Preoperative Planning for Conservative Robotic Hip Surgery

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ABSTRACT — *Femoroacetabular impingement (FAI) is a medical condition that usually affects young athletes who suffer from hip pain during certain physical activities. Typically, the diagnosis is confirmed by radial magnetic resonance imaging (MRI) and it is treated during conservative hip surgery. This procedure requires an orthopedic surgeon with much experience, as the femoral head bone must be drilled to correct the loss of sphericity due to the cam type FAI. However, revision surgeries may be required mainly because of inappropriate bone resection, due to poor visualization or planning.*
The current project features a preoperative planning tool to be part of a robot-assisted conservative hip surgery. With robotic technology it is possible to perform more accurate movements, making results reproducible regardless of the surgeon and improving patient safety. An interactive application was developed in MATLAB® in which the user can outline the contour of a healthy femoral head over each 2D radial MRI view of the unhealthy femur in an easy-to-view manner. In addition, the software can successfully create the 3D surface correspondent to the limits of the region to operate which will act as safety zone in which the robot arm will be constrained to work. Lastly, the registration between this surface and the surface of the real femoral head was completely mapped and calculated using the Iterative Closest Point algorithm with an error around 2mm.

KEYWORDS: Femoroacetabular Impingement; radial MRI; Preoperative Surgical Planning; Registration

1 Introduction

Medical robots have gained popularity among orthopedic surgeries because they can perform more precise movements, making their results reproducible regardless of surgeon and patient, reducing variation in outcomes and facilitating minimally invasive surgery [1].

One good applicant for robotic technology and computer-assisted methods is femoroacetabular impingement (FAI) due to its simple concept of mechanical collision of rigid bodies.

FAI is a medical condition recognized as a cause of hip pain, cartilage or acetabular labral lesions and recently correlated with early osteoarthritis in adults. It is estimated to have a prevalence of 10-15% in the general adult population and is highly related to sports activity, especially its cam-type [2].

In cam-type FAI, the proximal femur has an abnormal morphology in which femoral head loses its sphericity and the femoral head-neck offset decreases. During hip flexion and internal rotation, the aspheric femoral head is forced into the anterosuperior acetabulum, which causes shear stress between cartilage and the labrum and also compression into the cartilage. Thus, patients with this type of impingement, have mostly chondral and labral lesions located anterosuperiorly.

To carefully evaluate the FAI condition, several imaging studies can be performed, such as radiographs, magnetic resonance imaging (MRI), computed tomography (CT) or ultrasound. Yet, MRI is preferred for a better assessment of FAI, since it can easily detect joint effusion, labral pathologies and early cartilage changes.

When patients with FAI present serious damage and considerable deformities, they need surgical treatment, to alleviate the femoral impingement against acetabular rim, allowing for better and unobstructed hip motion.

Hip arthroscopy being less invasive, is considered the best alternative with smaller incisions, shorter recovery times and lower morbidity rate, particularly for professional athletes. After this surgery, most patients reached near normal or normal levels of functionality, returning to activity and sports [3,4].

As a surgical procedure, it requires perfect planning and technique for successful outcomes and is a procedure with a long learning curve. During this technique, the goals to be achieved are to reshape the femoral head to reach its spherical contour, normalize femoral offset, correct the acetabulum coverage, repair or rebuild both chondral and labrum damage to improve joint sealing and restore its normal mechanics.

Revision surgeries may be required mainly because of incorrect bone resection, due to poor visualization or planning, and lack of experience. While under resection can be treated with revision surgery, excessive resection leads to permanent damage to the hip joint. If, on the one hand, an overly aggressive rim trimming promotes hip instability with gross dislocation, on the other hand, over-resection on cam impingement leads to abnormal hip mechanics and possible fracture at the head-neck junction [5,6].

In recent times, N. Kobayashi *et al.* [7] presented a computer-assisted hip arthroscopic surgery for FAI. It included three stages: preoperative evaluation, planning by virtual osteochondroplasty and intraoperative navigation assistance, where the 3-dimensional model of the acetabulum and femoral head was built based on a set of axial CT images.

Moreover, C. N. Park *et al.* [8] have recently proven that robotic-assisted femoral osteochondroplasty is more accurate than a conventional technique for the treatment of cam-type FAI. In this study, the surgeon could create a preoperative plan through the 3D computerized model generated by the CT scans and intraoperatively during osseous resection, a robotic arm could guide the surgeon providing visual and haptic feedback. The main advantage of this system was that the robot limits the movements of the surgeon within the confines of the predetermined resection zone. Also, the robotic-assistance surgeries were significantly faster during bone resection than the freehand technique because there was no need to spend time carefully contouring the femoral head-to-neck junction since the robot induces a haptic barrier in the planned resection zone.

