Spatiotemporal Big Data Analytics for Osteoarthritis Knee*

Tram Nghi Pham[1]
University of California, Berkeley

tram.pham18@berkeley.edu

Abstract— **Osteoarthritis (OA) is the most prevalent disease amongst knee joint which mostly affects the cartilage in elderly and overweight people. Articular cartilage is simply defined as a soft connective tissue at the end of bones which prevents the bones from erosion and allows smooth glide bones in the joint. OA is characterized by the gradual degeneration of cartilage in knee joint. In Osteoarthritis, cartilage seizes up, erodes away, and eventually disappears in some regions causing the bones to rub again one another with severe pain during motions. Measurement of cartilage loss and 3D visualization can help to quantify the severity of osteoarthritis. Nowadays, Magnetic Resonance imaging (MRI) is extensively used to image the knee joint due to its high resolution and contrast displacement between the bones and cartilage. Though a profound work has been done to detect boundary, there is lack of discussion on cartilage measurement of severe OA knee and the advantages of image pre-processing have not been fully exploited. Encouraged by initial research, this paper proposes a semiautomatic method to improve clinical evaluation of osteoarthritis disease. It emphasizes on improving image pre-processing techniques and the treatments to severe osteoarthritis cases. We explore the image processing techniques applied on MRI in the progression of osteoarthritis diagnosis. Namely, we will identify the clinical biomarkers for early detection of OA by (1) pre-processing MR images, (2) detecting boundary of cartilage by modified radial search method, (3) 2D and 3D cartilage visualizing and (4) calculating volume and thickness of cartilage for OA quantification.**

I. INTRODUCTION

Osteoarthritis (OA) is the prime causes of loss in motions and commonly seen in female, elderly, and overweight people. OA happens when the cartilage at the end of femur and tibia bones starts degenerating and often leads to severe pain in joint movements. Articular cartilage is a thin layer of high quality, ultra-slippery hyaline material which covers the end of patella, femur, and tibia bones to help smooth movements between knee joints as well as prevent them from rubbing against each other [4]. The most common causes of OA due to intensive tear movements with aging, previous knee injury, continuous stress on the knee, or obesity problems. Once the cartilage starts to break down and wear away, the remaining cartilage will deteriorate rapidly. The sample of normal and affected osteoarthritis knee images are shown in Fig.1.

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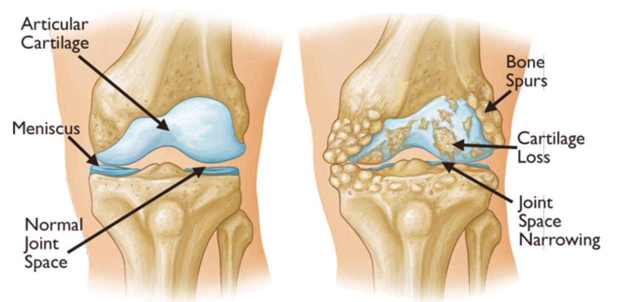


Fig. 1: Normal Knee vs Affected Osteoarthritis Knee Image.

Today, 35 million people (13 percent of the U.S. population) are 65 and older, and more than half of them have radiological evidence of osteoarthritis in at least one joint. By 2030, 20 percent of Americans (about 70 million people) will be exaggerated by OA 15. The major symptoms of OA are pain and difficulty while moving, but gets better with rest, stiffness in the knee joint, or decreasing in mobility of knee, etc. Most of OA treatments work best if start early. Measurement of cartilage loss can be used to quantify the severity of osteoarthritis; hence, establishing an accurate quantification for early detection is significant. However, the thickness of knee cartilage in OA is difficult to measure due to knee's complexity. Usually, MRI can be analyzed by physicians, but it is biased, time-consuming and low accuracy. Despite its prevalence and severity, osteoarthritis still remains poorly understood. Therefore, in this paper, we aim to explore the image processing techniques on Magnetic Resonance Imaging (MRI) for better quantification of knee osteoarthritis with an emphasize in severe OA knee.

