Differences in trabecular bone texture between knees with and without radiographic osteoarthritis detected by fractal methods

P. Podsiadlo Ph.D.†,* L. Dahl M.D.†, M. Englund M.D., Ph.D.‡§, L. S. Lohmander M.D., Ph.D.‡ and G. W. Stachowiak Ph.D.‡
† Tribology Laboratory, School of Mechanical Engineering, University of Western Australia
‡ Department of Orthopaedics, Clinical Sciences Lund, Lund University, Sweden
§ Boston University School of Medicine, Boston, MA, USA

Summary

Objective: To develop an accurate method for quantifying differences in the trabecular structure in the tibial bone between subjects with and without knee osteoarthritis (OA).

Methods: Standard knee radiographs were taken from 26 subjects (seven women) with meniscectomy and radiographic OA Kellgren & Lawrence grade 2 or worse in the medial compartment. Each case knee was individually matched by sex, age, body mass index and medial or lateral compartment with a control knee. A newly developed augmented Hurst orientation transform (HOT) method was used to calculate texture parameters for regions selected in X-ray images of non-OA and OA tibial bones. This method produces a mean value of fractal dimensions (FDMEAN), FDs in the vertical (FDV) and horizontal (FDH) directions and along a direction of the roughest part of the bone (FDSta), fractal signatures and a texture aspect ratio (Str). The ratio determines a degree of the bone texture anisotropy. Reproducibility was calculated using an intraclass correlation coefficient (ICC). Comparisons between cases and controls were made with paired t tests. The performance of the HOT method was evaluated against a benchmark fractal signature analysis (FSA) method.

Results: Compared with controls, trabecular bone in OA knees showed significantly lower FDMEAN, FDV, FDH and FDSta and higher Str at trabecular image sizes 0.2–1.1 mm (P < 0.05, HOT). The reproducibility of all parameters was very good (ICC > 0.8). In the medial compartment, fractal signatures calculated for OA horizontal and vertical trabeculae were significantly lower at sizes 0.3–0.55 mm (P < 0.05, HOT) and 0.3–0.65 mm (P < 0.001, FSA). In the lateral compartment, FDs calculated for OA trabeculae were lower than controls (horizontal: 0.3–0.55 mm (P < 0.05, HOT) and 0.3–0.65 mm (P < 0.001, FSA); vertical: 0.3–0.4 mm (P < 0.05, HOT) and 0.3–0.35 mm (P < 0.001, FSA).

Conclusion: The augmented HOT method produces fractal signatures that are comparable to those obtained from the benchmark FSA method. The HOT method provides a more detailed description of OA changes in bone anisotropy than the FSA method. This includes a degree of bone anisotropy measured using data from all possible directions and a texture roughness calculated for the roughest part of the bone. It appears that the augmented HOT method is well suited to quantify OA changes in the tibial bone structure.
in bone structures, with the ever popular fractal dimensions (FDs) used as descriptors of texture roughness\textsuperscript{6,12,13}. Of many techniques used to estimate FDs of TB a fractal signature analysis (FSA) method and a modified Hurst orientation transform (HOT) method were found particularly useful\textsuperscript{6,12,13}. The FSA method has the unique ability of producing a fractal signature, i.e., FDs calculated locally at individual scale, in the horizontal and vertical directions. Previous study showed that this method provides the most precise characterization of TB texture as it calculates FDs at individual TB widths (i.e., fractal signature). Unlike other methods, the HOT method provides FDs in all possible directions. The directions are not manually chosen by the human user, e.g., the vertical and horizontal directions or every \textsuperscript{10}, but automatically selected by the method. The number of directions depends on image sizes only. In previous studies it was suggested that this allows an accurate measurement of both the degree of anisotropy and the dominating direction for surface texture exhibiting either weak or strong anisotropy\textsuperscript{13}. However, the HOT method has a limitation in that it does not produce a fractal signature. Since the FSA and HOT methods are complementary to one another the HOT method was augmented by adding fractal signatures in the horizontal and vertical directions. This modified HOT method, called an augmented HOT method, was developed in this study.