Additionally, M. Masjedi *et al* [9] validated the use of robotic technology during the corrective surgery of cam-type FAI, where under-resection and over-resection of femoral cam deformities were prevented. They performed a 3D surgical plan based on a 3D model from a set of CT scans in which they fit a best sphere for the femoral head and used the Acrobot Sculptor robot which again restricted the movement of the surgeon's cutting burr.

Being the preoperative planning one of the essential prerequisites for the success of this type of orthopedic procedure [10], this work features a preoperative planning tool in order to be part of a robot-assisted conservative hip surgery procedure to correct the cam type FAI.

Differently of the previous studies, it was developed a software using the MATLAB® image processing tools assembled on the MRI radial sequence acquired during diagnosis of patients with cam-type FAI.

The work developed is divided into the following objectives:

- Creation of an application in which the surgeon can delineate the region to operate in order to recreate the sphericity of the femoral head;
- Surface formulation that delimits the bone area to be removed during the surgical procedure that will act as the safety zone in which the robot arm is constrained to work;
- Registration between the formulated surface and the head of a plastic femur, which mimics the patient's coordinates in the operating room.

2 Methods

There were used different MRI sets (radial_DP, radial_DP-FS and T1_tse_axial) from two different patients performed at Hospital da Luz during the diagnosis of cam type FAI and all data were processed with MATLAB® version R2018a.

2.1 DICOM Files

Along this work was necessary to visualize in 3D space each MRI scan. To do that, it was necessary to understand how to handle each MRI slice which is saved in Digital Imaging and Communications in Medicine (DICOM) format.

DICOM files contain the medical image intensity values and different aspects of the patient, including personal information and the coordinate system, such as image position and orientation in relation to the patient's anatomy. Each information is encoded in an attribute in the form of a tag that includes the group and element numbers of the DICOM format. Table 1 displays the attributes used along this work and their description [11,12].

Table 1 - DICOM attributes. [11,12]

Name	Tag	Description
Image Position (Patient)	(0020,0032)	Coordinates (x,y,z) of the upper left corner of the slice with respect to the patient anatomy coordinate system.
Image Orientation (Patient)	(0020,0037)	Direction cosines of the first row and the first column of the slice with respect to the patient anatomy coordinate system.
Pixel Spacing	(0028,0030)	Numeric pair that corresponds to the physical distance in mm between the center of each pixel between adjacent row and adjacent columns.
Columns	(0028,0011)	Number of columns in the image.
Rows	(0028,0010)	Number of rows in the image.

The reference coordinate system (RCS) of the DICOM files is the LPS coordinate system, in which the x-axis goes from right to left (L axis), the y-axis goes from the anterior region to the posterior region (P axis) and the z axis goes from inferior region to superior region (S axis). The image coordinate system of each MRI slice is defined regarding to the patient anatomy coordinate system [11,12].

Using the attributes relative to the image plane and pixel spacing, it is possible to position and orient each MRI slice regarding to the patient coordinate system, as illustrated by Figure 1.

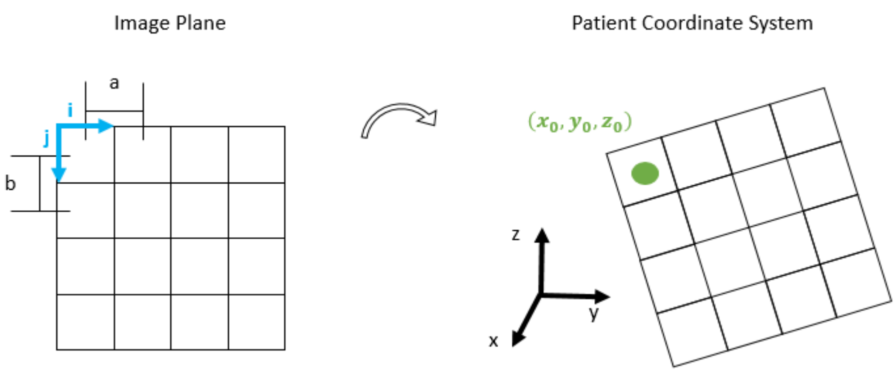


Figure 1 - Mapping of pixels into the patient coordinate system.

The mapping of pixel location (i,j) to the RCS is given by:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + \begin{bmatrix} aR_1 & bC_1 \\ aR_2 & bC_2 \\ aR_3 & bC_3 \end{bmatrix} \begin{bmatrix} i \\ j \end{bmatrix} \quad (1)$$

where:

- (x,y,z) are the spatial coordinates of the pixel in the frame's image plane in mm;
- (x_0,y_0,z_0) are the three values of the Image Position (Patient) attribute which corresponds to the location in mm from the origin of the RCS;
- *a* represents the column pixel resolution given by the first number of Pixel Spacing attribute in mm;
- *b* corresponds to the row pixel resolution given by the second number of Pixel Spacing attribute in mm;
- (R_1,R_2,R_3) are the three values from the row direction cosine of Image Orientation (Patient) attribute;
- (C_1,C_2,C_3) are the three values from the column direction cosine of Image Orientation (Patient) attribute.
- *i* is the column index to the image plane;
- *j* is the row index to the image plane.