A. BACKGROUND INFORMATION

Medical imaging is the process of generating a visualization of the internal structures hidden by skin and bones. It incorporates various of imaging technologies such as X-ray 4, Magnetic Resonance Imaging (MRI), Ultrasound, Computed Tomography (CT) etc. for the purpose of clinical diagnosis, treatment, and disease monitoring. This paper will be focusing on MRI. MRI is particularly useful for scanning and detecting abnormalities of soft tissue structures of the body like cartilage tissue or soft organs like brain or heart [15]. In the case of knee osteoarthritis, it also preserves a high resolution and contrast between bones and cartilage. MRI has been intensively used by many scientific research for early quantitative analysis regarding to characterize the status of the disease and monitor its progression. Although quantitative analysis on MRI has been showing promising evaluation towards early clinical biomarkes, it has a limited responsiveness to monitoring development of the disease. Hence, prolific research and work are still on going to continue developing better image processing tools for a more accurate disease measurement. Example of MRI for normal knee is shown in Fig. 2.

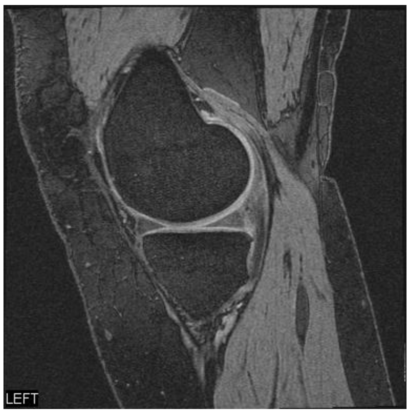


Fig. 2: Sample MRI of Normal Knee.

B. RELATED WORK

In previous work, researchers have intensively investigated on various methods that detect the cartilage boundary to determine the thickness of cartilage using MR Images. Bhagyashri L.Wagaj et al [2] used pixel segmentation method to segment the cartilage. The area of cartilage is then calculated to determine the image is OA affected or normal knee. Nadeem Mahmoog et al [14] used various image segmentation and edge detections method to visualize the cartilage for better quantification. Dipali D.Deokar et al [5] developed a new automatic approach based on image pre-processing, feature extraction, and artificial neural network to quantify the status of disease. However, attempt to a fully automatic cartilage segmentation for osteoarthritis quantification is still an on going research in many groups [8]-[13].

The structure of the rest of the report is as follows. Section II briefly describes the source of data and how the data looks like. Section III describes the methodology for image processing on MRI concerned to cartilage measurement of knee, the procedure, and metrics used for visualization and quantification of osteoarthritis. Section IV explains how the volume, area, and thickness of segmented cartilage are calculated. Section V discusses the experimental results and finally, the last section will summary our work and potential future plans.

II. DATA DESCRIPTION

The knee joint MR images are obtained from Osteoarthritis Initiative with more than 4,000 participants of different groups of age, weight, aesthetic, etc. Osteoarthritis Initiative (OAI) is a multi-center, longitudinal, prospective observational study of knee osteoarthritis (OA). The overall OAIs primary objectives is to develop a public domain research resource to facilitate the scientific evaluation of radiographic and MRI joint images as biomarkers for osteoarthritis [15]. They provide database of X-ray and MR images for the entire cohort from baseline up to 96 months follow-up. These images consists of 384x384 pixels which acquired from Siemens 3.0T Trio system in Sagittal 3D DESS with Water Excitation. This acquisition will provide information for total joint cartilage thickness and volume. In addition, information about osteophytes, subarticular bone cysts and bone attrition, and possibly collateral ligaments will be available [15]. Sample of dataset is already shown in Fig.2.

III. METHODOLOGY

In this project, we first pre-processing MR images to remove noise and do image conversion. Image processing techniques will then be implemented to detect the boundary of cartilage, followed by cartilage segmentation. A thickness measurement in 2D and visualization in 3D are proceeded. Finally, volume and thickness calculation are computed to evaluate the status of knee osteoarthritis. Fig.3 shows a block diagram of knee detection process.

