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

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Abstract— **In this article, we propose a new method for the fast 3D reconstruction of simulated osteoarthritic holes in a human patella. Initially, clean patella slices were extracted from MRI scans of the knee using Region-Based Segmentation (region-growing) and Bounding Box techniques. Osteoarthritic (OA) holes were then simulated in the patella slices. Our contour interpolation/RBF (CI/RBF) method was then used to detect the hole automatically and reconstruct 3D models of both the patella and OA hole separately. The method presented here proves fast, reliable and efficient for reconstructing a 3D model of the patella from MRI images with an extremely low error of 0.33%.**

I. INTRODUCTION

Osteoarthritis (OA) [1] is a musculoskeletal condition that is internationally identified as cause for disability in people over 65 years. Magnetic Resonance Imaging (MRI) [3 – 7] has emerged as the preferred technique for accurate non-invasive, clinical assessment of the structural composition and integrity of knee articular cartilage. Emerging research has shown its value as a research tool for studying knee cartilage morphology in both healthy and arthritic volunteers. The identification of osteoarthritis typically requires measures of volume and thickness. Loss of articular cartilage and its deformation results in Osteoarthritis. Therefore, it is important to study the deformational characteristics of cartilage to fully understand the pathogenesis of OA.

The physiology of the knee is as follows. The lower end of the femur and upper end of the tibia constitutes the knee joint. The femur runs from the hip to the knee and is the largest bone in the human body. The tibia which is also known as the shin bone forms the lower portion of the knee joint. The patella or the knee-cap covers the knee joint and moves in the groove between the femur's two condyles. The articular cartilage, a hyaline cartilage, covers the ends of the bones at the joints. This structure can be torn away by missing or damaged menisci, a tough cartilage that appears as two crescent-shaped pieces [2] residing between the articular cartilage ends of the femur and tibia at the knee.

3D Modelling of bodily parts have been performed using Radial Basis functions (RBF). Hardy [8] introduced a multi-quadric method, known as the Radial Basis Function (RBF) method in 1971. The RBF method is an interpolation technique based on the formula (1):

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

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 φ (r) = exp(-cr^2) was proposed by Shagen [9], Thin Plate Spline φ (r) = r^{2}log(r+1) was used by Duchon [10]. φ (r) = r and (φ (r) = r^3) are linear and tri-harmonic basis functions respectively. Micchelli [11] and Wright [12] solved the theoretical stability and solvability problems of the RBF. Later Wright [12] added the polynomial function p(x) of degree k to the Radial Basis function for solving the stability issues. The resultant Radial Basis Function becomes (2):

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

Carr et al. [13] and Ohtake et al. [14] applied RBF interpolation for surface reconstruction from scattered data. The RBF was used for inpainting removal by Bertalmio et al. [15] and Wang [16]. Turk and O'Brien [17, 18] applied RBFs for modelling laser scan data. Carr et al. [19] used RBFs for smooth surface reconstruction from noisy data.

There are a number of hole filling techniques used by researchers. Carr et al. [13] used an RBF to fit an implicit representation of sample points by creating and fitting an RBF to a signed distance function. Later an iso-surface extraction of the fitted surface was done. Davis et al. [20] constructed a signed distance function and extracted a zero set to get the surface. They used the volumetric diffusion to extend the signed distance function from the vicinity of the observed surfaces to fill the holes. Curless et al. [21] employed a volumetric representation for detecting mesh portions that required filling. Clarenz et al. [22] use finite

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element methods to reduce the integral of the mean curvature to the smallest amount of the filled hole. In addition, Liepa [23] performed a geometric approach for detecting and filling holes with a minimum area triangulation method of its 3D contour. Furthermore, Xin Chen et al. [24] proposed a two-step tetrahedral meshing algorithm to form finite element meshes from medical images. In this article, we propose the use of RBFs for a 3D reconstruction of a simulated osteoarthritic hole in a human patella. The patella slices were extracted from the MRI scans of the knee using Region-Based Segmentation (RBS) [25, 26]. Holes were then created in the patella contours using a specific criterion. The holes were later identified, filled and a 3D model of both patella and osteoarthritic hole were separately reconstructed using the contour interpolation/RBF method. As per the authors' knowledge this is being the first time simulated Osteoarthritic holes (of known volume) in the MRI of a human patella are being identified and filled automatically.

II. MATERIALS AND METHODS

A. Resources

Philips Medical Systems 1.5-T Gyro scan Intera was used for MRI scans of the knee. MRI prescription parameters such as field of view of 160 mm, flip angle 55^o, repetition and echo times of 57 and 12 ms respectively were used for this study. The image sequence of size 512 x 512 and slice thickness of 1.5 mm was done in sagittal plane with T1-weighted fat-suppressed 3D spoiled gradient recalled acquisition in the steady state. The software is written in MATLAB.

