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Extraction of Menisci and Detection and Characterization of Meniscal Tears in M.R.I. Images

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ABSTRACT

Osteoarthritis has become a very rapidly spreading disorder of bones and joints among old people and young athletes indulging in sports such as soccer, hockey, etc. Injuries of the knee like tears in the meniscus can be seen very commonly in young athletes as well as the aged people. The Computer-Aided Diagnosis (CAD) systems help to a large extent and can play a major role in their detection. In this paper, we deal with the extraction of the meniscus from the M.R.I. images of the knee joint and then assigning scores to the tears, if any, which can be used for quantification of the severity of tear. The proposed system was evaluated on a database of 40 individuals; and sensitivity and specificity were found to be 88% and 96% respectively. The results are encouraging and this system may prove to be a stepping stone in development of more sophisticated algorithms for detailed classification of the tears.

Index Terms: Computer Aided Diagnosis, meniscal tears, Magnetic Resonance Imaging.

1. INTRODUCTION

In today's quick-paced world, where achieving fast-track objectives and rat race are common things; health and fitness are given secondary importance. As a result, people tend to be injured frequently; sporting different types of injuries. Out of the wide varieties of physical injuries, musculoskeletal injury is very common as well as very complex. Knee related injuries are very common and occur frequently in almost all age groups.

A meniscus is a crescent or c-shaped structure, present in the knee [1]. The menisci, lateral and medial, keep the knee structure intact when it undergoes tension and torsion. The menisci act as load-balancers, and help in reducing friction during movement. Figure 1 shows the structure of the knee joint along with both the menisci. A tear of a meniscus is a sudden breakage of the menisci. Menisci can be torn during innocuous activities such as walking or squatting or by impactful force encountered any form of physical exertion or by prolonged 'wear and tear' in adults [2].

Magnetic Resonance Imaging (MRI) of the knee has become preferred standard for imaging of a meniscus tear. The high-resolution pictures from multiple views provide us with a higher sensitivity for detection of a meniscus tear. A non-pathological meniscus appears as uniform, dark triangular or polygonal objects in sagittal view of MR images.

Figure 2 consists of the sagittal (side) view of a Proton Density (PD) MR image of the knee joint. Whenever a meniscus undergoes a tear, the triangular objects show some abnormal high-intensity signal, or some part of the object itself goes missing. The M.R.I. scanners, though driven by technicians, need and consume the doctors' time as well for diagnosis and interpretation. Besides, villages in remote areas do not

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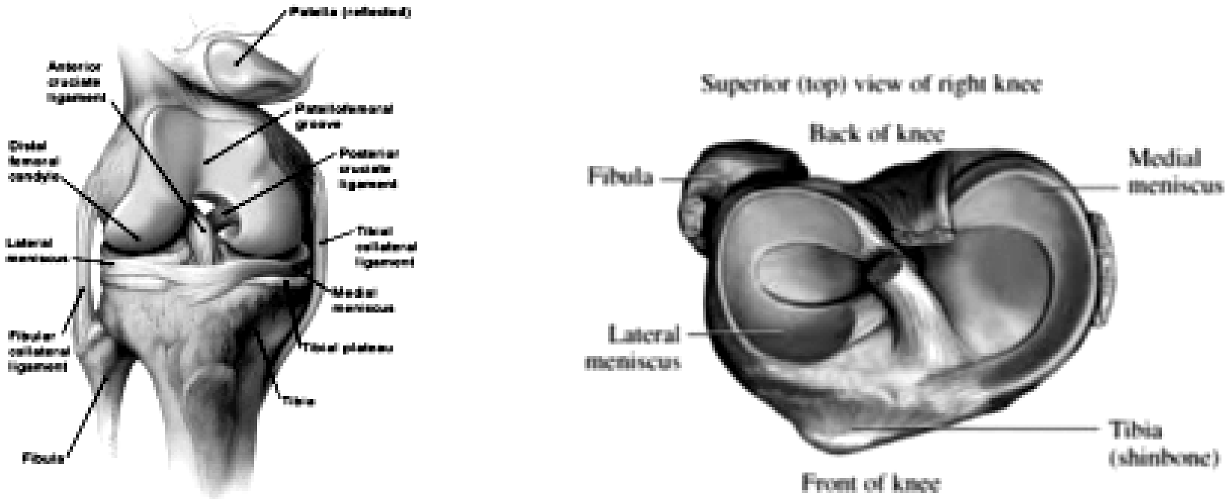

