Fig. 1. Segmented knee bones from CT scan in *3D Slicer*

Fig. 2. The compresed bone and the missing part of a tibial plateau fracture

tibial plateau fracture. Using *Analyze 12.0* software we segmented manually three regions: the compressed bone, the compressed bone together with the missing part and the difference between the previous two.

We obtained the volume and the number of voxels for each segmented region. The results are concordant and can be seen in table 1. More accurate results could be obtained if we use more images which means a much thinner slice spacing (for example 0.5 - 1 mm)

Table 1

Segmented region	Number of voxels	Volume [cm^3]
Compressed bone and missing part	14453	5.40773
Compressed bone	11888	4.44801
Difference	2906	1.08731

3.Segmentation and volume computation of an osteochondral lesion

We used an MRI scan data set in DICOM format, sagittal section (fig. 3). The slice spacing was 0.8 mm and we had 21 images of the osteochondral lesion. Using *3D Slicer* (Segment Editor Module) and *Analyze 12.0* we segmented manually the ostheocondral lesion.

We calculated the volume of the osteochondral lesion using three different methods described above. The results are shown in table 2.

Fig. 3. Osteochondral lesion

Table 2

Software used	Number of voxels	Volume [cm^3]
3D Slicer (Segment Editor Module)	24641	1.47349
Analyze 12.0	25148	1.50291
Netfabb Studio Basic 4.9	–	1.52

4. Segmentation and volume computation of a distal femoral cyst

We used MRI scan data set in DICOM format. The slice spacing was 5 mm and consequently we had 4 images of the cyst (fig. 4).

We calculated the volume of the distal femoral cyst using three different methods described above. The results are shown in table 3. More accurate results could be obtained if we had more DICOM images which means a much thinner slice spacing (for example 0.5-1 mm) for the segmentation phase. The volume computation is segmentation dependant.

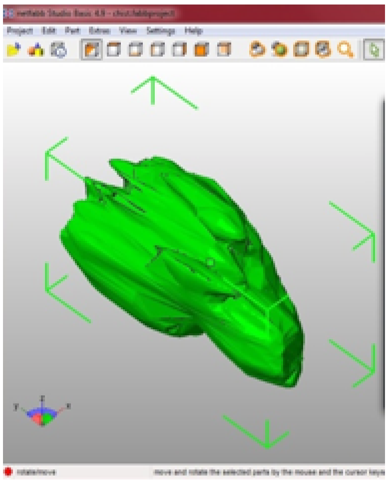


Fig. 4. Visual representation of a bone cyst defect

Table 3

Software used	Number of voxels	Volume [cm^3]
3D Slicer (Editor Module)	2653	1.63987
3D Slicer (Segment Editor Module)	2715	1.67819
Analyze 12.0	2707	1.67322
Netfabb Studio Basic 4.9	–	1.61

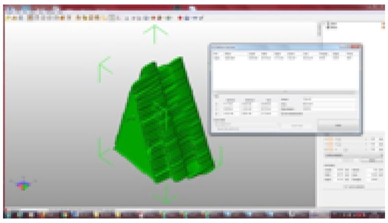
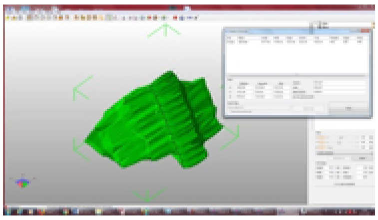
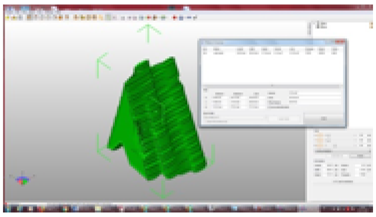
5. Geometrical shape segmentation and more volume computation for the same osteochondral lesion

We used an MRI scan data set in DICOM format, sagittal section. The slice spacing was 4.5 mm and we had 4 images of the osteochondral lesion. We estimated the area where the vascularisation of the bone is affected as having roughly a triagular shape (zone 1) and also we enclosed the defect in a triangular shape (zone 2) as in figure 5.

