Fast Detection & Modelling of the Real Osteoarthritic Holes in the Human Knee with Contour Interpolated Radial Basis Functions

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***Abstract*— In this article, we propose a novel method for the fast 3D reconstruction of real osteoarthritic (OA) holes in a human femoral cartilage. Initially, semi-automated Region-Based Segmentation (region-growing) and Bounding Box techniques are used to extract femoral cartilage slices from MRI scans of the knee. OA holes were detected and filled automatically by our contour interpolation/RBF (CI-RBF) method and 3D models of both the femoral cartilage and OA holes were reconstructed separately. The method was then applied to a single human knee and results proved it fast, reliable and accurate for reconstructing a 3D model of the femoral cartilage from MRI images with an extremely low root mean square error of 1.67% in the estimated volume of the automatically filled to the manually filled femoral cartilage slices. As per authors' knowledge this is the first time real OA hole has automatically been identified and filled.**

I. Introduction

Osteoarthritis (OA) [1], a musculoskeletal condition, is internationally recognized as a cause for disability in elderly people. Magnetic Resonance Imaging (MRI) [2-6] is used as a tool for accurate non-invasive and clinical assessment of the knee articular cartilage. Emerging research has shown its value as a research tool for studying knee cartilage morphology in both healthy and arthritic volunteers. Volume and thickness of the cartilage are used for identifying osteoarthritis. Osteoarthritis is caused by loss or deformation of the articular cartilage. Therefore, to understand the origins and effects of OA it is important to study the deformational characteristics of cartilage.

The physiology of the knee shows that the knee joint is formed by lower end of the femur and upper end of the tibia. The femur is the largest bone in human body and runs from the hip to the knee. The tibia, the shin bone, constitutes the lower portion of the knee joint. The patella (knee-cap) moves in the groove between the femur's two condyles. The ends of the bone at the joints are covered by a slippery surface (a hyaline cartilage) known as articular cartilage. The articular cartilage is protected against torn away by menisci which is a tough cartilage and shaped as two crescent-shaped pieces [7].

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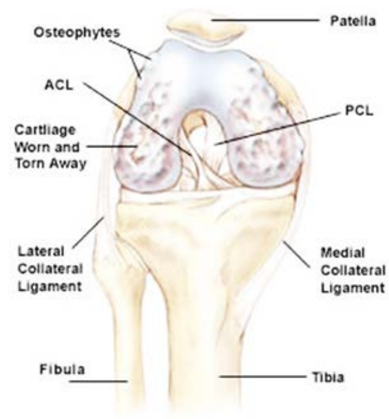

Figure 1. Arthritic Knee showing cartilage worn and torn away

The menisci reside between the articular cartilage ends of the femur and tibia at the knee. An arthritic knee [8] with worn and torn away cartilage is shown in Fig. 1

3D Modelling of bodily parts have been performed using Radial Basis functions (RBF). It was introduced by Hardy [9] as a multi-quadric method in 1971. The RBF method is an interpolation technique based on the formula (1):

$$s(x) = \sum_{i=1}^{N} \lambda_i \, \varphi(|x - x_i|) \qquad (1)$$

where: N is the number of RBF centers x_i, λ_i are the RBF coefficients and φ is the real valued function called the basis function. The Gaussian basis function $\varphi(r) = \exp(-cr^2)$ was proposed by Schagen [10]. Duchon [11] used the Thin Plate Spline $\varphi(r) = r^2\log(r+1)$. Linear and tri-harmonic basis functions are $\varphi(r) = r$ and ($\varphi(r) = r^3$) respectively. The theoretical stability and solvability problems of the RBF were solved by Micchelli [12] and Wright [13]. Later the stability issues of the Radial basis function were addressed by Wright [12] by introducing the polynomial function $p(x)$ of degree k. So the revised Radial Basis Function is (2):

$$s(x) = p(x) + \sum_{i=1}^{N} \lambda_i \, \varphi(|x - x_i|) \qquad (2)$$

RBF interpolation is used for surface reconstruction from scattered data by Carr et al. [14] and Ohtake et al. [15]. RBFs are later employed by Carr et al. [16] for smooth surface

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reconstruction from noisy data. Bertalmio et al. [17] and Wang [18] applied RBF for in-painting removal. RBFs are also used for the modelling of laser scan data by Turk and O'Brien [19, 20].

A number of hole-filling techniques have been employed by researchers. To fit an implicit representation of sample points Carr et al. [14] created and fitted an RBF to a signed distance function. Later an iso-surface was extracted from the fitted surface. Davis et al. [21] filled the holes by employing the volumetric diffusion which extended the signed distance function from the vicinity of the observed surfaces. Volumetric representation was used by Curless et al. [22] to detect mesh portions that required filling. Finite element methods were applied by Clarenz et al. [23] for reducing the integral of the mean curvature to the smallest amount of the filled hole. In addition, Liepa [24] performed detection and hole-filling by using geometric approach which uses the minimum area triangulation method of its 3D contour. Furthermore, a two-step tetrahedral meshing was used by Xin Chen et al. [25] to form finite element meshes from medical images.