(a) (b)

Figure 1: Structure of the knee. (a) Anterior view. (b) Menisci – top view

have proper medical facilities, especially, in case of such scanners. Thus, they have to either wait for a visiting doctor or travel long distances to cities, where the medical fees and living costs are a great burden for them to bear. Thus, having an automated system, which could detect, as well as interpret these scans, will prove to be very beneficial in all these circumstances.

The menisci may crack, or get torn, when the knee is forcefully rotated or bent. There are two general types of 2

meniscus tears, sudden emergent tears which are often the result of trauma or a sports injury and slow-healing or wear-and-tear type tears. They are often treated with surgeries, as they rarely heal on their own owing to the avascular portion of the meniscus. Surgeries are guided with medical imaging techniques like X-ray scans, C.T. scans, M.R.I. scans, etc.

The research in this field is very meager. Segmentation of the cartilage has been quite an area of research, where the menisci are also segmented eventually; but the detection and characterization of meniscal tears is not achieved; or, very rare. There were a few major methods adopted for the segmentation of meniscus in the past. The fuzzy if-then rule method by Hata et al. [3] was experimented on T1-weighted and T2-weighted MR images; and described a method to segment the menisci. But the use of manual registration and first voxel initialization were its drawbacks. Amongst the types of boundary tracing-based approaches, Stammberger et al. [4] proposed an algorithm for the accurate determination of the cartilage thickness in articular surfaces. Besides lacking in full automation, this method was studied on healthy patients and not on the osteoarthritic ones. The research work by Tang et al. [5] is a study on ankle articular cartilage surface tracking using directional gradient vector-flow B-spline snake. This approach concentrated on the ankle cartilage and needed human intervention. Li et al. [6] presented a general technique based on graph theories, for simultaneously segmenting multiple closed surfaces. These methods are not very suitable for automated and accurate detection of the cartilage and menisci, because they require an accurate initialization provided by human intervention. Manually segmenting the surfaces, is both a labor intensive task and prone to error and is influenced by judgment of the operator, which is subjective, and may vary from observer to observer.

Before subjecting the knee joint to different radiological examinations, a few knee examinations like the medial and lateral joint-line tenderness test, the McMurray test, the Apley compression and distraction test, the Thessaly test at 5° of knee flexion, and the Thessaly test at 20° of knee flexion [7], are conducted by hand. During the M.R.I. scan, any abnormality visible in the normal form and shape of meniscus is considered as a tear, and then subjected to classification for further surgical purposes. There have been

Figure 2: Sagittal view of PD MR Image of knee joint

many approaches used in the classification of the meniscal tears. Crues et al. [8] devised a 3-grade grading system in which grade 1 was given to an irregularly edged intra-meniscal signal in MR images and signal did not end on an articular margin; grade 2 was a nearly linear signal that did not end on an articular margin; and grade 3 was a clearly linear signal intensity that ended on an articular border. Stoller et al. [9] used a 3-grade grading system depending on the presence of spread meniscal signal in relation to an articular surface, where grade 1 was given one of several interrupting signal intensities not ending on an articular surface, grade 2 was a linear intrameniscal signal intensity, not touching the articular surface and grade 3 was a signal intensity portion that reached to at least one articular surface. Reicher et al. [10] advanced to a 4-grade grading system where grade 1 is a thoroughly black meniscus; grade 2 is portion of very slightly increased signal intensity inside the meniscus; grade 3 is a tiny, linear region of increased signal intensity and grade 4 is distortion of regular non-pathological meniscus shape, breakage of the meniscus or line of increased white part inside the meniscus. Mesgarzadeh et al. [11], in his study, detailed the classification into eight categories, called as types 0 to VII, where type 0 is a healthy meniscus; type I is an irregular intra-meniscal signal intensity; type II is a band of intra-meniscal signal intensity; type III is unusually short meniscus with a conically shaped end; type IV is a cut or pointless end of the meniscus; type V is a band of increased signal intensity reaching to one surface of the meniscus; type VI is a band of increased signal intensity reaching to two boundaries of the meniscus; type VII a connected and increased intra-meniscal signal intensity reaching to one or both surfaces. Fox [12] researched into an 8-class classification of tears without any specific assignment of grades. He classified the tears into easily recognizable classification such as horizontal tears, vertical tears, complex tears, bucket-handle tears, flap tear with displacement, free fragments, root tears and meniscal tears in setting of anterior cruciate ligament tears. He concluded that developments in the area of 3T and faster imaging techniques promise for accurate meniscal examination with shorter scan times. Smet et al. [13] observed that although menisci with internal signal in contact with the meniscal surface are usually torn, a tear has less chances of existence if such signal is present on only one image and that the tears may be identifiable on only one image plane, but the chances of discovering them totally would be large, if adjacent slices are considered.