2.2 Preoperative Planning Tool

This section presents the developed software application.

2.2.1 Outline Region to Operate

The interface of the interactive application settled to perform the preoperative planning of hip preserving surgery is presented in Figure 2.

It is divided into three sections: (1) file region where the user can load the DICOM files of the 2D radial sequence of a specific directory located on his computer; (2) presentation of each editable radial slice with interactive tools to delineate the region to operate; (3) 3D space in which the radial sequence is represented and also the interpolated surface of the region to be operated.

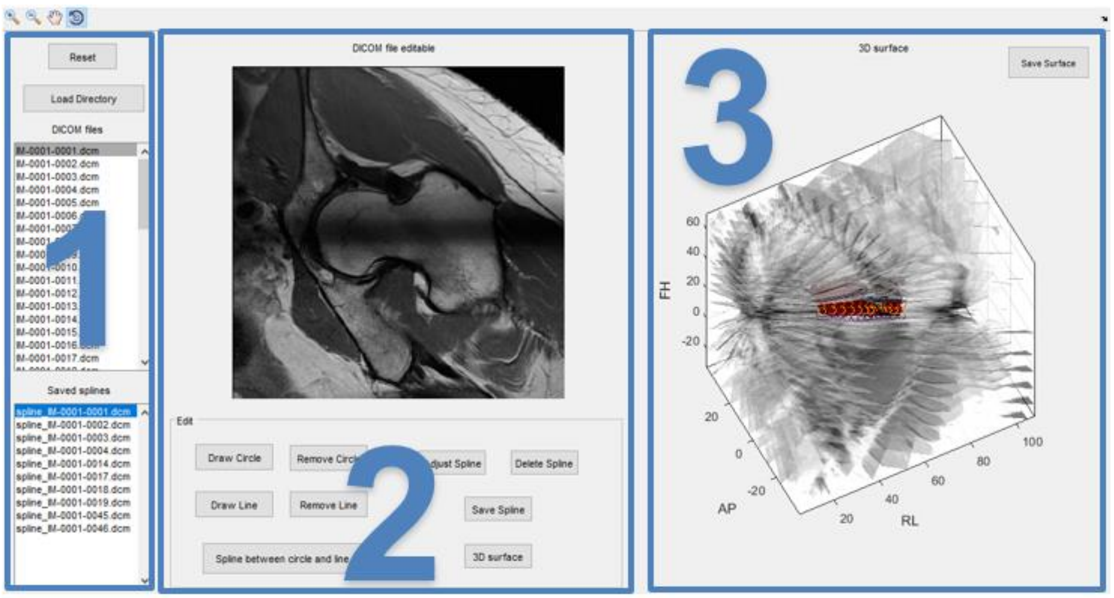


Figure 2 - GUI of the interactive application to outline the section to operate: (1) file region; (2) editable region; (3) viewing region of the 3D surface of the section to operate.

This preoperative planning tool is designed for the orthopedic surgeon to analyze each 2D radial MRI slice to outline the contour of a healthy femoral head. For that, he has two different tools at his disposal: a circle, because the main goal is to correct the non-sphericity of the femoral head, and a line to establish how the circle would be connected to the other part of the femoral head.

Figure 3 illustrates the various steps the user must perform to obtain the corresponding delineation in an example of a 2D radial scan.

When the user has delineated several splines in different radial scans, he can press the ‘3D Surface’ button, which will produce a 3D plot of the interpolated surface based on the points of diverse spline lines in red. Also, in the same 3D space it will be displayed all the slices of the 2D radial sequence, as shown in Figure 4.

2.2.2 Principal Component Analysis (PCA)

To ensure that the interpolated surface generated by this application works correctly for each radial MRI sequence, it was necessary to resort to the Principal Component Analysis (PCA) method.

PCA is normally used to reduce the dimensionality of large data sets, maintaining most of the variation present in the original data set [13].