Previously, we demonstrated how CI-RBF can be used to fill synthetically generated holes in a patella [26]. In this article, we propose the use of our CI-RBF for a 3D reconstruction of real osteoarthritic holes in a human femoral cartilage. Region-Based Segmentation (RBS) [27, 28] and bounding box method was used to extract the femoral cartilage slices from the MRI scans of the knee. The holes were detected and filled automatically by our CI-RBF method and separate 3D model reconstructed for both femoral cartilage and osteoarthritic hole. The error is compared with our work on the synthetic osteoarthritic holes [26]. As per the authors' knowledge this is being the first time Osteoarthritic (OA) holes in the MRI of a human femoral cartilage are being identified and filled automatically.

II. Materials and Methods

A. Resources

A Siemens Magnetom Skyra syngo MR D13 was used for MRI scan of the right knee. MRI prescription parameters such as field of view of 150 mm, flip angle 10^o, repetition and echo times of 700 and 11 ms respectively were used for this study. The image sequence of size 640 x 640 and slice thickness of 1.5 mm. Imaging of the fat saturated sequence was done in sagittal plane with a t1SPACE (Sampling Perfection with Application optimized Contrasts using different flip angle Evolutions). The software was written in MATLAB.

The subject in the study provided written informed consent and ethical approval for the study was granted by institutional ethics committee.

B. Extracting femoral cartilage from MRI scans

The extraction of the femoral cartilage from MRI scans consists of five steps which are listed below.

1. To remove noise and preserve edges 60 MRI scans were passed through a low pass (median) filter.

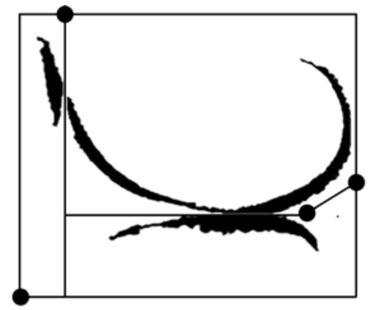

Figure 2. Bounding Box (4 clicks marked with black dots)

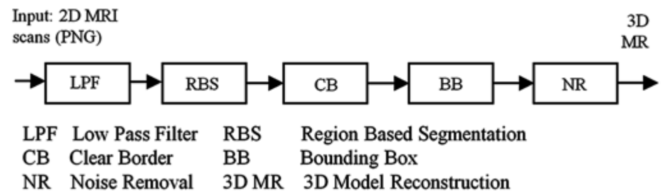

Figure 3. Schematic for the femoral cartilage extraction

2. Region Based Segmentation [27, 28] (region-growing), an image processing technique, was used to separate the femoral cartilage from the tibial cartilage, muscles and bones. The region-growing started with a set of "seed" points. A seed value of 200, determined from many trials, was employed. Neighbours which have similar predefined properties for example, colour or gray level, were appended to each seed to form regions. We used the gray-level range property (region-growing stopped when no more pixels are left to match the property).
3. The segmented (RBS) images have traces of the tibial and femoral muscles touching the border and their intensity was the same as that of cartilage. All the objects touching the border were removed using a clear border procedure (that is masking all the objects touching the border and subtracting it from the image itself).
4. A bounding box as in Fig. 2 was created (by 4 clicks) to separate the femoral cartilage from the patellar and tibial cartilage.
5. Finally, unwanted objects in the image were removed by removing regions except with the largest area which was the region of interest. The schematic is shown in Fig. 3 [26].

C. Criteria for Identifying a Hole in the Femoral Cartilage Slices

The minimum criterion for an OA hole in the femoral cartilage is that the hole should be of at least two layers (i.e. an OA hole if its depth is at least 1.5 mm) [26]

D. Contour Interpolation/RBF Method for Reconstructing 3D Models

Osteoarthritic holes in the slices were filled and later a 3D model of the filled femoral cartilage (femoral cartilage with filled OA holes) and fill were reconstructed separately using a contour interpolation/RBF (CI-RBF) method, described below and fully in [29].

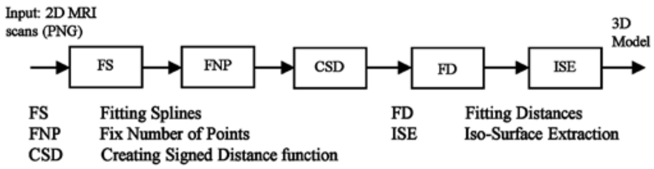

Figure 4. Contour interpolation/RBF method

CI-RBF method comprises of five steps. Briefly, femoral cartilage contours were obtained by identifying the pixels on the boundary.

1. Splines were fitted to the femoral cartilage contours.
2. Divide the fitted splines into fix number of points (for example 300) in each contour.
3. In and out off-surface points were created for the newly created points by projecting along the in and out surface normals [20] respectively (creating signed distance functions).
4. RBF is fitted to the signed distance functions.
5. Finally, iso-surface is extracted to achieve the 3D model of the filled femoral cartilage and the fill.