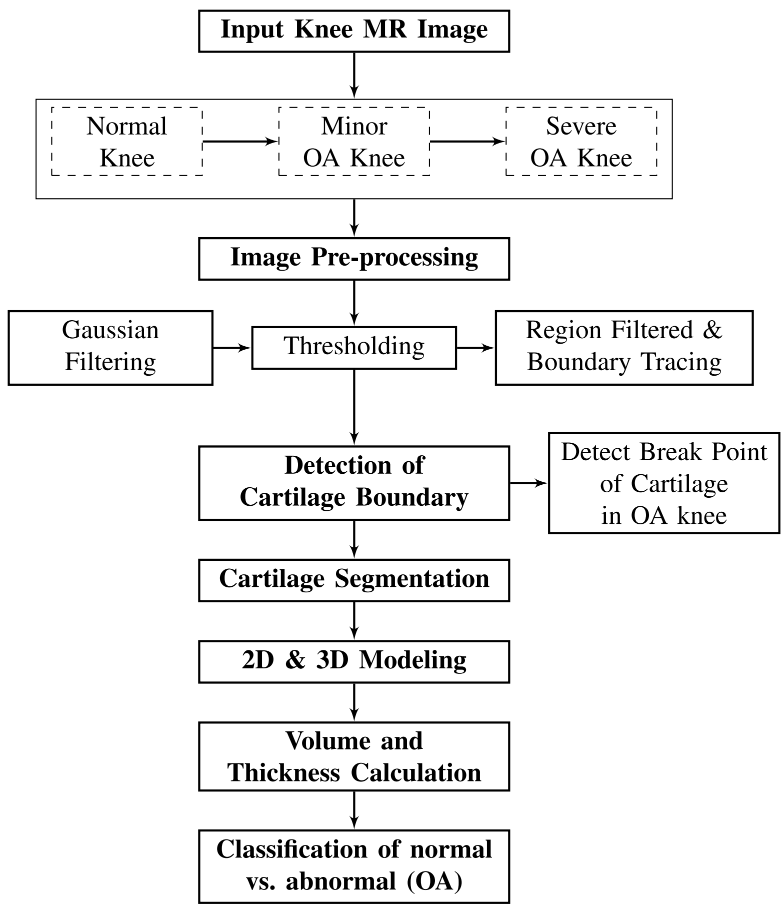


Fig. 3: Block Chart for Knee OA Detection System.

A. Image Pre-processing

Image pre-processing is used in the main purpose of reducing the complexity, image type conversion, enhance some image features by removing unwanted distortions (e.g noise) to increase the accuracy of the applied algorithm. In this paper, image preprocessing is the most crucial step that will directly help to detect the cartilage boundary. The algorithm of image pre-processing is summarized in algorithm 1.

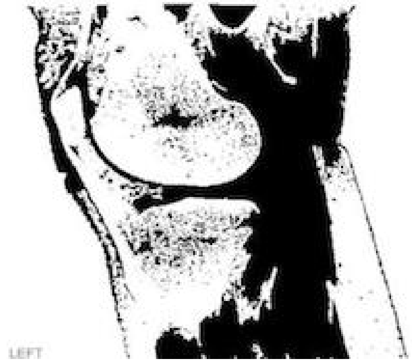


Fig. 5: Thresholding.

Algorithm 1 Pre-processing MR Image

function IMAGE_PRE(img)
    INPUT
    @param img: original MR image
    OUTPUT
    @return boundaries: vector stores inner boundary values.
    @return bigBoundary: vector stores outer boundary values.
    procedure
        $rgbImage \leftarrow imread(img)$
        $grayImage \leftarrow rgb2gray(rgbImage)$
        `# Apply Gaussian Filter`
        $grayImage \leftarrow imgaussfilt(rgbImage)$
        `# find thresholding value a`
        $binaryImage \leftarrow imbinarize(rgbImage, a)$
        `# Extract largest blobs`
        `# traces the boundary of objects`
        $boundaries \leftarrow bwboundaries(binaryImage)$
        for i `from 1:length(boundaries)` **do**
            if length of `boundaries(i)` < 1000 **then**
                `remove boundaries(i)`
            end
        end
        $outer \leftarrow$ `dilate image`
        $bigBoundary \leftarrow bwboundaries(outer)$
        end
        return $boundaries$
        return $bigBoundary$
        end

1) **Gaussian Filtering:** Gaussian filtering is used to filter out random noise in the image and unnecessary high frequency edges around the cartilage [2]. Filter applied on MRI is shown in Fig.4.