Even though much research has been carried out in the area of meniscus tear detection and classification as mentioned above, the performance still depends on human interpretation by human eye. In this paper, we attempt to take a step ahead in this direction by working on a computer-aided diagnosis system, which will detect and characterize the meniscal tears in the MRI scans, if any. The wide-range classification of tears can be adopted to enhance the diagnosis stage in a CAD, so that, the CAD can be surely used as an essential pre-operative diagnosis aid for amateurs and experts at large.

2. DATABASE AND METHOD

2.1. Database used

The database required for this project was provided by Nanavati Hospital, Mumbai. Out of the available scans, we used a database of 40 patients between the age-range of 20 to 70 years. The M.R.I. machine used for scanning was GE Medical Systems' Discovery MR 750w 3T scanner. The protocol followed was Knee Nanavati. In this protocol, an MRI sequence consists of 25 images. Each image is of 512 rows and 512 columns. Sagittal proton density sequences (TR = 3000 – 3500 ms, TE = 34 – 36 ms with slice thickness = 3mm) were used. A sample scan is shown in figure 3.

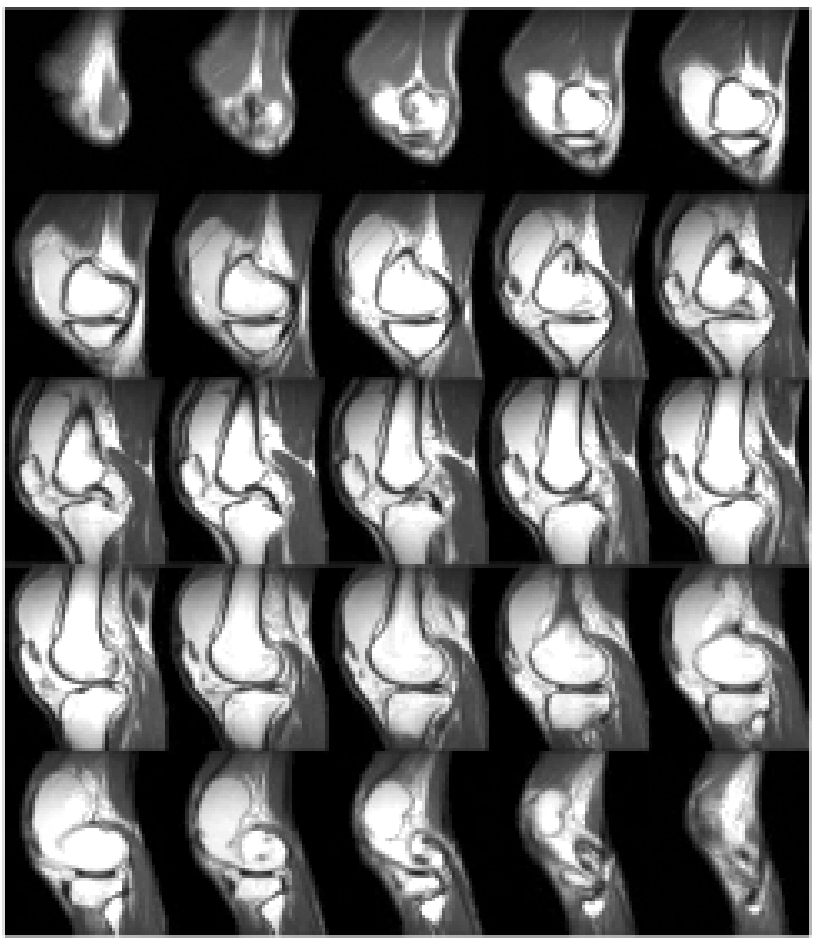

Figure 3: Sample M.R.I. scan

2.2. CAD Process

This CAD system has three basic stages: The first is a pre-processing stage for selecting the region of interest (ROI) and image slices, followed by a stage consisting of a process for extracting menisci from MR images. The third stage consists of a system that gives scores and characterizes tears. Each of these three stages is described as follows (Figure 4).

1) *Pre-processing Stage:* Region of interest (ROI) and slice selection are important steps in pre-processing stage. Since the meniscus positions do not fall in line with each other in consecutive slices, if the selected ROI is too small in area, then it might not include the meniscus totally. The experience of researchers from