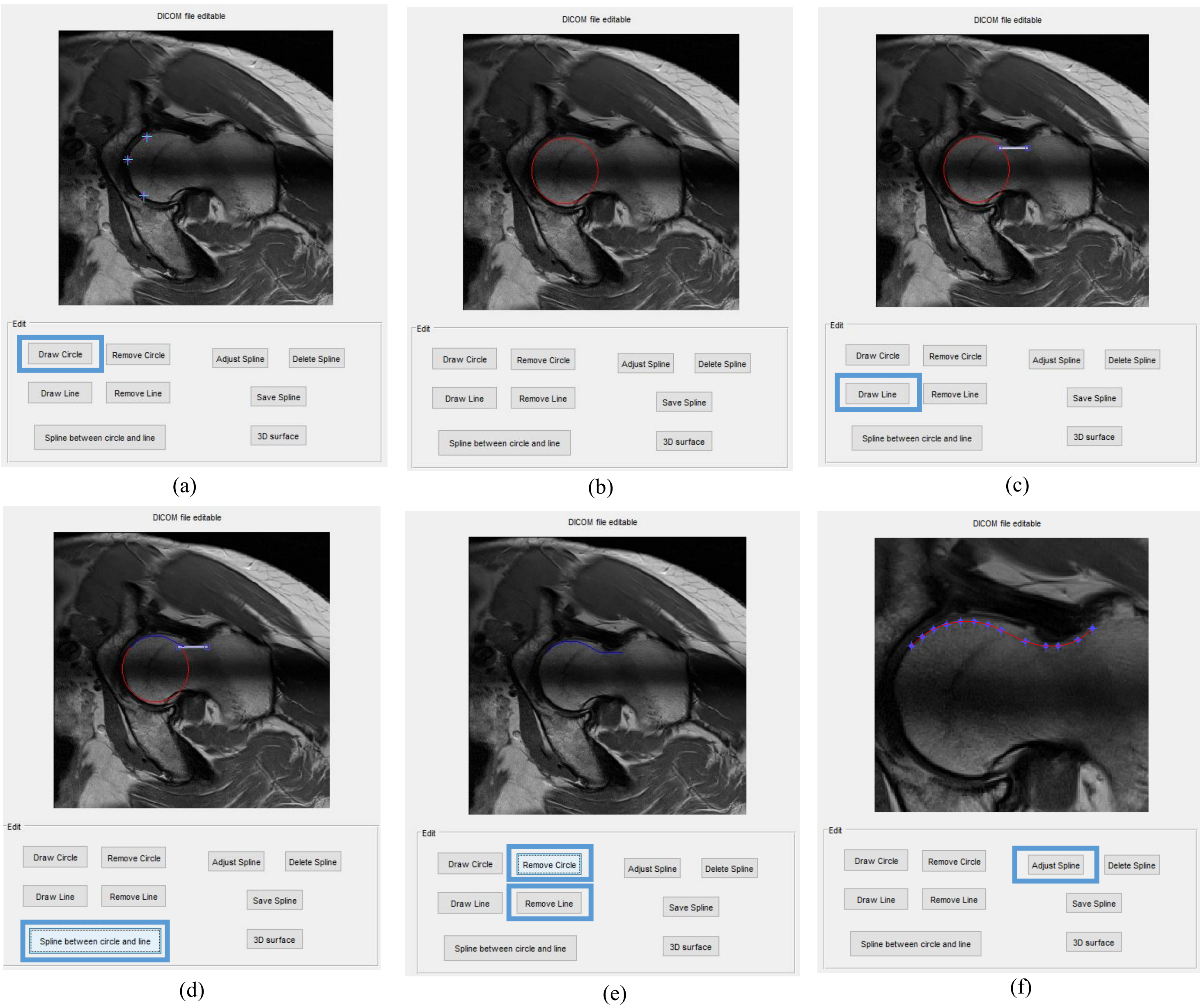


Figure 3 - Performing the contour of a healthy femoral head in an example of a 2D radial scan. (a) After clicking 'Draw circle' button, over the editable image, the cursor will change its appearance to a cross and the user will be responsible for clicking at least three different points of the image belonging to the circumference that will be drawn. (b) Circle is drawn in red passing throw the points previously selected, thus the user must choose peculiar points from the femur that characterize the desired sphericity of the bone that will undergo an operation. (c) When the 'Draw Line' button is clicked, a small line will appear in the center of the editable image. The user should drag it to where he thinks the circle will line up with the remains of the femoral head. (d) Then the user will click on the 'Spline between circle and line' button to create a blue line representing the section of bone to be operated. (e) For a clear view, it is advisable to remove both circle and line using the 'Remove Circle' and 'Remove Line' buttons. (f) The spline line can be easily adjusted by dragging several points that pop up when the user clicks the 'Adjust spline' button. Whenever any point within the line is moved, a red line follows the adjustments made so that the user can interactively change the contour of the region to operate.

Principal components are new uncorrelated variables constructed as linear combinations of the initial variables and their order is made so that the first ones have the most information in terms of variation of the original variables. Geometrically, principal components correspond to the lines that capture most of the data information, because they represent the directions of the data that explain a maximum amount of variance [14].

By thinking the principal components as new axes that provide the best angle for viewing and evaluating data, the surface developed in the application presented in the previous section was implemented in this new reference frame.

