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Relation between Cartilage Volume and Meniscal Contact in Medial Osteoarthritis of the Knee

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Abstract

Background—The purpose was to determine the relationship between the cartilage volumes in different regions of the femur and tibia, and the lengths of contacts between the meniscus and cartilage. The rationale was that less meniscal contact would make the cartilage more susceptible to loss of volume due to degeneration and wear.

Methods—Fifty MRI scans of osteoarthritic knees at varying degrees of severity were obtained. Computer models of the cartilage layers of the distal femur and proximal tibia were generated, from which cartilage volumes and thicknesses were calculated for different regions. The lengths of meniscal contact and heights were measured in frontal and sagittal views.

Results—Cartilage loss progressed initially on the central and inner regions of the distal femur, and on the tibia in the region uncovered by the meniscus. As the cartilage volume decreased further, the wear spread medially, and to a lesser extent anteriorly and posteriorly. There were inverse relations between the loss of volume on both the femur and tibia, and the meniscal contacts and heights.

Conclusions—Cartilage loss initially occurred where there was direct contact between the cartilage of the femur and tibia. The meniscus did not prevent this, nor prevent the spread of the wear medially. This may have been due to the progressive reduction of cartilage-meniscal contact as the meniscus subluxed or lost substance, as the cartilage loss and deformity progressed. This suggested that the meniscus was not able to ameliorate the forces and pressures on the cartilage surfaces to prevent degeneration.

Keywords

Knee Osteoarthritis; Cartilage Wear; Meniscal Function; Progress of Knee Osteoarthritis

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INTRODUCTION

The term ‘cartilage degeneration’ usually refers to a disruption of structure, fibrillation, softening, or loss of material. Wear refers specifically to loss of material from the surface, resulting in a loss of volume, whereas internal structural changes are not accounted for. In this context we refer to cartilage loss as the same as wear. In our study, we measured cartilage thickness and volume based on MRI images and interpreted wear in a qualitative way by observing relative thicknesses in different regions of the femoral and tibial cartilage layers. The cases ranged from little sign of degeneration based on KL grade and the MRI cartilage thickness maps to severe degeneration with full-thickness defects. To obtain a measure of the relative loss in two different regions of cartilage we plotted volume A versus volume B and calculated the best-fit line. The slope represented the mean value of the ‘cartilage volume loss ratio’ or ‘loss ratio’ for the cohort. Hence, in this cross-sectional study, in plotting the cartilage volumes in different regions, the progression from high volume to low volume among our cohort was also used as an indicator of mean cartilage loss.

In the classical study on degenerative changes in different age ranges[1], cartilage damage or loss was found to be most prevalent on the distal medial femoral condyle and on the tibial area not covered by the meniscus, and there was increased degeneration of the cartilage surfaces and meniscus with age. In a visual study of 12 normal knees used for contact area studies, the medial tibial cartilage which was not covered by the meniscus was soft and fibrillated, making it susceptible to wear, in contrast to the cartilage beneath the meniscus which was undamaged[2]. Observations of full-thickness defects at the time of joint replacement showed femoral lesions centered at 11 degrees flexion on average and central tibial lesions in the anterior-posterior (AP) direction, the lesion centers being within 4 mm of center in an ML direction[3]. From autopsy specimens, smaller, full-thickness lesions on the distal end of the femur were biased towards the center of the knee in a medial-lateral (ML) direction, but became central for more extensive lesions[4]. Analyzing the bone pieces resected at TKA surgery, full thickness defects were mainly seen on the central band of the distal femur, while on the tibia the defects were central in an AP direction, and usually extended to the medial margin[5].

To measure cartilage volume in OA cases, segmentation of the cartilage layers from MRI images has been established as an accurate method to determine cartilage volumes and thicknesses[6–8]. In recent papers, analysis of MRI images was used to show the patterns and progression of degeneration for different severities of OA[9–13]. Regions of interest were defined on the femoral and tibial bearing surfaces. The highest rates of loss were identified on the central band of the distal femur and the central region of the tibia, with some variations depending on the extent of the OA, as indicated by Kellgren-Lawrence (KL) grade and other factors. In other studies, a relationship was determined between the clinical severity of the OA, and the degree of medial subluxation of the meniscus as seen in the mid-frontal plane[14–16]although the association could be inconsistent due to other factors such as meniscal tears[17,18].