experiments indicated that the location of menisci, relative to the area scanned, tends to be stable when a uniform scanning protocol was used for acquiring the scans [14]. Using the information provided in Table 1, a set of slices, called S_{final} are obtained.

ROI Selection: A fixed window sized ROI, of 50 rows × 150 columns, is considered empirically optimal. This window size is seen to be covering the menisci of the people between the ages of 20 years to 70 years and also excludes most of the unwanted hindrances like cartilage and bone. We can define and select the location of ROI automatically using the following steps.

Table 1
Percentage of slices in each section of the MR scan

Section	*Meniscal tears diagnosed*	*Range*
Medial Periphery	No	20%
Medial Meniscus	Yes	15%
ACL-PCL crossover sections	No	30%
Lateral meniscus	Yes	15%
Lateral Periphery	No	20%

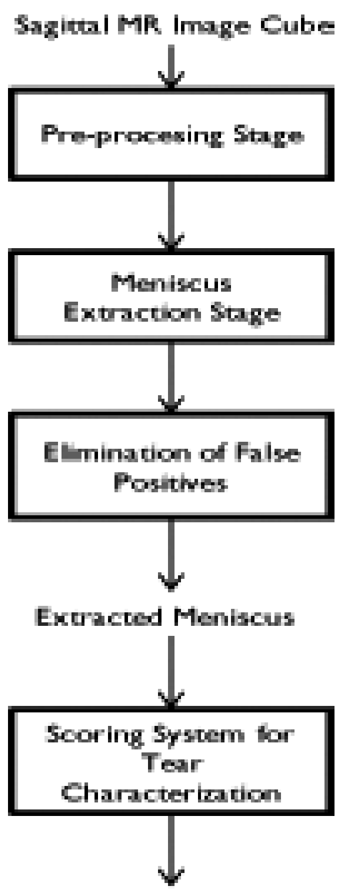

Figure 4: Stages of CAD system

1. Calculate the mean image of the image slices using

$$M_{(i,j)} = mean\left\{I_k(i,j) \mid I_k \in S_{final}\right\} \tag{1}$$

where I_k is the k_{th} slice in S_{final}

2. The matrix M is then horizontally split into small equal sized matrices W_n of size of 16 rows × 150 columns.
3. A small matrix n* yields the minimum average intensity and can be calculated using the equation,

$$n^* = \arg\left\{ \min_n \left[mean\left(W(i,j)\right) \right] \right\} \tag{2}$$

4. The middle row of this n* small matrix is used to fix the middle row of the desired ROI, and 25 rows above and 24 rows below this middle row are chosen to be used as the ROI, which add up to the 50 rows in the ROI. The image thus obtained is represented as I_k^{ROI} where subscript k indicates the k^{th} image.