Differences between studies in matching controls and OA subjects could create inconsistencies in findings. Previous studies were generally heterogeneous in their subject matching\textsuperscript{6,11}. Since the structure of TB changes with age and gender, and body weight influences OA progression\textsuperscript{6,12,13}, this could affect whether or not OA knees showed differences in texture parameters when compared to the controls\textsuperscript{6,13}

In this study, controls and OA subjects were closely matched by age, gender, BMI and lateral and medial compartment. The newly developed augmented HOT method was applied to TB texture regions selected on X-ray images of the matched OA subjects and controls. The regions selected are located on the subchondral bone immediately under the cortical plates. Previous studies suggested that changes in these regions in the density, anisotropy and connectivity of the underlying subchondral bone play an important role in the initiation of OA and effect the progression of OA in knee joints\textsuperscript{1,2}. Differences in the bone texture anisotropy and roughness between OA subjects and controls were analysed. Reliability tests were performed to check the accuracy of results obtained and values of fractal signatures were compared against those obtained by the benchmark FSA method.

Subjects and methods

SUBJECTS AND RADIOGRAPHIC TECHNIQUE

We use a matched case–control study design. Case knees (n = 26) were from 26 subjects (seven women) with median meniscectomy performed 17–22 years earlier and radiographic OA in the medial tibiofemoral compartment\textsuperscript{18}. Three subjects also had OA in the lateral tibiofemoral compartment. Mean (SD) age was 55.2 (11.2) years and mean (SD) BMI was 26.6 (2.7). Each case knee was individually matched by sex, age, BMI and medial or lateral compartment with a knee from 26 controls without knee surgery, meniscal cruciate ligament injury, and no signs of radiographic knee OA (joint space narrowing (JSN) = 0 and sum of marginal osteophyte grades = 0 in the tibiofemoral joint)\textsuperscript{18}.

The standing anteroposterior radiographs of both knees were obtained in 15° of knee flexion using a fluoroscopically positioned X-ray beam (Siemens Basic Radiological System (Siemens GmbH, Erlangen, Germany) with film-focus distance 1.4 m at 70 kV and 10 mA). A 24 = 30 cm Wicor-X RP film (CEA AB, Strängnäs, Sweden) was used for all patients. The tibiofemoral joint was assessed for JSN and osteophytes according to the atlas from Osteoarthritis Research Society International\textsuperscript{18}. The presence of these features was graded on a 4-point scale (range 0–3, with 0 = no evidence of bony changes or JSN) as detailed in a previous study\textsuperscript{25}. We considered radiographic OA of the knee to be present if any of the following criteria was achieved in any of the two tibiofemoral compartments: JSN of grade 2 or higher, the sum of the two marginal osteophyte grades from the same compartment >2, or grade 1 JSN in combination with a grade 1 osteophyte in the same compartment. This cut-off approximates a grade 2 knee OA based on the Kellgren & Lawrence (K/L) scale\textsuperscript{21}.

All radiographs were digitized using a Microtek ScanMaker 9800XL scanner and a TMA 1600 transparency media adapter (Microtek International INC, Hsinchu, Taiwan) with a scan mode of 16-bit RGB and an optical resolution of 800 dpi. Each radiograph was converted to 8-bit grey scale level images with a pixel resolution of 0.05 x 0.05 mm.