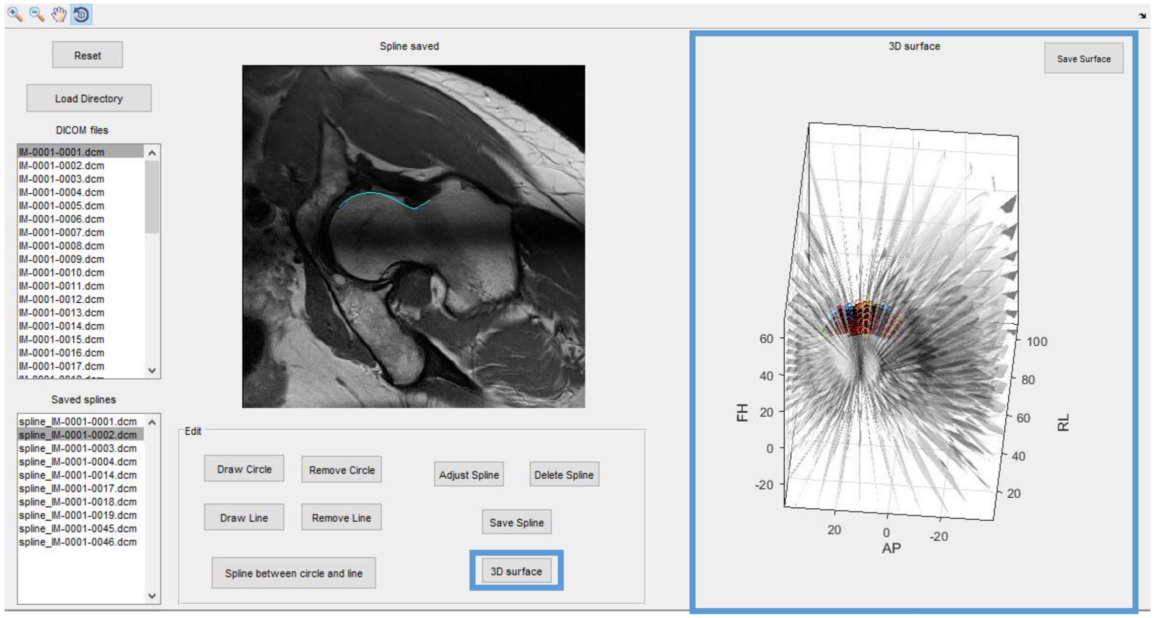


Figure 4 - 3D visualization of the radial sequence and the interpolated surface of the region to operate in red.

MATLAB®'s *pca* function returns the principal component scores, which are the representations of the input data in the principal component space, being, in the developed application, the new coordinate values of the points collected from the splines drawn by the user. Thus, using the function *fit* of MATLAB® it was possible to create the surface through cubic piecewise interpolation ('cubicinterp' as 'fitType') for each case in its best principal component space. In this way, the femur of several patients, which translates into different radial MRI sequence in distinct patient's coordinate system and, consequently, in particular pre-planned splines, it is possible to construct 3D surfaces of the regions to operate regardless and independently of their spatial location.

Hereafter, it was required to transform the surface of the principal component space into the original patient's coordinate system so that it visually appears in the right place where the user pre-planned the section to operate the femur. For that, the transformation matrix was built through the rotation matrix and translation vector, which described the transformation between the input data into the output scores of the *pca* function.

2.3 Registration

With the 3D surface that outlines the section to operate, it is required to merge the coordinate systems of that surface and the patient in the operating room (OR).

Being hip arthroscopy performed laparoscopically, one has to imagine that the surgeon would have to collect points along the surface of the unhealthy femur with a pointer, before correcting the cam type FAI.

This procedure was recreated in the lab with a real dimensions femur made of plastic stabilized on top of a table, using the NDI Polaris Spectra System, as shown in Figure 5.

The NDI Polaris Spectra System used is based on optical measurement technology to determine the location and orientation of the tool, which has four spherical markers that reflect infrared light emitted by illuminators on the position sensor – Polaris spectra.

Initially, it is required to compute the offset of the pointer tip through the collected positions of the spherical markers allocated in the tool. This procedure called pointer pivoting, is performed with the help of the NDI Polaris Track software.

After that, the data acquisition was performed by collecting points from the plastic femur surface in the same region as the pre-planned surface. In the NDI Polaris Track software, it was chosen for data acquisition 1 minute of time acquisition with 60 frames per second (maximum value permitted). During this operation, the points on the plastic surface were attentively acquired in slow movements to ensure that the spherical markers are within the measurement volume that can be traced in the Polaris position sensor coordinate system and, also, correctly facing the sensor without obstacles so that their position can be tracked. After collecting points from the plastic femur surface, the registration between this point cloud and the preplanned surface was performed by applying the Iterative Closest Point (ICP) algorithm through the MATLAB® *pcregistericp* function.

(b)

(a)

Figure 5 - Setup for registration process. NDI Polaris Spectra System (a) facing towards the realistic plastic femur and pointer (b).

3 Results and Discussion

3.1 Region Validation

To ensure that the 3D surface that is interpolated based on the splines drawn by the user which is created through a piecewise cubic interpolation function from MATLAB® is functional for the purpose of delineating the region to operate, the interactive application was used to segment some portion of the femoral head, as shown in Figure 6, to verify if it would correspond to the real surface of the femur that is available in the T1 axial MRI set.