We obtained segmentations for three regions (zone 1, zone 2 and zone 1 - zone 2) in *3D Slicer*and measured the corresponding volumes using *Netfabb*. The results are shown in table 4.

We notice we obtained inconsistent results with the previous results from table 2. Zone 2 (from table 4) which supossedly include the osteochondral lesion has 0.94 cm^3, while the lesion itself (from table2) has approximately 1.50 cm^3. This is due to the big difference in slice spacing (and therefore in number of images) for the two MRI scan data sets (0.8 mm /21 images for table 2and 4.5 mm/4 images for table 4).

Table 4

Volume for zone 1 [cm^3]		7.25
Volume for zone 2 [cm^3]		0.94
Volume for zone 1 – zone 2 [cm^3]		6.19

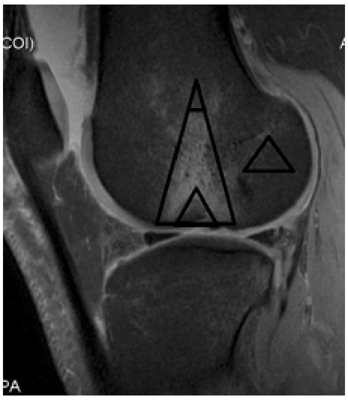


Fig. 5. Segmented defect and affected area in osteochondral lesion

6. Normal knee bones: preparation of STL files and3D printing

In order to 3D print the knee bones we saved the previous segmented regions (presented in Section 1) in STL format. We performed some repairing and cutting in the software *Meshmixer*and we got the STL file ready for printing (fig. 6).

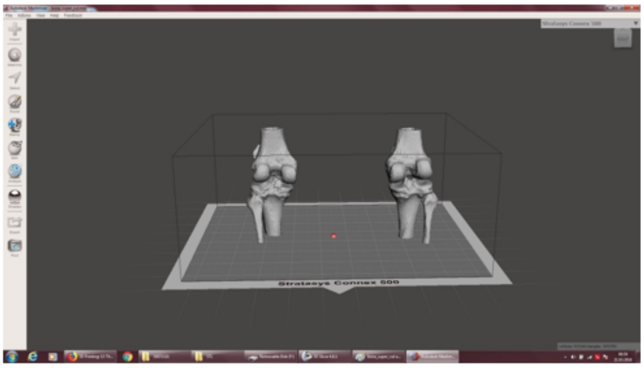


Fig. 6. Knee bones in *Meshmixer*

For 3D printing the STL file we used *Velleman Vertex K8400* 3Dprinter (fig. 7) and we obtained distal femur, patella, proximal tibia and fibula 3D printed in natural size (figs. 8-15).

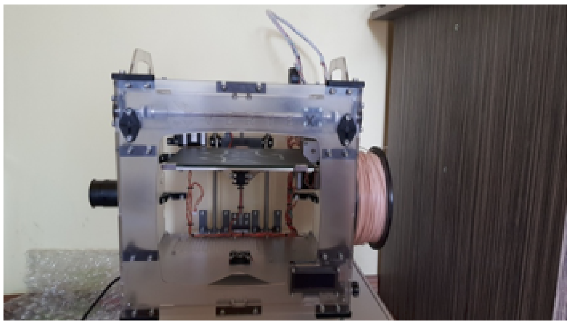


Fig. 7. 3D printer used in the printing process

Fig. 8-9.3D printed distal femur

Fig. 10-11.3D printed patella –AP and lateral view

Fig. 12-13.3D printed proximal tibia and fibula

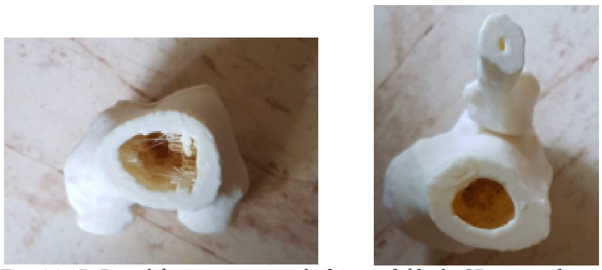


Fig. 14-15. Distal femur, proximal tibia and fibula 3D printed - cut-out view

7. Tibial plateau fracture– STL file preparation

For the tibial plateau fracture previously presented, using *3D Slicer* software, we segmented manually the total defect (compressed bone and missing part) in order to prepare it for 3D printing (figs. 16 and 17).