IMAGE FILTERING

Filtering was applied to the images obtained from digitization of radiographs to compensate for high- and low-frequency noise. High-frequency noise consists of quantum noise of the X-ray source, thermal noise in the electronic devices and noise associated with fluctuations of the power supply. Low-frequency noise is identified as slow variations in background brightness over the entire image area. These variations are usually associated with the diffusion of X-rays in soft tissues, the nonuniform intensity of the X-ray bundles and the nonhomogeneous illumination of a radiographic film during a scanning process\textsuperscript{22}. Since noise does not present TB texture this may create difficulties in texture characterization. A 5 x 5 pixel median filter was used to reduce the amount of high-frequency noise in the image. The low-frequency was eliminated using a background image subtraction\textsuperscript{23}, and this was accomplished in two steps. First, an average filter with a window of 63 x 63 pixels was applied to the original image and as a result, a smooth low-frequency image was obtained. The smooth image was then subtracted pixel by pixel from the original image.

REGIONS OF INTEREST

In the X-ray image, 256 x 256 pixel TB texture regions of interest (ROIs) were manually selected on the subchondral bone immediately under the medial and lateral cortical plates of the tibia. The horizontal distance of the ROI from the tibial border was set to about 1/4 of the compartment width measured from the outer tibial border to a vertical line drawn from the medial or lateral tibial spine. The outer 1/4 of the width was used to avoid the periarticular osteopenia adjacent to marginal osteophyte formation. Some ROIs were moved horizontally towards the vertical line to avoid an overlapping with the fibula. As an example, a knee radiograph with selected TB regions is shown in Fig. 1. Since the image resolution 0.05 mm per each region covers an image area of 12 x 12 mm. Similar size TB regions were used in previous studies\textsuperscript{24–26}.

FRACTAL METHODS

A newly developed method, called an augmented HOT method was applied to the selected TB regions. The method is an augmented version of the modified HOT method previously developed by the authors\textsuperscript{17}. This augmentation is done by adding fractal signatures in the vertical and horizontal directions. The signature shows a variation of the FD with TB width sizes and it is useful for the measurement of a TB texture roughness at individual sizes\textsuperscript{18–19}. The performance of the augmented HOT method was compared against a FSA method, which is considered as a benchmark for the calculation of fractal signatures of bone textures in horizontal and vertical directions.

AUGMENTED HOT METHOD

First, an original HOT method is described and then, its augmented version is defined.

HOT method

Unlike other methods, this method calculates a 2D FD for all possible directions and provides information on both the degree of anisotropy and the texture roughness. The HOT method is based on finding the greatest differences between all pairs of texture data points in a circular region, moving across the entire X-ray image and building a HOT image. In the image, the pixel brightness value represents the magnitude of the greatest difference between a pair of texture data points, the horizontal axis represents the Euclidean distance between the data points, called the length size, and the vertical axis represents the direction of a line running through the data points. This direction is calculated with respect to the horizontal reference line. An automated line fitting is individually performed on a log–log plot of the greatest differences vs the length sizes for each direction (i.e., each horizontal line of...
TEXTURE ROUGHNESS (i.e., A “ROUGHER” TEXTURE IS REPRESENTED BY A HIGHER FD).

THE HOT IMAGE. THE RESULTING SLOPES, CALLED HURST COEFFICIENTS (H), ARE PLOTTED ON POLAR COORDINATES AS A FUNCTION OF ORIENTATION (ROSE PLOT). THE HURST COEFFICIENT IS USED TO CALCULATE A FD (FD = 3 – H), WHICH IS A MEASURE OF BONE TEXTURE ROUGHNESS (i.e., A “ROUGHER” TEXTURE IS REPRESENTED BY A HIGHER FD).