Laboratory studies indicated that in normal knees, as much as one half of the force across the medial side was transmitted by the meniscus, based on contact area and pressure measurements[19–21] although the highest pressures may have occurred on the spine area and the central area of the condyles[22,23]. Hence a relation between the extent of contact with the meniscus might be expected. However in knees with moderate to severe OA, the high frequency of meniscal damage including horizontal cleavage lesions may have diminished the mechanical functionality[24–27]. In support of this, meniscal extrusion has been associated with tears[17,18].

The purpose of our study was to determine the cartilage volume loss among our cohort, as a function of the extent of contact between the meniscus and the femoral and tibial condyles, and the maximum heights of the menisci, in both frontal and sagittal views. The hypothesis was that there would be close correlations between the volume of cartilage and the meniscal contact and height parameters. To investigate this, we analyzed MRI images from clinical cases of OA with different severities.

METHODS AND MATERIALS

Patient Selection

All cases included in this study were randomly selected from a cohort of patients who were part of a non-therapeutic NIH study (R01 AR052873) at our teaching hospital. In accordance with HIPAA regulations and with IRB approval, all patients enrolled in the main study had anteroposterior standing semiflexed radiographs of the knees, then the signal, painful knee, also underwent a T1 weighed fat suppressed 3D gradient echo fast low angle shot sequence (25/4 [TR/TE]: flip angle, 25°, repetition time, 25 msec; echo time, 4.93 msec; bandwidth, 75 Hz/pixel; matrix size, 512×512 pixels; voxel size, 0.292×0.292×1.5 mm^3) using a 3T MRI machine (Siemens, Malvern, PA). Radiographs had been reviewed by a musculoskeletal radiologist who assigned a KL grade and measured the radiographic joint space width (JSW) for each case. The KL grade was defined as follows: 0 – no osteoarthritic changes; 1 – Doubtful narrowing of joint space and possible osteophytic lipping; 2 – definite osteophytes and possible narrowing of joint space; 3 - moderate multiple osteophytes, definite narrowing of joint space, some sclerosis, and possible deformity of bone ends; and 4 – large osteophytes, marked narrowing of joint space, severe sclerosis and definite deformity of bone ends. Joint space width was manually measured at the narrowest point in the tibiofemoral compartment, according to established protocol[30].

A total of 65 cases were randomly selected from the above NIH cohort. These cases were screened for those with primary medial OA and without damage to the cruciate ligaments or menisci seen on the MRI scan; cases with MRI artifacts were excluded. Upon inclusion, X-Rays were reviewed to determine KL grade. There were 50 cases which satisfied these criteria of which there were 18 males and 32 females with average age of 61 yrs, ranging from 38 – 83, and average body mass index (BMI) of 26.5, ranging from 15.4 – 32.6.

qMRI Analysis

Each MRI scan was analyzed in 3DDoctor software (Able Software Corp., Lexington, MA) where the contours of the femoral and tibial cartilage were outlined on each sagittal slice. The sagittal outlines were then rendered to create polygon-based 3D surface models which were exported into Rapidform software for thickness and volume analysis (Inus Technology, Inc., Seoul, S. Korea). In Rapidform, color-coded thickness maps were produced on the cartilage models of the distal end of the femur, and of the lateral and medial tibial plateaus. The maps were color-coded to the same scale between 0 – 4 mm thickness. The maps were then visually sorted in order of severity of osteoarthritis and six representative cases were selected to show the patterns of medial cartilage thickness from ‘normal’ to ‘severe’ OA.