8. *Osteochondral lesion –trapezoidal shape - – STL file preparation*

For the osteochondral lesion previously presented we managed to prepare for 3D printing the trapezoidal shape (zone 1) (fig. 18-20).

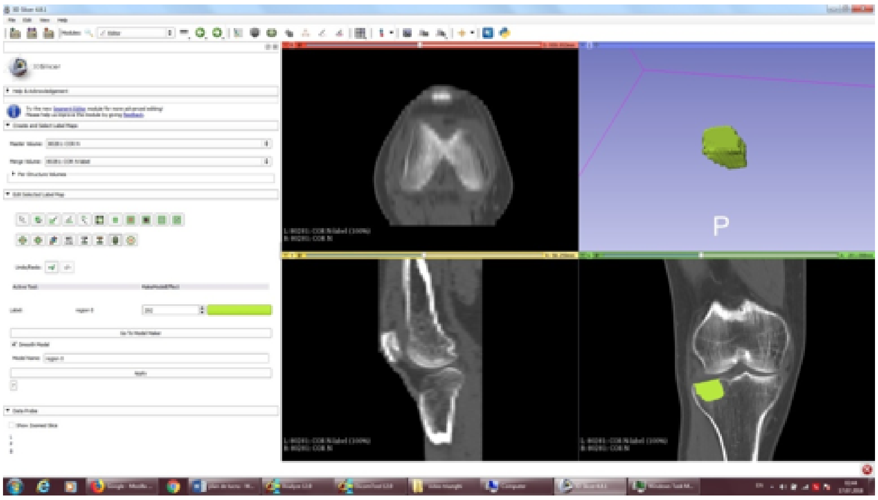


Fig. 16. Manual segmentation of the total affected area in a lateral tibial plateau fracture

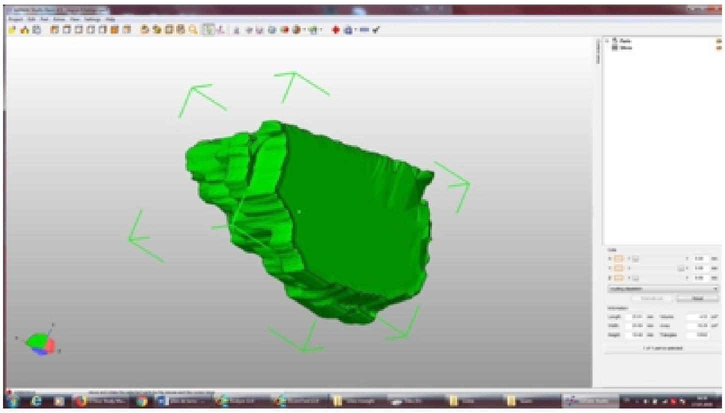


Fig. 17. Visual representation of the total affected area in a lateral tibial plateau fracture