TEXTURE PARAMETERS ARE CALCULATED FROM THE ROSE PLOT OF HURST COEFFICIENTS:

1. **MINOR AXIS FRACTAL DIMENSION (FD_{MIN})**: A TEXTURE MINOR AXIS PARAMETER (Sta) IS USED TO CALCULATE A FD, i.e., FD_{Sta} = 3 – Sta. THE TEXTURE PARAMETER Sta IS DEFINED AS HALF THE MINOR AXIS LENGTH OF AN ELLIPSE FITTED TO THE ROSE PLOT OF HURST COEFFICIENTS. THE FD_{Sta} PROVIDES A MEASURE OF TEXTURE ROUGHNESS IN THE DIRECTION OF THE ROUGHEST PART OF TB. THE PART CONTAINS THE SHORTEST BONE LENGTH COMPONENTS AND IS ASSOCIATED WITH THE PRINCIPLE LOADING DIRECTIONS OF THE TB. OA CHANGES SUCH AS THE MERGING OF ADJACENT TRABECULA AND THE THICKENING OF TRABECULAE CAN AFFECT THE BONE LENGTH. THE FD_{Sta} IS USED TO QUANTIFY THESE BONE CHANGES.

2. **TEXTURE ASPECT RATIO (Str)**: THIS TEXTURE PARAMETER IS DEFINED AS THE RATIO OF THE MINOR AND MAJOR AXES OF AN ELLIPSE FITTED TO THE ROSE PLOT OF HURST COEFFICIENTS. THE FD_{Sta} PROVIDES A MEASURE OF TEXTURE ROUGHNESS IN THE DIRECTION OF THE ROUGHEST PART OF TB. THIS DIMENSION IS A MEASURE OF THE OVERALL ROUGHNESS OF A TB TEXTURE.

3. **MEAN (FD_{MEAN}), HORIZONTAL (FD_{H}) AND VERTICAL (FD_{V}) FRACTAL DIMENSIONS**: THEY ARE CALCULATED FROM THE ROSE PLOT OF HURST COEFFICIENTS. THE MEAN FD_{MEAN} IS EQUAL TO 3 (THE MEAN VALUE OF ALL HURST COEFFICIENTS). THIS DIMENSION IS A MEASURE OF THE OVERALL ROUGHNESS OF A TB TEXTURE. THE FD_{H} AND FD_{V} ARE FDs CALCULATED IN THE VERTICAL AND HORIZONTAL DIRECTIONS, RESPECTIVELY. IT HAS BEEN SHOWN THAT OA CHANGES IN TB ARE SIGNIFICANT IN THESE DIRECTIONS.

EFFECTS OF RADILOGRAPHIC NOISE (>5%), BLUR (FINE AND REGULAR FILM-SCREEN SYSTEMS), MAGNIFICATION (UP TO 1.35X), PROJECTION ANGLE (0–15°) AND EXPOSURE (2.5–30 mA) ON THE TEXTURE PARAMETERS HAVE BEEN EVALUATED. IT WAS FOUND THAT THE FD CALCULATED BY THE HOT METHOD IS SENSITIVE TO IMAGE NOISE (>5%), IMAGE BLUR AND IMAGE MAGNIFICATION, HOWEVER, IT DOES NOT CHANGE SIGNIFICANTLY WITH PROJECTION ANGLE AND EXPOSURE. THE Str IS AFFECTED BY IMAGE NOISE (>7%), IMAGE BLUR AND PROJECTION ANGLE, WHILE IT DOES NOT CHANGE SIGNIFICANTLY WITH IMAGE MAGNIFICATION AND IMAGE EXPOSURE. IT WAS SHOWN THAT THE PERFORMANCE OF THIS METHOD IS COMPARABLE TO, OR BETTER THAN, COMMONLY USED FRAC TAL METHODS.

**RESULTS**

**RELIABILITY**

IN GENERAL, THE INTRA-RATER RELIABILITY OF THE TEXTURE PARAMETERS OBTAINED FROM THE HOT METHOD WAS HIGHER FOR THE TRAINED TECHNICIAN (0.95–0.98) THAN TWO OTHER TECHNICIANS (0.83–0.95, TABLE I). THE LOWEST RELIABILITY OF 0.83 WAS CALCULATED FOR THE ASPECT RATIO PARAMETER Sta. THE INTER-RATER RELIABILITY WAS VERY HIGH (>0.9) FOR ALL TECHNICIANS.