(a) (b)

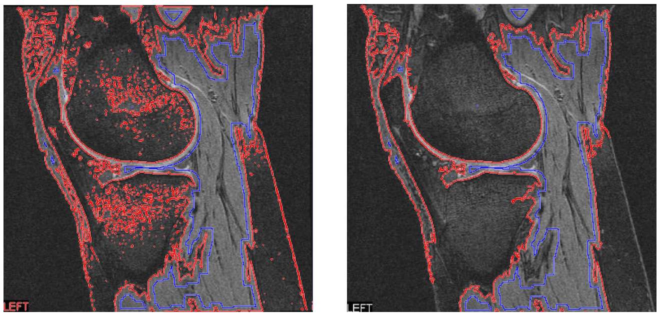
Fig. 4: MR image of normal knee (a) without Gaussian filter and (b) with Gauss filter.

2) **Thresholding:** Thresholding is used to convert RGB image into white and black values by using a determined threshold. It is helpful to distinguish the edges of cartilage and extract largest blobs/essential parts of the image. Fig.5 shows the image after thresholding.
3) **Area Filtering and Boundary Tracing:** all the connected components which have less than 1000 pixels will be removed. Doing so will keep only largest blobs in the image; in this case, it is the cartilage and its connected surrounding parts. After the unnecessary small regions are removed, the present holes get filled for the purpose of cartilage boundary displacement (red and blue lines). A sample of this process is shown in Fig.6.

The boundary values in this step will be recored to account for detecting the boundary of cartilage in the following step.

B. Detection of Cartilage Boundary

Loss of cartilage measurement is considered as feature components of osteoarthritis quantification. Thickness measurement provides detailed information for clinical evaluation, optimal methods for more accurate diagnosis, and OA progression monitoring. Based on initial research by Holi (2013) [5], the Radial Research Method



(a) (b)

Fig. 6: MR image of normal knee with (a) region filtered and (b) non-region filtered.

is modified to maximize the advantages of image pre-processing. The method used to detect cartilage boundary in OA knee will be focused here as well.

In the Radial Search Method developed by Holi, the origin is fixed at the center of femur bone. The search vector of radius R and incremented angle θ are first drawn in a specific direction. A threshold value is determined. Pixel intensity and coordinates along the line will be iterated until the pixel intensities are greater than the threshold value within an appropriate range. The pixel coordinates at which the intensity is greater than the threshold is recorded as inner boundary value. In the same manner, a search with an opposite direction is used to detect the outer boundary value. The search is set up to be s distance away from the inner boundary in the direction towards the origin. The procedure is repeated from $0°$ to $300°$ with an increment of $5°$ to cover the whole cartilage. Fig.7 shows an animation of Radial Search Method. Mathematically,

- Let (x_0, y_0) be the origin of the search.
- The equations of x_k and y_k at which the boundary is detected are

$$x_k(n) = x_0 + r_k cos(\theta_n) \tag{1}$$

$$y_k(n) = x_0 + r_k sin(\theta_n) \tag{2}$$

where k, n are the indexes of pixel coordinates and θ.

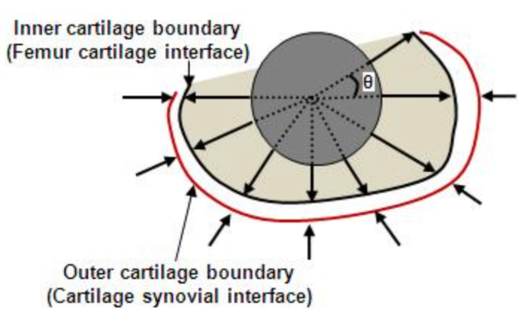


Fig. 7: Radial Search Method.

Inspired by Radial Search Method (RSM), the modified RSM is done in a slightly different scheme. In modified RSM, a region in the center of femur bone is chosen to determine the threshold of intensity, center, and radius of the search. In Modified RSM, the inner boundary values are not identified based on the significant shift in the intensity value, but the value of boundary recorded in image pre-processing step. In short, It will keep searching until the search pixel coordinate matches the coordinate in the vector which stores tracing boundary value from pre-processing step. Since the procedure is proceeded up to increment of $300°$, only inner boundary will be observed. Another modified point is that instead of reversing the direction after the inner boundary value has been detected, the method will keep searching in the same direction until the outer boundary is found based on either the change in intensity or a match in stored vector, whichever happens first.