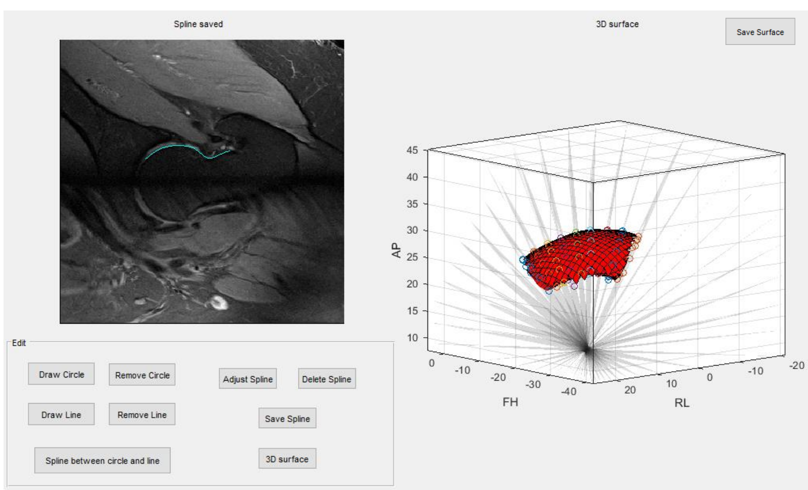


Figure 6 – Example of one 2D radial scan in which was performed the delineation of the real contour of the femoral head (left) and the resulting interpolated surface of consecutive radial scans (right).

Figure 7 displays in red the interpolated surface within axial MRI set. The different viewing angles allow to confirm that the cubic spline interpolation method is acceptable to define surfaces from points of multiple spline lines acquired from radial slices.

To further evaluate whether the developed surface recreates the true surface of the femur, another interactive application has been developed where it is possible to further explore the 3D coordinate system of the two MRI sets (radial and axial).

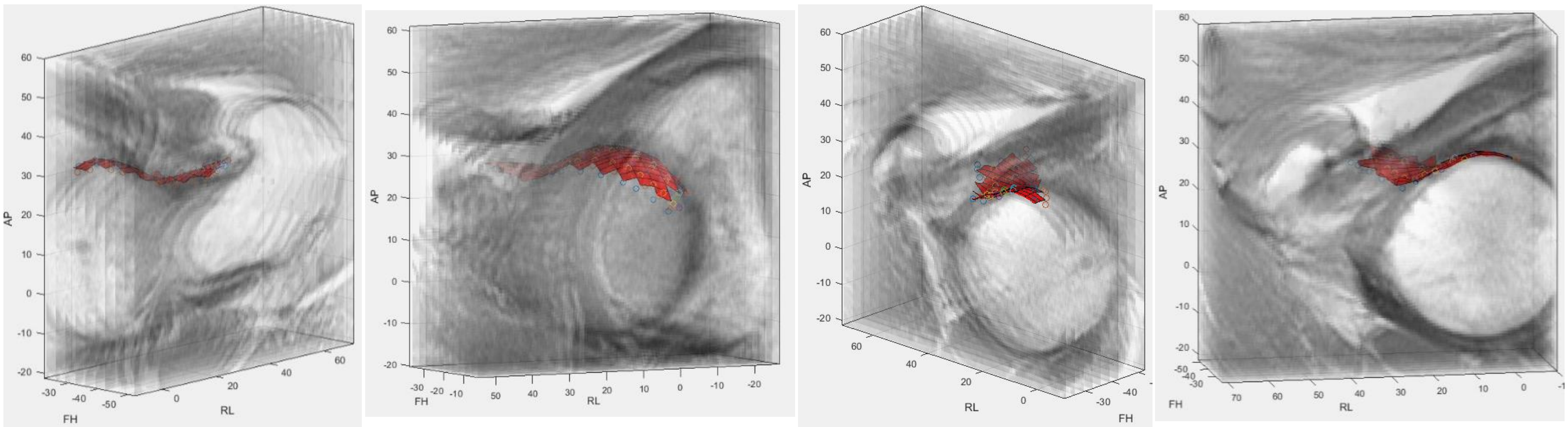


Figure 7 - Interpolated surface representing the femoral head surface within the T1 axial set from different viewing angles.

Figure 8 shows its layout which is divided into four sections: (1) file region where the user can load the DICOM files of the 2D radial and axial sequence from a specific directory located on his computer and also load the surface output MATLAB® file; (2) presentation of each 2D slice already loaded (radial, axial or radial with the drawn spline slices); (3) 3D space in which the radial or axial MRI sequence is represented, the interpolated surface of the region to be operated in red and in blue the plane schema represented in the following section; (4) surface presentation in the same 3D space as specific transverse femur planes or axial planes.