**CONTROLS VS MATCHED OA KNEES**

COMPARED WITH CONTROLS, THE MEANS OF FD$_{MEAN}$, FD$_{Sta}$, FD$_{H}$ AND FD$_{V}$ CALCULATED FOR OA CASES WERE SIGNIFICANTLY LOWER (MEDIAL: $P$ = [0.001, 0.001, 0.002, 0.001], LATERAL: $P$ = [0.001, 0.001, 0.003, 0.038]) IN BOTH COMPARTMENTS AT TRABECULAR IMAGE SIZES BETWEEN 0.2 AND 1.1 MM (FIG. 2).
In the medial compartment (Fig. 3), FDs calculated for OA horizontal and vertical trabeculae were significantly lower than controls at trabecular image sizes 0.3–0.55 mm \((P < 0.05, \text{FSA})\) and 0.3–0.65 mm \((P < 0.001, \text{FSA})\). In the lateral compartment (Fig. 3), FDs calculated for OA horizontal trabeculae were lower than controls at sizes 0.3–0.55 mm \((P < 0.05, \text{FSA})\) and 0.3–0.65 mm \((P < 0.001, \text{FSA})\). In the vertical direction, FDs calculated for OA cases were lower than controls at sizes 0.3–0.4 mm \((P < 0.05, \text{FSA})\) and 0.3–0.35 mm \((P < 0.001, \text{FSA})\).

In the medial compartment, TB texture in OA cases showed a significantly higher mean \([SD]\) of the aspect ratio \(\text{Str} \) than controls (OA mean 0.71 \([0.12]\), control mean 0.58 \([0.15]\), \(P < 0.008\)). The \(\text{Str} \) parameter was not significantly different in the lateral compartment.

### Discussion

In this study, the pairs of control and OA knees matched by sex, age, BMI, medial and lateral compartment were analysed by plain radiography and fractal methods to evaluate changes in TB. The intra- and inter-rater reliability of individual texture parameters was assessed for three investigators, i.e., a trained technician and two technicians who were not trained in the selection of bone ROIs, and found to be high (ICC \(> 0.8\)). These results are comparable or better than the reproducibility of commonly used radiographic measures in knees such as JSN and osteophytes\(^6\). Generally, values of the ICC greater than 0.75 represent a good agreement beyond chance\(^8\). This indicates that the reproducibility of all texture parameters was very good or excellent.

Several problems can be associated with the use of plain radiographs. One problem is that the radiography produces X-ray images, called TB texture images, which are two-dimensional (2D) projections of a three-dimensional (3D) bone. Previous studies, however, showed that the TB texture images contain data directly related to the 3D structure of the bone. A correlation between 3D histomorphometric parameters assessed by the micro-computed tomograph (\(\mu\)-CT) and the 2D texture analysis of X-ray radiographs of iliac bone was found. For the texture analysis, the skeletonization, run-length distribution and “skyscrapers” and “blanket” fractal methods were used\(^6\). Recently, a relation between 3D and 2D TB parameters has been described in a rigorous manner, i.e., \(S_{2D} = S_{3D} + 0.5\), where \(S_{2D} \) and \(S_{3D} \) are self-similarity parameters calculated for 3D image and its 2D projection. The parameters have been estimated on \(\mu\)-CT images of frozen human femoral heads and 2D projections obtained by summing the image data in orthogonal directions\(^9\). The intensity variance method was used to estimate \(S_{2D} \). These results indicate the radiographic technique is suitable for analysing bone structures.

X-ray images often have a spatial resolution of at least 0.2 mm. It has been suggested that this resolution might not be enough to capture the complexity of TB. Recent studies showed that OA changes occur in trabeculae ranging in sizes from 0.12 to 1.14 mm\(^1\). Based on this finding, the resolution of 0.2 mm appears adequate. There is also a problem associated with maintaining the same position and distance for all patients with respect to the film. If the position varies between patients or between repeat examinations of the same patient, a subsequent analysis of TB might not produce accurate results. This problem was overcome by placing subjects in a standardized position\(^9,10\).