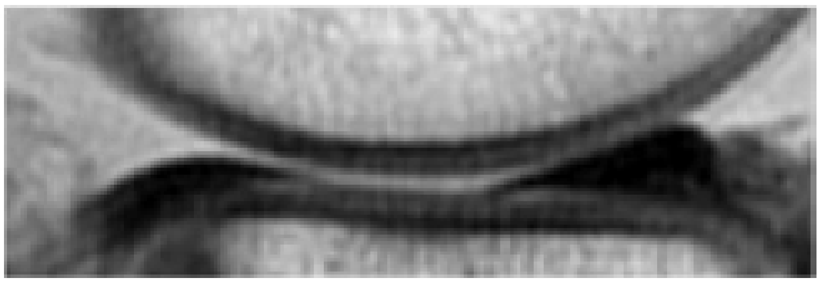

Figure 5: Sample ROI

2) *Meniscus Extraction Stage:* In this stage, menisci are separated from unwanted areas like cartilage of the knee after ROI selection. In order to make the thresholding process adaptive for efficient segmentation, the procedure followed is,

1. First, the mean of the ROIs in the slice set, is calculated by the equation (3) and is to be used as the basic set of reference for threshold selection.

$$\mu = mean\left\{ \sum_{I_k \in S_{final}} \sum_i \sum_j I_k^{ROI}(i,j) \right\} \tag{3}$$

2. All the images in the set, I_k^{ROI} for $final\ k \in S_{final}$ are thresholded into binary images by using the threshold $\tau = 0.2\mu$.
3. Now, the process of meniscus extraction is performed in order to separate out the meniscus from the images obtained in step 2. Some shape conditions are also imposed on all the parts extracted from thresholding along with a condition of their bounding box in order to remove undesired objects [12].
   a. Area restriction: It is used to eliminate noisy part and minute unwanted objects in the image. It is achieved by setting a fixed range size of objects that could be assumed to be meniscal.
   b. Shape condition: Shape conditions are imposed on each meniscal-object separated out from thresholding and the parameters of its bounding box are also specified so that unwanted objects may be eliminated to ease the identification process of the meniscus. The shape of the meniscal object is constrained by the axis ratio and a bounding. The criteria used for applying shape constraints are as given in the table2
   c. Forming a convex image mask: Next, a convex image is found, that compacts and assimilates all of the extracted meniscal objects. The convex image can hence be used effectively as a mask to separate out the desired meniscal object from the original image.

4. After application of the shape conditions, the remnant resulting objects are noted. Step 2 is then reiterated by stepping up the threshold by 0.05 μ to again threshold the image. This process is iterated till $\tau = 0.8\mu$. The same procedure is applied to all the I_k^{ROI} in the set S_{final}.
5. The thresholding value that gives us the maximum count of desired meniscal objects extracted from S_{final} is set as the optimal threshold for extraction of meniscal objects. The optimal threshold τ^* can be adaptively selected for each individual.

$$\tau^* = \arg\left\{ \max_{\tau} \left[\sum_{I_k e S_{final}} no.\_of\_meniscal\_objects\left(I_k^{ROI}, \tau\right) \right] \right\} \quad (4)$$

The output of the above step shows that some part of cartilage is also segmented out because it satisfies the shape and area constraints of a meniscus.

6. In order to remove any false positives, we strictly maintain that there should be only one object, at most, on both the sides.
7. We compare the objects on the same half side of the extracted image with each other, to determine the meniscal object accurately. If there is more than one object on either side, we find the axis ratios of those objects. The axis ratios are compared, and the object with the least axis ratio is retained.

The meniscal objects thus obtained are forwarded to the scoring and characterization stage.

Table 2
Shape constraints on each of the segmented objects

Area	The area of the objects is >50 pixels and <360 pixels
Axis Ratio	The ratio of the major axis to the minor axis is >1 and <5
Bounding Box	The ratio of the length to the width is >1 and <5

Figure 6: Sample extraction result

3) *Scoring and tear characterization:* The important requirement for tears to be characterized is to divide the extracted meniscal portion into the broad partitions: the lateral meniscus and medial meniscus, which are then divided into posterior (hind side) and anterior (front side) sections. Majority of the scan sequences in our database were scanned from medial direction to the lateral direction. In the situations where the scans were from lateral to medial direction, the images were reordered to appear from medial to lateral. Thus the first half of the image slices is considered as the medial part and the second half of the slices is considered as the lateral part.