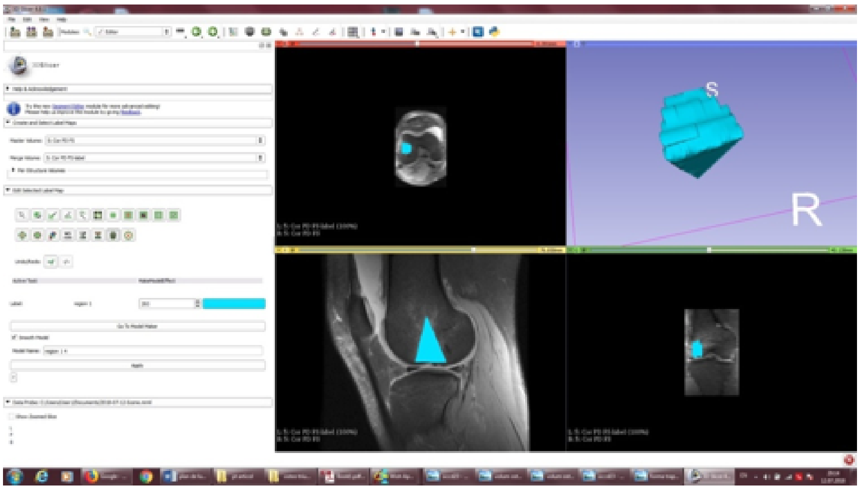


Fig. 18. Zone 1 segmented for 3D print

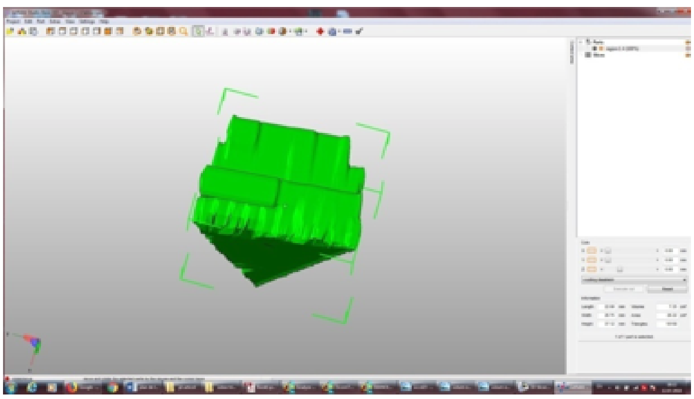


Fig. 19. Zone 1 segmented for 3D print - distal to proximal view

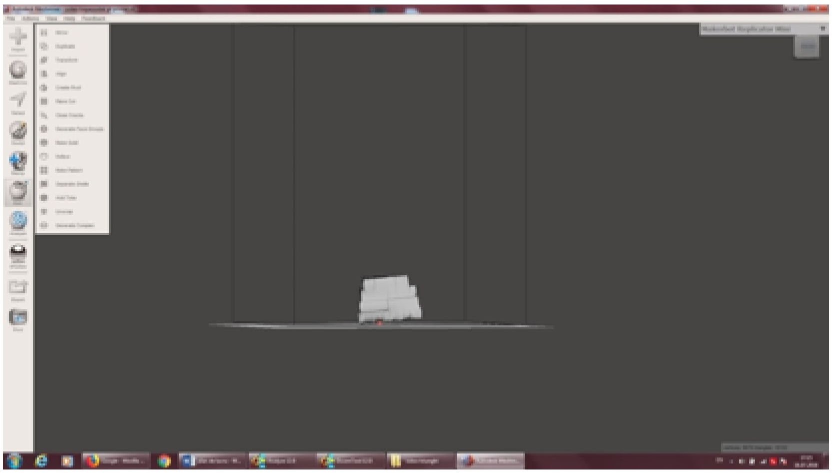


Fig. 20. Zone 1 segmented for 3D print - geometrical model

We found the automated segmentation of the normal knee bone segments to be facile using the dedicated software package *3D Slicer*, keeping in mind that we had 286 DICOM images to work with, with a slice spacing of 0.7 mm, from which we created an STL file. This allowed for an easy processing of the STL file in *Meshmixer,* followed by printing in a 1:1 ratio of the STL file using the *Velleman Vertex K8400* 3D printer. This produced an adequate representation of the distal femur, the patella, the proximal tibia and the proximal fibula, allowing for a detailed visual, kinetic and textural comprehension of the anatomy of the particular joint bones, in an unaltered state. In effect this surpasses the aim of the article (to explore the three dimensional geometry of bony defects as they are prepared for 3D printing), but we feel that it provides an important input into the significance of 3D printing for the clinician, helping the surgical team acquire a complex understanding of the normal and abnormal anatomy of a particular patient. This is important because the surgical act is, on one hand, an exercise in precision and on the other hand, it is a creative act, which requires a deep understanding of the problem that is to be resolved.