For the bone ROIs used in this study, the FDs described TB texture for trabeculae thicknesses ranging from 0.2 to 1.1 mm and the fractal signatures from 0.3 to 0.65 mm in increments of 0.05 mm. These values fall within the range of 0.12–1.14 mm used in other studies\(^5\). The ROIs were similar to subchondral and subarticular regions used in the FSA of knee macroradiographs\(^8\) and three regions, i.e., juxtaarticular, epiphyseal and metaphyseal, selected for the analysis of scintigraphic scans and the bone histomorphometry of healthy and OA knees\(^1^4\). According to the scintigraphic and histomorphometric analyses, the bone in these regions responds to altered conditions of the joint\(^1^5,1^6\).

Although variations in texture parameters were evident between individual subjects, OA subjects showed lower values of FD\(_{\text{MEAN}}\), FD\(_H\), FD\(_V\) and FD\(_{\text{SDa}}\) (Fig. 2) and higher values of anisotropy than controls. These results indicated a change in TB structure in OA subjects that was also observed in previous studies\(^1^3\). Lower values of FD\(_{\text{MEAN}}\) could be associated with a decrease in the overall number of trabeculae (merging of adjacent trabeculae) in the weight bearing parts of OA TB\(^3\).

Lower values of FD\(_H\) calculated for OA subjects might indicate thickening of the coarse horizontal trabeculae\(^8\). The changes measured in the anisotropy (Str) of OA bone can be explained by the fact that OA trabeculae are oriented more in the vertical direction than horizontal\(^3\). The decrease in FD\(_H\) and FD\(_V\) was more apparent in the medial than the lateral compartment and the changes in Str were significant only for the medial compartment. This finding was consistent with the fact that all case knees used in this study had OA in the medial compartment and three knees had OA in the lateral compartment. However, the decrease in FD\(_{\text{MEAN}}\) and FD\(_{\text{SDa}}\) was similar for both compartments.

This can be explained by the fact that values of these FDs are more sensitive to OA bone changes occurring along the principle directions of loading that might not be necessary in the horizontal or vertical directions. This interpretation is supported by Wolff’s law which states that the TB remodels in accordance with the stresses placed upon it\(^30\). In OA subjects the predominant stresses occur in directions nearly perpendicular to the articular surface\(^1^–^3\). Therefore, it appears that the lower complexity of TB in OA than in controls is a response to changes in a loading pattern of the OA joint and biomechanical properties of the bone.

Both the FSA and HOT methods were used to calculate fractal signatures. When comparing local FDs calculated at individual trabecular image sizes, these two methods produced similar results. However, the HOT method exhibited

### Table I

<table>
<thead>
<tr>
<th>Texture parameter (HOT method)</th>
<th>Intra-rater reliability</th>
<th>Inter-rater reliability</th>
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<tbody>
<tr>
<td>FD(_{\text{SDa}})</td>
<td>0.97</td>
<td>0.86</td>
</tr>
<tr>
<td>FD(_{\text{MEAN}})</td>
<td>0.98</td>
<td>0.86</td>
</tr>
<tr>
<td>FD(_H)</td>
<td>0.97</td>
<td>0.89</td>
</tr>
<tr>
<td>FD(_V)</td>
<td>0.98</td>
<td>0.91</td>
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<tr>
<td>Str</td>
<td>0.95</td>
<td>0.88</td>
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</table>

Investigators: A = trained technician; B,C = technicians who were not trained for the selection of ROI. Intra-rater reliability was calculated for texture parameters of bone regions selected by the individual investigator at time \(t_1\) and \(t_2\) (\(2 – t_1 = \) week). Inter-rater reliability was calculated for three pairs of investigators at time \(t_1\).
larger variations in the FDs than the FSA method and it did not show differences at large sizes (0.6 and 0.65 mm). This was because the HOT method was specially constructed to be more sensitive to changes occurring at small sizes (i.e., the highest differences in grey level values in a small neighbourhood) in bone texture. This high sensitivity might be useful and lead to the earlier detection of bone changes associated with the development of OA.