The algorithm of Modified Radial Search is summarized in algorithm 2.

Fig. 8 shows an animation of Modified Radial Search Method.

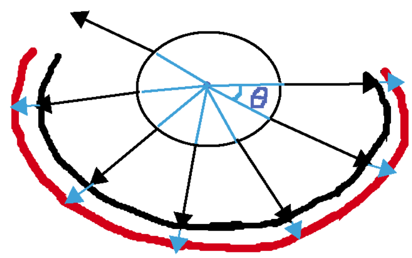
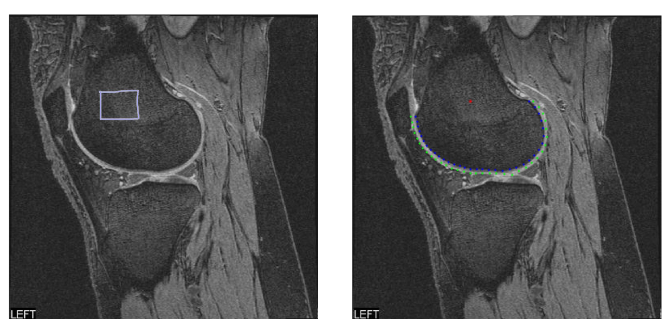


Fig. 8: Modified Radial Search Method.

The Modified Radial Search method is applied to normal knee and the boundary recorded shows a promising result as shown in Fig. 9



(a) (b)

Fig. 9: (a) Region of Interest is chosen to find center of the search, and (b) Boundary of Cartilage is successfully detected by Modified Radial Search method.

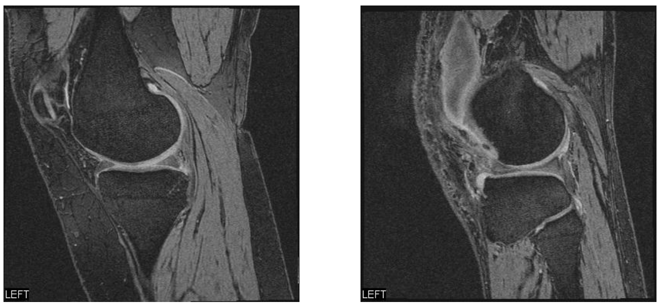
C. Detecting the End Point of Cartilage in OA Knee

Unlike normal osteoarthritis knee whose cartilage forms a somewhat semi-circle shape and can be seen from

Algorithm 2 Algorithm for Detecting the Cartilage Boundary

```
function CARTILAGE_DETECTION(radius, x_0, y_0, I, mean_itensity, sd, boundaries, bigBoundary, coeff_x, coeff_y, s)
    INPUT
    @param, x_0, y_0 = coordinates of origin of the search
    @param, I, s = image needed to analyze and number of previous values used to predict the next one
    @param, mean_intensity, sd = average intensity and standard deviation of ROI femur bone
    @param, boundaries, bigBoundary = vectors that store boundaries value from image pre-processing steps
    @param, coeff_x, coeff_y = training coefficients used to predict the next boundary value
    OUTPUT
    @return, boundary; outer_boundary= vectors contains inner and outer boundary values
    procedure
        terminate ← false; boolean ← false
        theta ← 0 : 5 : 300
        k ← radius
        index ← 1 # keep track of theta
        while terminate && length(theta) > 0 do
            x_k ← ceil(abs(y_0 + k * cosd(theta(index))))
            y_k ← ceil(abs(x_0 + k * sind(theta(index))))
            plot x_0, y_0
            if [x_k, y_k] ∈ boundaries then
                boolean ← true;
            end
            if [x_k, y_k] ∉ size of image I then
                index ← index + 1 #change direction
                n ← n − 1;
                k ← k + 1
            else if boolean ← true then
                check for break point of cartilage
                call function to calculate x_predict, y_predict
                if [x_predict − x_k]  or  [y_predict − y_k] > threshold then
                    # display break point found
                    terminate ← true;
                    break;
                else
                     #record and plot inner boundary
                    k ← k + 6
                    # KEEP DETECTING THE OUTER BOUNDARY
                    while [x_k, y_k] ∈ size of image & terminate= true do
                        x_k ← floor(abs(y_0 + k * cosd(theta(index))))
                        y_k ← floor(abs(x_0 + k * sind(theta(index))))
                        change ← abs((x_k, y_k) − (mean_intensity) + sd/2)
                        if change < mean_intensity then
                            Record and plot outer boundary
                            break;
                        else
                            k ← k + 0.5 #keep searching outer boundary
                        end
                    end
                    #update index and k for different direction
                    index ← index + 1
                    k ← radius + 1
                    n ← n − 1
                end
            else
                k ← k + 0.5
            end
        end
        return boundary, outer_boundary
```