To identify the anterior from the posterior part: 1. When two objects are extracted, the left object is considered to be the anterior one and 2. When only one object is extracted, then the object whose centroid lies to the left of the ROI midline is considered to be the anterior one.

The four sections, thus identified, of the extracted meniscus, can then be checked to detect tears. For the characterization stage, three broad categories of tears are taken into consideration. Type 1 is the degenerative tear seen in adults and elderly. Type 2 is when the meniscus is broken into pieces. Type 3 is a frequently occurring tear which can be recognized by a linear vent. Figure 7 shows the types.

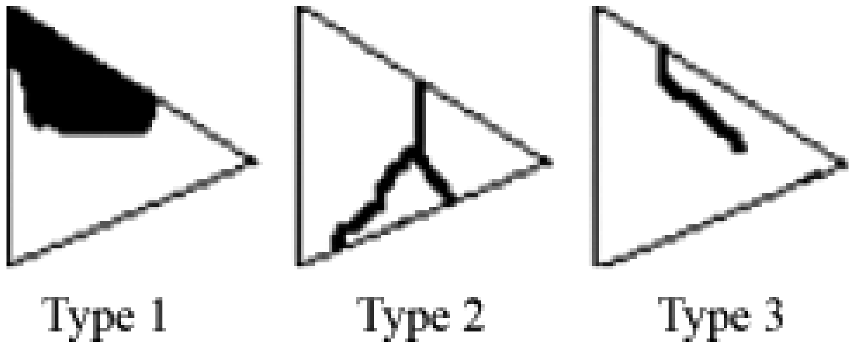

Figure 7: Types of tears

2.2.1. Measures for tear quantification

Two measures, T1 and T23, capture crucial information about the tears.

i. *T1*

The measure T1 shows the reducing changes caused by using intensity thresholds that break the meniscus into parts.

It is calculated as under,

a. A set of five multiples of the optimal threshold and their corresponding scores are used to measure T1

$$\tau = 0.7\tau^* , 0.6\tau^* ......0.3\ \tau^*$$
$$Score = 90, 70, 50, 30, 10.$$

b. Threshold τ^n = is applied to individual meniscal objects ϕ_k from the largest to the smallest threshold by,

$$n_k^* = \arg\left\{ {}_{n}^{\max} \chi\left(\varphi_k, \tau_n\right) \geq 2 \right\} \text{ For n = 1 to 5} \tag{5}$$

Where χ counts the number parts

c. The value of n_k^* is used to assign T1 scores

$$\alpha_k = score\left(n_k^*\right)$$

ii. *T23*

The measure T23 shows the reduction in area caused by using intensity thresholds. It takes into account, the degenerated meniscus pixels. It is calculated as under,

a. A set of five multiples of the optimal threshold and their corresponding scores are used to measure T1

$$\tau = 0.7\tau^* , 0.6\tau^* ......0.3\ \tau^*$$
$$Score = 90, 70, 50, 30, 10.$$

b. Threshold τ^n = is applied to individual meniscal objects ϕ_k using the following equation,

$$\beta_k = 100\left(1 - \sum_n \left(\frac{1}{2^n}\right) \xi_n\left(\varphi_k, \tau_n\right)\right) \tag{6}$$

Where ζ_k ƒè is defined by,

$$\zeta_k(\varphi_k, \tau_n) = \frac{area\_of\_\varphi_k\_thresholded\_by\_\tau_n}{area\_of\_\varphi_k} \tag{7}$$

2.2.2. Discussion on T1 and T23

Absence of any desired meniscal object in the output of stage 2, indicating a heavily torn meniscus, should have T1 and T23 scores set to 100. The slices that do not belong to S_{final} will have score 0. T1 gives information for type 2 and type 3 tears, and T23 for type 1.