B. Extracting Patella from MRI scans

The extraction of the patella from MRI scans consists of five steps which are now described. As a first step, 60 MRI scans were passed through a low pass (median) filter to simultaneously remove the noise and preserve edges. In the second step, an image processing technique namely, Region Based Segmentation [25, 26] (region-growing) was used to separate the patella from the femoral cartilage, muscles and bones. The basic approach started with a set of "seed" points. A seed value of 200, determined from many trials, was used. Regions were grown from the seed points by appending to each seed all those neighbors which have similar predefined properties (such as gray level or colour). We employed the criteria of gray-level range (where the growing region was terminated when no more pixels left to satisfy the criteria). The images obtained after applying RBS contained some part of the tibial and femoral muscles touching the border and their intensity was the same as that of cartilage. In step three, all the objects touching the border were removed using a clear border procedure (i.e. a mask of all the objects touching the border was obtained and then this was subtracted from the image itself). A bounding box as in Fig. 1 was created (by 4 clicks) to separate the patella from femoral and tibial cartilage in step four. Finally, in step five, a noise removal routine was applied to the separated patella slices. A noise removal routine was logically developed to remove all regions except with the largest area which was the region of interest. The schematic is shown in Fig. 2.

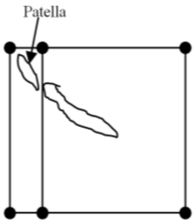

Fig. 1 Bounding Box for separating Patella

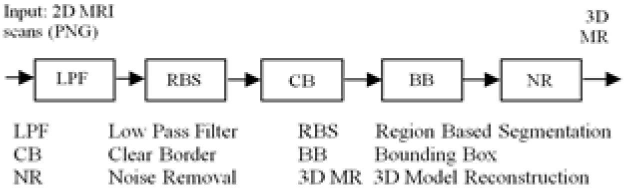

Fig. 2 Schematic for Patella Extraction

C. Criteria for Creating Holes in Patella Slices

Synthetic holes depicting OA in the patella were created through three MRI slices of the Patella. The holes were of different diameters (3, 2 and 1.5 mm respectively) as shown in Fig. 4. The minimum criterion for an OA hole in the patella 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)

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

Holes in the slices were filled and later a 3D Model of the filled patella (patella with filled OA holes) was reconstructed using a contour interpolation/RBF method which is described below and fully in [27].

The method consists of five steps. Briefly, contours of the patella were obtained by identifying the pixels on the boundary. In the first step, line segments (or splines) were fitted to the contours. In step two, splines were divided into fix number of points (for example 100) in each contour. In step three, in and out surface points were created for the newly created points (by creating signed distance function). Off-surface points were generated by projecting along surface normal as done by Turk & O'Brien [18]. Out off-surface points were created by projecting along out surface normals and consequently in surface points were created projecting along in surface normals.

In step four, signed distance functions were fitted [13]. Finally, in step five, iso-surface extraction was done to get the 3D Model of the filled patella. The schematic of Contour interpolation/RBF method is given in Fig. 3.

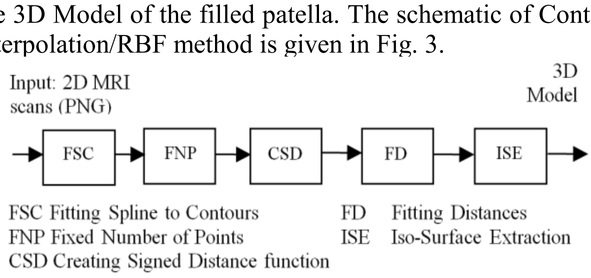

Fig. 3 Contour interpolation/RBF method

III. RESULTS

Fig. 5 (left) shows a 3D model of the patella without holes. Figs 5 (middle) and (right) show the front and back view of 3D model of the patella after filling in the OA hole in the two layers. Similarly, Fig. 6 (left) shows a 3D model of the patella without holes. Fig. 6 (middle) and (right) show the front and back view of 3D model of the patella after filling in the OA hole in the three layers. So Fig. 5 and 6 present models of patella with holes of depth two and three layers respectively. The red surface shows the filled OA hole. The 3D model of the filled patellar cartilage is smooth and the hole boundary seamlessly joins the fill boundary.