MRI, a large amount of cartilage in OA knee wears away and disappears in the half way of covering the femur and tibia bones. Thus, a method to observe the end point of cartilage in OA knee is needed. Though a profound work has been done to detect boundary of cartilage, there is lack of discussion on cartilage measurement of severe OA knee. In this section, a simple method is proposed with an emphasize on improving treatments to severe OA cases. Fig.10 shows the major difference in cartilage between normal and severe OA knee.



(a) (b)

Fig. 10: Cartilage in (a) Normal Knee and (b) Severe OA Knee.

The break point in OA knee is determined based on the smoothness of the cartilage curve. Linear regression and normal least square equation are used to identify the change. Basically, the previous boundary values will be taken into account to predict the next boundary value. The training data is obtained by the boundary point of normal knee, in which, the smoothness is reflected. The procedure is as follows,

Suppose we have a sequence of numbers $\{x_n\}_{n=1}^{k}$ The goal is to find coefficients a_1, a_2, a_3, a_4 such that

$$a_1 * x_1 + a_2 * x_2 + a_3 * x_3 + a_4 * x_4 = x_5$$

$$a_1 * x_2 + a_2 * x_3 + a_3 * x_4 + a_4 * x_5 = x_6$$

$$...$$

$$a_1 * x_{k-4} + a_2 * x_{k-3} + a_3 * x_{k-2} + a_4 * x_{k-1} = x_k$$

Plug in x_n value and let

$$X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ x_2 & x_3 & x_4 & x_5 \\ \cdots & & & \\ x_{k-4} & x_{k-3} & x_{k-2} & x_{k-1} \end{bmatrix}$$

$$a = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}, b = \begin{bmatrix} x_5 \\ x_6 \\ \cdots \\ x_k \end{bmatrix}$$

In order to solve for a in $Xa = b$, the **Normal Equations for Least Squares** is used. Normal Equations for Least Squares states that given the system

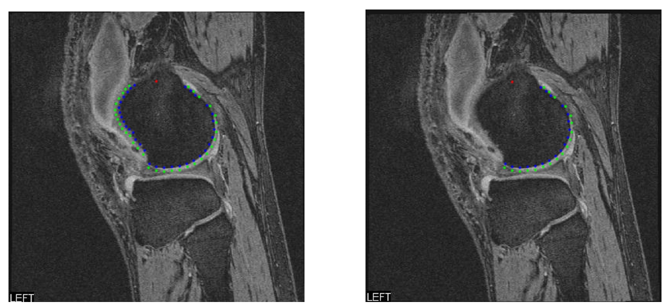
$$Xa = b \tag{3}$$

solve

$$X^T X\bar{a} = X^T b \tag{4}$$

for the least squares solution $\bar{a}$ that minimizes the Euclidean length of the residual $r = Xa - b$, where $\bar{a}$ is the column vector that contains coefficient a_i used to compute the next predicted value.

After implementing the Normal Equation to Modified RSM and running it on severe OA knee, it gives an accurate detection of cartilage break point. Figure 11 shows the major difference in Modified RSM and Break-point Detected Modified RSM.



(a) (b)

Fig. 11: Detecting cartilage boundary in OA knee using (a) Modified Radial Search and (b) Modified Radial Search with Break-Point Detection Implemented.

D. *Cartilage Segmentation*

Cartilage segmentation supports the visualization of cartilage in both 2D and 3D. The segmentation is done depending on the boundary values found in the previous sessions. Sample of cartilage segmentation is shown in Fig. 12. After segmenting the cartilage, the area is then computed. The area of cartilage is the value which corresponds roughly to the total number of *on* pixels in the image. For numeric input (e.g matrix form as in MATLAB), any nonzero pixels are considered to be *on*. The area of each individual pixel is determined by its 2x2 neighborhood. There are six different patterns to identify the area of a pixel. For example, patterns with zero on pixels (area = 0) and patterns with one on pixels (area = 1/4).