When both T1 and T23 scores are large, it can be considered that the meniscus is broken into pieces and has many high-intensity signals. When both the scores are low, it indicates that the meniscus is healthy. If only T1 is high, then there is a chance of type 1 tear. If only T23 is high, then there are chances of type 2 or type 3 tears.

2.2.3. Tear Continuity

The tear continuity should be considered in consecutive slices, when calculating the average T1 and T23 scores using the following equations.

$$\begin{aligned} \hat{\alpha}_k &= 0.25\alpha_{k-1} + 0.5\alpha_k + 0.25\alpha_{k+1} \\ \hat{\beta}_k &= 0.25\beta_{k-1} + 0.5\beta + 0.25\beta_{k+1} \end{aligned} \tag{8}$$

The final score of any slice needs to take into account, the scores of its successor and predecessor for the existence of the tear on that slice to be confirmed.

2.2.4. Final score – combination of T1 and T23

Since the scores T1 and T23 give us the information of specific types of tears, they can be combined together, using the equations below, based on which score is comparatively larger.

$$\begin{gathered} If\ \hat{\alpha}_k > 1.5\hat{\beta}_k,\ then\ \gamma_k = \hat{\alpha}_k\ or \\ If\ \hat{\beta}_k > 1.5\hat{\alpha}_k,\ then\ \gamma_k = \hat{\beta}_k\ or \\ else\ \gamma_k = \frac{1}{2}\left(\hat{\alpha}_k + \hat{\beta}_k\right) \end{gathered} \tag{9}$$

Where γ_k is the final score.

71	‘deg’	72	‘deg’
94	‘deg’	96	‘deg’
96	‘deg’	95	‘deg’
100	[]	72	‘deg’
0	[]	0	[]

Figure 8: Sample scores

3. RESULTS AND EVALUATION

3.1. Training Phase of the CAD

Training phase is necessary in order to assign scores to tears so that a threshold on the final score can be established from which we can interpret the meniscus as “torn” or “normal”. A 10-case set was used for training, and the decider thresholds were set with the help of radiologists as – lateral anterior (95), medial anterior (90), lateral posterior (80) and medial posterior (70).

3.2. Accuracy of the system - Sensitivity and Specificity

Sensitivity and specificity are the measures used to statistically evaluate the performance of a binary categorization test. Sensitivity measures the proportion of true positives (desired meniscal objects in our case); and Specificity measures the proportion of true negatives correctly identified (unwanted objects like cartilage). Thus sensitivity tests the avoidance of false negatives, as specificity does for false positives. The equations for sensitivity and specificity are as under,

$$sensitivity = \frac{no\_of\_true\_positives}{no\_of\_true\_positives + no\_of\_false\_negatives}$$

$$specifity = \frac{no\_of\_true\_negatives}{no\_of\_true\_negatives + no\_of\_false\_positives}$$

The sensitivity and specificity of the CAD system are approximately 88% and 96%.

4. CONCLUSION AND FUTURE WORK

In today's world which is full of different kinds of genetic disorders and people with deficiencies of minerals such as calcium, the dangerous state of osteoarthritis is rapidly spreading amongst people of various age groups. One of the states of osteoarthritis is the tear of meniscus. To detect the tears, M.R.I. scans are taken, which then show the presence or absence of tears; and if present, the type and magnitude of the tears. These scans are done by radiologists, manually. Thus human errors may occur due to some faults in human visual perception. To avoid the faults, reduce human intervention, and to ease the process of detection of the tears, a computer-aided diagnosis system is very beneficial. Once given the proper methods and benchmarks, it can provide good and accurate diagnosis. This CAD system concept allows radiologists to detect and extract meniscus tears. It also facilitates for the quantitative assessment of the tears. This system has three stages. One is preprocessing, in which, regions of interest and slices are selected. The second stage, which is the meniscus extraction stage, extracts menisci and detects tears using certain extraction and thresholding methods. The third stage uses two measures, T1 and T23, for assigning scores to identify the amount and severity of tears in the menisci. This concept seems beneficial to the radiologists in increasing their outcomes. It also seems promising to be developed to form a detailed and sophisticated system to identify specific types of tears like bucket-handle tears, radial tears and the like.

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