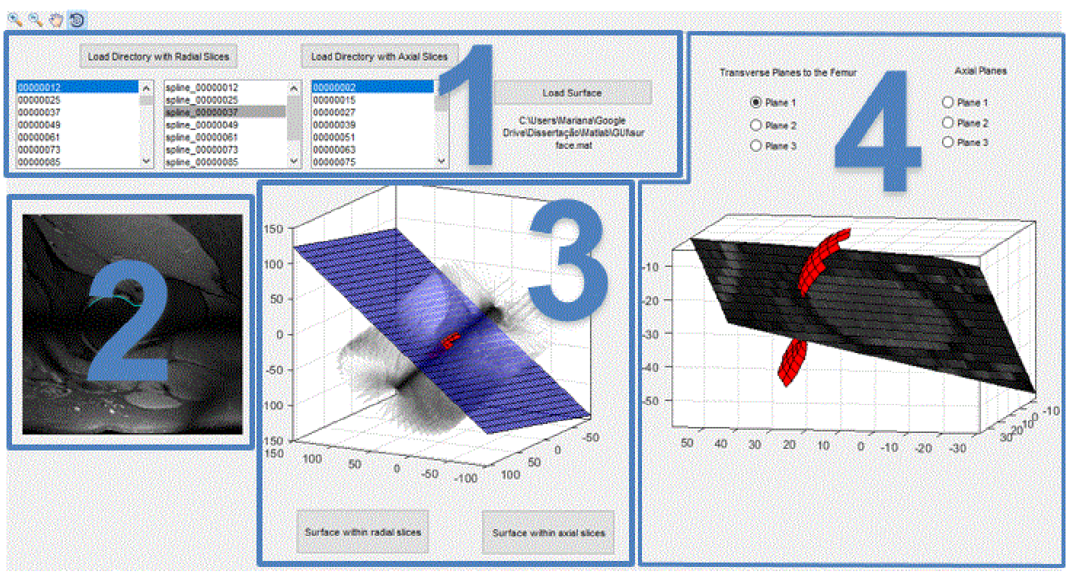
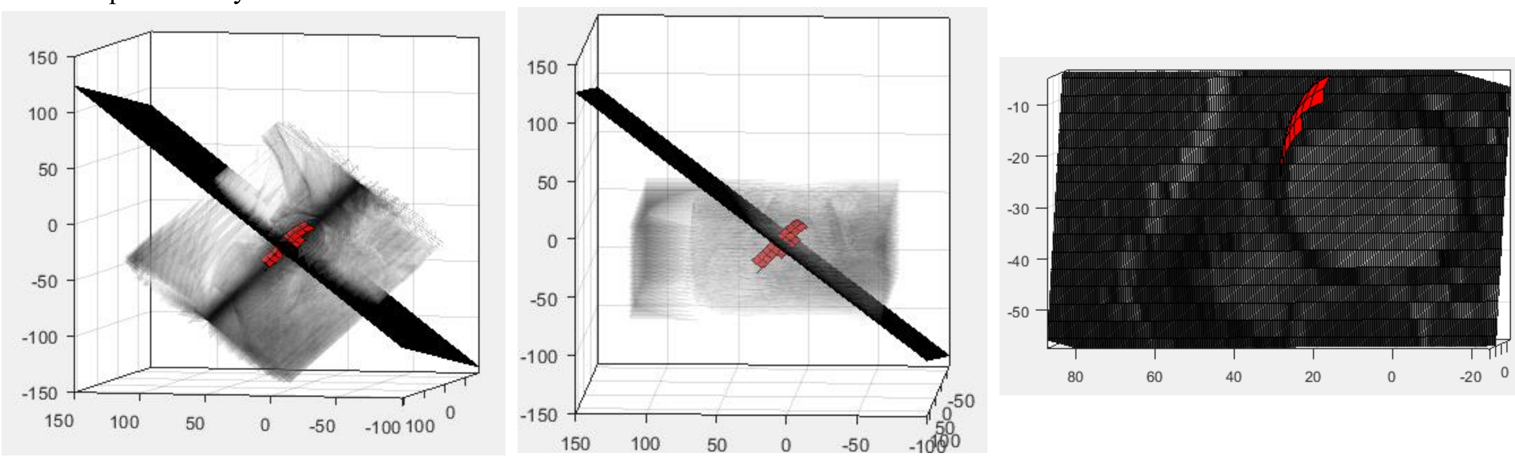


Figure 8 – GUI of the interactive application to evaluate the developed surface within the MRI sequences: (1) file region; (2) 2D plane; (3) viewing region of the 3D surface of the section to operate within radial or axial MRI sequence (4) viewing region of the 3D surface

There were created three transverse planes to the femoral head/neck by intersecting the 26 axial MRI slices with previously chosen planes. That is, a new transverse slice was created through the intensity values of the pixels collected from the axial sequence at each intersection, as illustrated in Figure 9. These three planes have a vertical resolution of 3mm, as it corresponds to the distance between consecutive axial slices of the T1 MRI set. In the horizontal direction, it is possible to have a better resolution of approximately 0.7mm, equal to each axial slice. Thus, resulting in a transverse slice that looks like pixelated rectangles with worse vertical resolution. Nevertheless, the intersection between the red developed surface with each transverse plane confirms that the surface represents the true femoral surface.