For a further description about area calculation, please see [7].

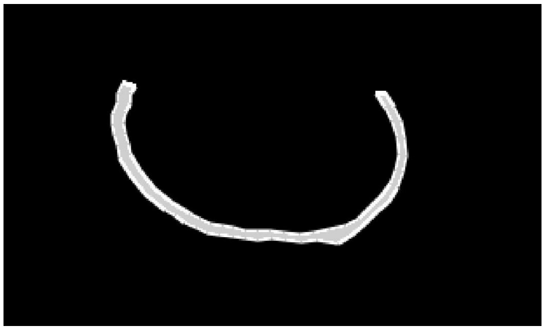
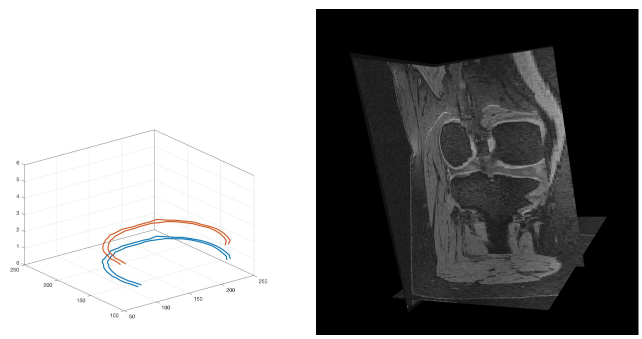


Fig. 12: 2D Cartilage Visualization.

E. 3D Modeling

Cartilage visualization in both 2D & 3D are essential components for better clinical evaluations and disease monitoring. An abundant 2D MRI slices can be stacked together for a better visualization in 3D. Volume App Viewer in MATLAB is utilized for this purpose. Cartilage segmentation can also be plotted and viewed in 3-dimensional. Examples for 3D visualization are in Fig.13.



(a) (b)

Fig. 13: (a) Cartilage Visualization in in 3D and (b) Excerpt from Volume App Viewer.

IV. Volume and Thickness Calculation

Thickness of cartilage is measure in different regions including femur, tibia, and patella. The cartilage thickness is computed using Euclidean distance formula along the inner boundary point towards outer boundary points. Thickness t_i is calculated using Euclidean distance using the formula

$$t_i = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{5}$$

where x_i, y_i are the column vectors containing inner and outer boundary values.

$$t = \frac{\sum_i t_i}{k} \tag{6}$$

where k is the total number of boundary points and t is the average thickness

The sample thickness of cartilage in Fig. 12 is $t_{\text{example}} = 4.072$ mm. The area of cartilage is computed by summing number of pixels in the object. The area of sample cartilage shown in Fig.12 is $A_{\text{example}} = 2.4736 * 10^3$ mm^2

The volume of cartilage is calculated by stacking 2D cartilage segmentation together. The volume varies depending on how many segmentations or slices are stacked jointly.

V. Experimental Results

The method described in previous sessions is applied to MRI of normal, severe, and minor OA knee. Selecting the region of interest- usually center of femur or tibia bone - is the only manual step in this method. The program takes 1 minute to select and detect the cartilage boundary in femur bone. From previous work, the usual thickness of articular cartilage between tibia and femoral bones of knee is ranging from 3.45mm on average with a standard deviation of 0.9mm. The cartilage thickness on tibia and femur bones are 0.73mm to 1.825 and 2.24 with a standard deviation of 0.34mm, respectively. The method was run on different MRI views of same patients to check the accuracy. The obtained result was in the range of 4mm to 5mm for normal knee, which is in-line with biological measurement. "More experiments will be conducted once the data is complete."

VI. Conclusions

This study shows that the developed image processing techniques in this paper acquired in MRI system can extract an adequate information for osteoarthritis quantification. The thickness calculated in femoral tibia bone can be used to produce a more accurate clinical evaluation. This method is potentially suitable for detecting cartilage in femur and tibia bones. Nevertheless, the accuracy of the method can be ameliorated by doing experiments and studying more number of cases.

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