In a fracture situation, we often see the case where a fragment is compressing the underlying bone, causing a defect larger that the fragment itself. In practice, after positioning the fragment in its proper place, we are left with a defect that needs to be filled, either with an autologous bone graft or with a bone substitute. With the method described in this article we are able to determine not only the relative shape, but also the relative volume of both the fragment as well as the compressed area, providing the surgical team with important data regarding the geometry of the fracture, data that aids the fracture reconstruction process by allowing the surgeon to better understand the 3D dimensions of the bony defects, and if necessary to 3D print a model of said bone defects. We admit that the situation presented is a simple one, and more often than not, the fracture patterns involve a complex combination of fractured fragments and compressed areas, but we suggest that the method described may be used as a stepping stone in developing a better process in the future.

A femoral cyst presents a less compelling challenge and the usefulness of the method resides in the visual representation of the bone defect, useful if a bone graft is to be used, and in the calculation of volume, which may prove useful in a situation where precise reconstruction parameters and expensive bone substitutes are used.

The calculation of the volume and shape of the osteochondral defect is, at this point, mostly an exercise of imagination on the surgeon's part, although planning based on a 3D reconstruction from preoperative CT using 3D planning software and segmentation software is already used and in common practice and described in the literature [14]. Our objective is to develop a novel method of approaching the arthroscopic treatment of bony and osteochondral lesions within the knee joint by using mathematics as a way of understanding the geometry involved in the knee, both in normal and degenerated knee joint surfaces. By doing this, we aim to further deepen the surgeon's understanding of this pathology, through the use of 3D technology as a way of representing the osteochondral defect. Thus, its dimensions and position may be better understood, and the surgical intervention may be better planned out, potentially resulting in a shorter operating time and an overall superior outcome for the patient, and even potentially diminishing the number of unnecessary surgeries performed. Also, we found that by using the method describes in this article we were able to determine (both visually as well as by volume) not only the detached area of bone and cartilage (the defect), but also the poorly vascularized area underneath, which in many clinical scenarios is proven to be of precarious structural integrity, often necessitating grafting or reconstruction itself.

In all cases, both in MRI and CT DICOM data sets, we found that a higher number of slices is the essential difference between a poorly and a well segmented STL image, and ultimately influences profoundly the quality of the 3D printed object.

3D printing is more and more finding its way into the operating theatre, as is shown by an increasing number of articles describing various uses of this technology in orthopedic surgery.

In their 2015 article, Bizzotto et al. [15] presents what is claimed to be the first instance of using 3D printing in the treatment of a bone fracture. They report using the DICOM files from the CT scans of 20 patients bones (wrist, knee, clavicle, tibial plateau), uploaded in the OsiriX Dicom Viewer, in order to create an *.stl file that was later prepared with MeshLab and 3D printed with HP Design 3D in a plastic resin. They report obtaining a 1:1 model that was found useful by the surgical team in better understanding the fracture pattern.

The software used by Bizotto in order to create the *.stl file, the OsiriX Dicom Viewer, was tested by another team [16] and was found to be reliable and accurate when it comes to using length measurements on 3D-CT for kinematic analysis of the knee.Other authors also describe preferring fully automatic segmentation [17].

Another described use of 3D printing technology is to create patient-specific personalized cutting guides, with promising results in the resection and reconstruction of malignant bone tumors [18] and associated with virtual

3D planning for osteotomies around the knee [19]. Other authors have described extending the use of 3D printed guides for bone tunnel placement for ACL reconstruction, using CT studies [20] or MRI studies [21] as a source of visual data.

In their 2018 article [22], Okoroha et al. describe the use of 3D printing in order to create a 1:1 scale replica of a distal femur with a bone defect, that was later on used to size a patient-specific allograft plug for an osteochondral transplantation procedure, announcing good results with the aid of tactile feedback and improved visualization.

It is our belief that with modern development in computer technology [23] we will see a broader use of it in medicine, ranging from preoperative planning to the design of better hardware [24] and better interfaces [25] between man and machine.

Conclusions

We found that mathematical models represent a way of fundamentally understanding the geometry of the knee joint, and thus a means of representing it in a visual form, as 3D printings of the joint surfaces. The development of geometrical models can be used in the form of 3D printing the damaged joint surfaces, based on acquired visual data (CT image files) thus providing an excellent visual and navigational help for the surgeon in planning an arthroscopic repair of osteochondral lesions in the knee joint or converting from an initially arthroscopic procedure to an open procedure.

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