Figs. 7 to 9 show an RBF fit of the three layered OA hole. The lowest slice has the largest hole of radius 3 mm; the middle slice has a hole of 2 mm radius whereas the top slice has a hole of 1.5 mm radius as shown in Fig. 4. Green lines show the RBF fit of the corresponding points of holes whereas red lines show the RBF fit of corresponding points of the three patella contours. Fig. 10 shows the 3D model of the filled three layered hole. Since the three holes are of different radii the 3D model of the fill is broad at the bottom and narrow at the top.

The volume of the patellar cartilage was estimated using Cavalieri's principle [28, 29] as employed by Cheong et al. [30] for estimating volume of the tibial cartilage. The error in the estimated volume was found to be 0.33% when the estimated volumes of the filled patellar cartilage and the patellar cartilage without holes were compared.

Fig. 4 Three-layered hole in the patella slices (left) slice 1 with a hole of radius 3 mm (middle) slice 2 with a hole of radius 2 mm (right) slice 3 with a hole of radius 1.5 mm

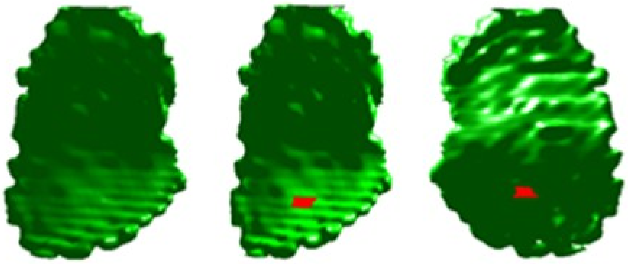

Fig. 5 (left) 3D Model of the Patella without holes (middle) Front view of 3D Model of the Patella with two layered hole filled (right) Back view of 3D Model of the Patella with two layered hole filled

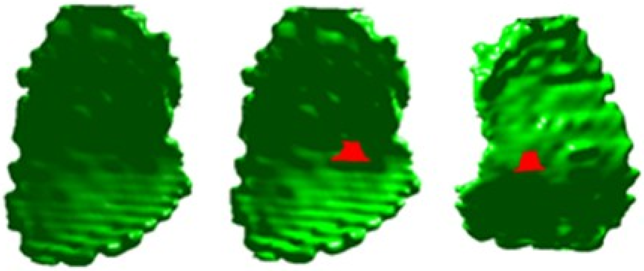

Fig. 6 (left) 3D Model of the Patella without holes, (middle) Front view of the Patella with three layered hole filled, (right) Back view of the Patella

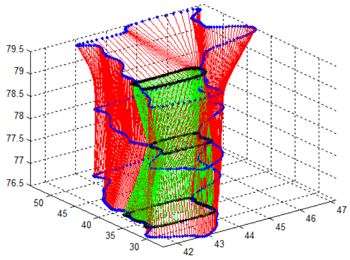

Fig. 7 Side view of RBF fit of Holes

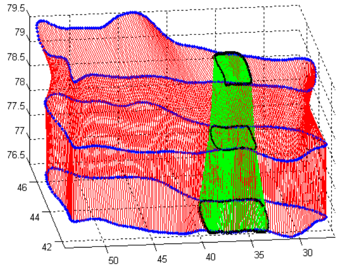

Fig. 8 Front view of RBF fit of Holes

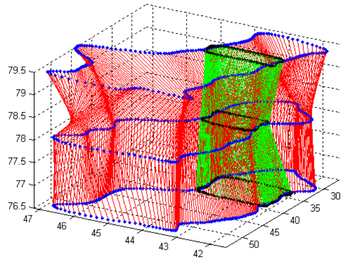

Fig. 9 RBF fit of Holes in three layers

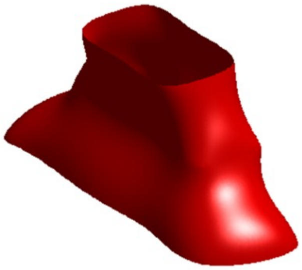

Fig. 10 3D Model of the three layered hole fill

IV. CONCLUSION

In this paper, we have applied a new contour interpolation/RBF (CI/RBF) method to automatically identify synthetically generated holes (of known volume) in the MRI of a human patella. The method achieves this by uniformly subsampling each contour of an MRI image with the same amount of pixels. Hence, the method provides a smooth and even interpolation between contours and faster reconstruction because of reduced image points. We have demonstrated that the method can automatically detect and reconstruct 3D models of the patella and OA hole separately to high precision with only a 0.33% error in the reconstructed volume. In addition, the results demonstrate that the CI/RBF method is an efficient robust method, which is fast and works effectively on sparse data. The algorithm though fast compromises on the volume of the patella.

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