In addition, three axial planes from the MRI sequence were selected for further analysis of the developed surface to confirm that it corresponds to the actual femoral surface. Considering Figure 10, it is noticeable how the red surface follows the contour of the femur on each axial slice, confirming that the technique used to create and interpolate this surface can be accepted to pre-plan the region to operate for cam type FAI correction, qualitatively.



(a) (b) (c)

Figure 9 – Example of one transverse plane created. (a) radial MRI sequence, surface and schema of the transverse plane in 3D space. (b) axial MRI sequence, surface and schema of the respective transverse plane in this 3D space (c) transverse plane created and surface overlap

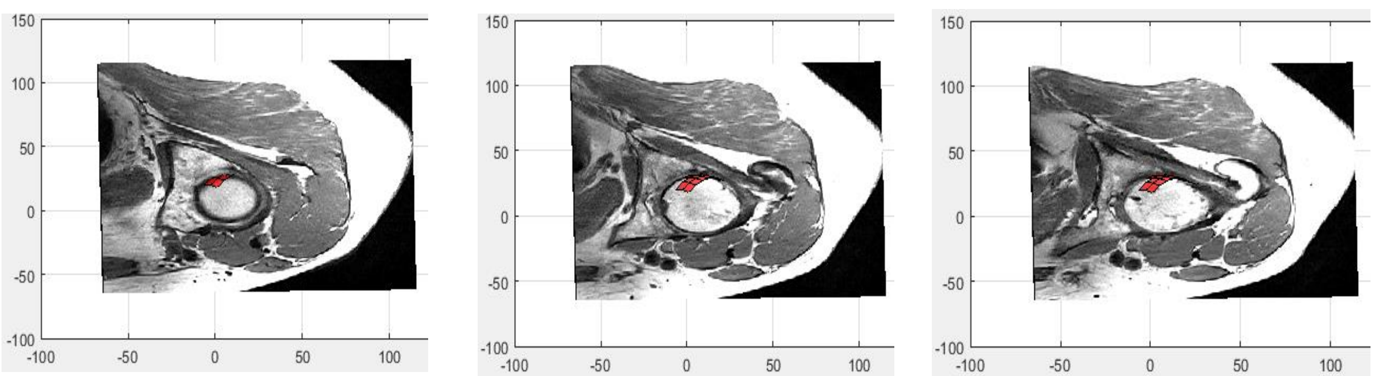


Figure 10 - Three selected axial planes represented with the surface corresponding to the real femoral surface.

3.2 Registration

After applying the ICP algorithm to perform the registration between the points collected from the plastic surface using the Polaris position sensor and the tool pointer and the point cloud acquired from the surface developed, the resulting transformation matrix was:

$$M = \begin{bmatrix} 0.8 & 0 & 0.6 & 1330.1 \\ -0.6 & 0 & 0.8 & 1614.8 \\ 0 & -1 & 0 & 395.4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

and the Euclidean distance between the aligned point clouds, designated as root mean square error was:

$$RMSE = 2.2616\,mm \tag{3}$$

Figure 11 illustrates the two point clouds in the same 3D space after registration, where the points from the developed surface are represented in green, considered as the fixed point set, and the purple points portray all coordinates points of the pointer tip position along the plastic surface femur, treated as the moving point cloud

4 Conclusion

In this work it was successfully developed a preoperative planning tool to be part of a robot-assisted conservative hip surgery. It lets the user to outline the contour of a healthy femoral head over each 2D radial view of the unhealthy femur, allowing the user to recreate the lost sphericity due to the cam type FAI in a user-friendly and easy-to-view manner. In addition, the software can successfully create the surface correspondent to the limits of the region to operate, as the use of the piecewise cubic interpolation function was validated.

Finally, the registration between this surface and the surface of the real femoral head was completely mapped with the help of the optical measurement technology NDI Polaris Spectra System and calculated using the Iterative Closest Point algorithm with an error on the order of 2mm.

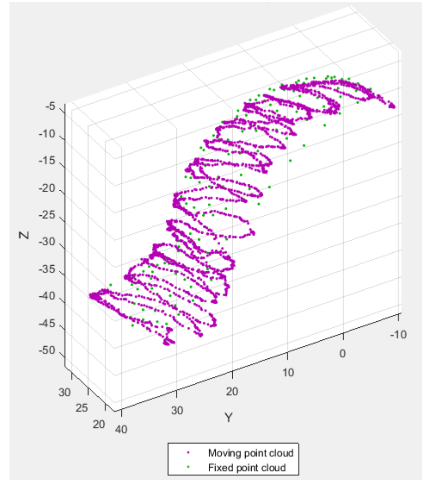


Figure 11 - Both point clouds after registration using ICP algorithm.

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