The schematic of Contour interpolation/RBF method is given in Fig. 4.

III. RESULTS

Fig. 5 shows a 3D model of the femoral cartilage after filling the three two-layered OA holes. The fill of the femoral cartilage OA holes is shown by red surface. One can observe that the 3D model of the filled femoral cartilage is smooth and the holes' boundary seamlessly joins the fills' boundary.

Figs. 6 to 8 show the RBF fit of the three two-layered OA holes. Red surface on the lateral condyle (Fig. 5) represent 3D model of the two-layered OA holes 'A' and 'B' and their RBF fit is shown in Figs. 6 and 7. Green lines depicts the RBF fit of the corresponding points of the hole whereas red lines show the RBF fit of the corresponding points of the two femoral cartilage contours. Similarly, Fig. 8 is the RBF fit for the OA hole 'C', present on the medial condyle of Fig. 5. Fig. 9 shows the 3D model of the three (A, B and C) two-layered OA holes' fill. These 3D models are zoomed to give a clear view of the model.

To verify results of the automatic filling, estimated volume of its fill was compared with the estimated volume of the manual fill. We applied spline boundary correction, as discussed in [29], before estimating the volume to enhance accuracy. Later the volume was estimated using Cavalieri's principle [30, 31] as employed by Cheong et al. [32] for estimating volume of the tibial cartilage. The root mean square error in the estimated volume was found to be 1.67% when the estimated volumes of the manually filled and automatically filled femoral cartilage slices were compared, whereas we have incurred an error of 0.33% when estimated volumes of the patellar cartilage without synthetic holes and filled patellar cartilage were compared [26].

IV. CONCLUSION

In this paper, a novel contour interpolation/RBF (CI-RBF) method [29] was applied to automatically identify OA holes in the MRI of a human femoral cartilage. In CI-RBF method, each contour in the MRI images is uniformly subsampled with same number of points or pixels. Thus, providing even and smooth interpolation between contours and reduction in points results in faster reconstruction.

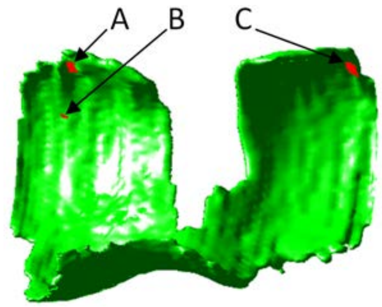

Figure 5. 3D Model of the femoral cartilage with three 2-layered holes filled

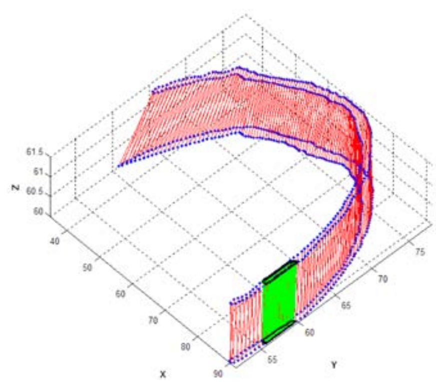

Figure 6. RBF fit of 2-layered Hole A

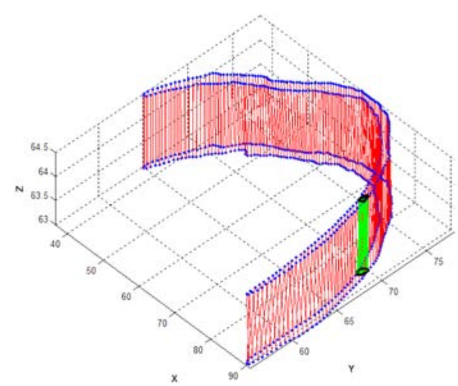

Figure 7. RBF fit of 2-layered Hole B

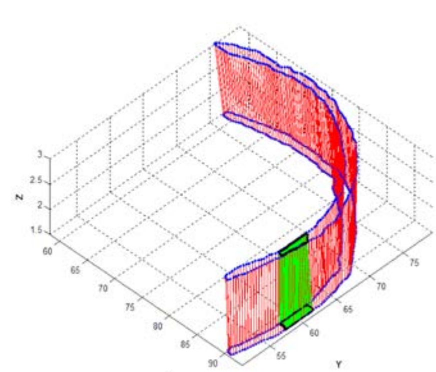

Figure 8. RBF fit of 2-layered Hole C

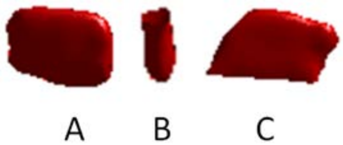

Figure 9. 3D Models of the three two layered holes' (A, B and C) fill

We have demonstrated that the method can automatically detect and reconstruct 3D models of the femoral cartilage and OA hole separately to high precision with only 1.67% root mean square error in the estimated volume of the automatic to the manually filled slices. In addition, the results demonstrate that the CI-RBF is an efficient, robust and accurate method, which is not only fast but works effectively on sparse data.

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