Fractal signatures calculated for OA knees were lower than controls over a size range of 0.3 to 0.65 mm, except

![Fig. 2. A comparison of (-) control and (--) OA mean values of FDs calculated for the (a) medial and (b) lateral compartments over all trabecular sizes 0.2–1.1 mm (paired samples t tests, P < 0.05). Boxes denote the mean value and whiskers are the SD value.](image)

![Fig. 3. A comparison of (-) control and (--) OA mean values of the fractal signatures calculated for the (a,c) medial and (b,d) lateral compartments in the horizontal (HD) and vertical (VD) directions, respectively. Asterisks denote statistically significant differences (paired samples t tests, P < 0.05) at individual trabecular image sizes.](image)
from vertical trabeculae in the lateral compartment. The decrease in FDs calculated for vertical trabeculae was limited to small sizes 0.3–0.4 mm. A possible explanation for the absence of significant differences at larger sizes may include the fact that only three OA subjects had OA in this compartment.

Some changes identified in the texture bone parameters may relate to the remodelling of bone marrow. Recent studies have shown that bone marrow changes with the progression of OA in knee joints. It has been reported that the fat content of marrow bone can affect values of texture parameters. This effect is most noticeable in texture parameters that are direction sensitive (especially, in the vertical direction), but occurs to a lesser degree in FDs. This suggests that results obtained from the HOT method may not be significantly affected by changes in marrow bone. It needs to be emphasized that our results were obtained for OA and healthy subjects that were individually matched by age, gender and BMI. However, the OA subjects had all undergone previous meniscectomy, and it is unclear if the texture parameters will be different for OA subjects without previous meniscal surgery. It has been shown that the increased cartilage contact stress that occurs after meniscectomy may both alter TB structure, and lead to OA development. Meniscal maceration and destruction is very common in “idiopathic OA” as well, which suggests that the changes found in our sample are not necessarily different from knee OA without meniscal surgery. Further, many cases of meniscectomy are performed due to degenerative meniscal lesions where there is no report of knee trauma. Thus, all cases studied here do not necessarily need to be “post-traumatic” OA. Sample size limits our possibilities to stratify according to type of meniscal tear and surgery. This is an area requiring further studies.

A previous study found that the BVF and the bone surface declined significantly in human tibial cancellous bone specimens of age 60 and older. It was also found that there was a direct proportional relationship between FD and bone porosity levels. The volume fraction and surface were inversely related to the porosity, i.e., a decline in the bone volume and surface results in an increase of porosity. Based on these results, as well as results obtained from the fractal analysis of plain radiographs of healthy women in age from 20 to 90 years, it is evident that FD increases significantly after the age of 60 years. Other studies showed that the spatial distribution of a bone mass density (BMD) measured in the proximal, central and metaphyseal slices of the proximal tibia differed in men and women. Using age- and sex-matched controls is therefore critical for the analysis of differences between healthy and OA knees.

In conclusion our findings indicate that the augmented HOT method can successfully be used to quantify OA changes in TB bone texture anisotropy and roughness. The HOT method gives comparable values of fractal signatures to those obtained from the benchmark FSA method. It also gives a more detailed description of OA changes in bone anisotropy than the FSA method. This includes a degree of anisotropy measured using data from all possible directions and a texture roughness calculated for the roughest part of the bone. Using this improved method, we aim to further characterize OA changes in bone structure and to assess the importance of these changes in OA initiation and progression by prospective, long-term studies on patient groups at high risk of OA development.

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