Regarding accuracy of the data, Eckstein et al[31] has shown qMRI volume measurements to exhibit reproducibility within 3.7% for tibial cartilage and 1.6% for femoral cartilage. This is consistent with our methodology which, in an unpublished study, was shown to have a reproducibility of 3.6% for the tibial cartilage and 2.7% for the femoral cartilage. To calculate this, one MRI was contoured and analyzed for the femoral and tibial cartilage volume measurements five separate times and the coefficient of variation (CV) in percent (CV% = standard deviation/mean×100) was determined, similar to Eckstein et al[31]. The

accuracy of qMRI volume measurements has also been shown by others to be within 3.5% [(6,32,7,8)]. In order to test the accuracy and repeatability of our analysis technique, a phantom scan was obtained. This scan was segmented five separate times in 3DDoctor (Able Software, Lexington, MA) and the five 3D models were imported into Rapidform XOV. To test repeatability, a deviation analysis was conducted among all five models and found that on average the points on each model were within 0.076 ± 0.011 mm. To test accuracy, the dimensions of the phantom were obtained with the use of a Mitutoyo Caliper. In Rapidform, the same dimensions were measured on the 3D model. The percent error was then determined as %error = [(Rapidform dimension – caliper dimension)/caliper dimension]×100 = −0.056%. This is similar to the technique of Kurmis et al[33]. Both the repeatability and accuracy of our technique was shown to be well within the voxel size of 0.292×0.292×1.5 mm^3 used for this study.

The model was then divided into sub-regions (Figure 1) based on studies referenced above[9,12], which indicated that the most cartilage loss in the tibiofemoral compartment occurred on the central band of the distal femur and on the area not covered by the meniscus on the tibia. The femoral cartilage was divided into medial and lateral compartments by a plane through Whiteside's line, and further divided into distal and posterior regions. The distal region, substantially loaded during the stance phase of gait, was defined relative to the intercondylar fossa and the center of the circular axis. The tibial cartilage was segmented into lateral and medial compartments. The medial compartment of the femur was further segmented into three evenly spaced bands, and the medial compartment of the tibia was further segmented into the regions uncovered and covered by the medial meniscus. The volumes were normalized based on the projected area of the distal femur. The projected area was defined as the average area for all cases divided by the area for the respective case, such that the normalized volume, $V=V_n*(A_{avg}/A_n)$.

To determine the relation between the medial meniscus and the condyles, the meniscus was delineated in the frontal and sagittal views (Figure 2). In several cases of severe OA, there was clearly a separation of the medial joint surfaces when the MRI was taken. This gap was closed up in the graphics routines used when taking the measurements, which was particularly relevant to the meniscal thickness HM and HP.

Analysis

In order to compare our results with literature data, cartilage volumes and thickness were calculated for all regions, for both lateral and medial sides. To compare the volumes for the range of severity between the posterior and distal femoral condyles, and between the lateral and medial sides, regression plots of volume ratios were produced involving the parameters shown in Figure 1.

In order to relate the volumes on the distal femur and proximal tibia to the meniscal contact, meniscal contact parameters were defined (Figure 2). The total contact between the meniscus and the condyle occurs at the anterior, posterior, and medial sides, and was expressed as a proportion of the AP or ML dimensions of the tibial plateau. The individual contact ratios were MM/TML, AM/TAP and PM/TAB, as defined in Figure 2. The sum of these was defined as a combined contact parameter. The heights of the meniscus at the periphery of the tibia were measured, HM, HA, and HP, their sum representing a combined height parameter. Regression analysis was then carried out between the femoral and tibial volumes, and the contact and height parameters.

RESULTS

From the cartilage thickness maps, the cartilage on the femur followed a consistent pattern, with the thickest cartilage on the central band of the distal femur (cDMF) becoming thinner until complete wear-through occurred (Figure 3). The wear band usually extended anterior of the intercondylar notch, lining up with the upward slope of the anterior tibia, an area which would be loaded in extension. The inner (iDMF) and outer (oDMF) bands also showed reduced thickness, especially adjacent to the central band, but complete wear-through was not seen. The posterior cartilage (PMF) showed thickness loss in most cases, but not as extensive as the distal femur and with infrequent wear-through. On the tibia, the thickest cartilage in the area uncovered by the meniscus (UNC) gradually thinned until wear-through. The location of the cartilage loss was usually central but in some cases had an anterior or posterior bias. As overall loss increased, the tibial lesion extended medially. Cartilage on the posterior of the medial tibia was inevitably preserved. The thickest cartilage on the lateral side, also central on the femur and tibia, reduced to a much lesser extent than medially.

The cartilage volumes on the distal femur (DMF) and proximal tibia (MT) are shown in diminishing order for the group of 50 OA cases (Figure 4). There was an almost constant rate of volume reduction except for more rapid rates for some cases at each extreme. Excluding the extremes, the percent of tibial volume loss among the cohort was only 0.47 that of the femur. The KL grades showed a low correlation with volume, except at the lowest volumes where KL grades 3 and 4 predominated.

Data on the relations between the different volumes for both the medial and lateral sides is shown in Table 1. There was a strong correlation of 0.86 between the central band of the distal femur and the total distal femur, but with the central band accounting for only 39 percent of the total cartilage loss. The inner band, also with a strong correlation of 0.82 accounted for 45 percent, the remaining 16 percent being the outer band.

The volume loss of the tibia was just under one half that of the distal femur. Dividing the tibia into the covered and uncovered areas, the former loss among the cohort was 62 percent compared with 38 percent for the latter. The loss on the posterior medial femoral condyle was 66 percent that of the distal, even though the MRI images rarely indicated any complete posterior wear-through. Loss on the distal lateral femoral side was one third that on the medial, while for the tibia the ratio was 26 percent, but with very low correlations.

Correlations between the DMF and MT, and the meniscus parameters are shown in Figure 5. For both, the femoral and tibial volumes, the higher the contact ratios, the higher the volume ratios, and vice versa, with moderate correlation coefficients. For the heights, the same relation applied with similar correlation coefficients. Correlations were calculated for the separate contact and height parameters (Table 2). The highest correlations were found for the anterior contact and height for both the femur and tibia.

DISCUSSION

In this study we generated computer models for the cartilages layers on the femur and tibia for OA cases at different stages of degeneration. We divided the layers into regions of interest based on previous studies and our own observations, and computed the cartilage volumes for the different regions. The advantages of selecting specific areas for analysis have been noted previously[38]. Qualitative visual data was obtained of the cartilage thickness patterns and the relative amounts of loss in the different regions from normal to the most severe OA cases. The major aim of our study was to determine the relation between the cartilage volumes on the femur and tibia, and the contact between the medial meniscus and

the bearing surfaces. The visual examination of the cartilage thickness maps provided initial qualitative data. There was a consistent pattern of cartilage thickness on the least affected OA cases consistent with a previous study of normal knees[34], while certain areas on the femur and tibia showed progressive cartilage loss. On the medial distal femoral condyle, three bands were obvious from the thickness maps, while on the tibia, the areas covered and uncovered by the menisci were distinct. It was evident that the areas of cartilage loss were those areas which did not contact the meniscus. Conversely, areas of cartilage in contact with the meniscus were those areas which wore the least, especially posteriorly, until the advanced stages of OA were reached.

The inner region of the distal femur exhibited slightly more cartilage volume loss than the central region, possibly due to a larger real area and interface with the tibial spine. The greater volume loss of the covered tibial region compared with the uncovered was also surprising, probably due to the progressive intrusion of the loss into the covered region with increased severity, as well as the larger initial cartilage volume. However it was clear that the loss in the least severe cases occurred mostly in the central region of the distal femur and the uncovered region of the tibia. The higher volume ratio of the distal femur compared with the tibia can be explained by the excursion of the femur of about 20 degrees in the stance phase of walking, when most of the cartilage loss is expected to occur[4,35,36].

The above data is consistent with other studies[2,4,9],. In cadaveric studies, the uncovered area of the tibia has been described as soft and fibrillated[2,3,23,37], and hence it would be subject to wear and breakdown if the contact stresses increased for any reason. In the normal knee, the medial meniscus was reported to carry approximately half of the load across the knee[19,20,21] consistent with the orientation of the collagen fibers[38]. Hence any reduction in the radial stiffness of the meniscus would lead to loss of weight-bearing capacity, resulting in increased stresses on the uncovered tibial cartilage. The more rapid fall-off in cartilage volume for the extreme cases (see Figure 4) could indicate material failure by fatigue due to a combination of high stresses and numbers of cycles. A related factor is that the increasing varus deformity is likely to increase the forces on the medial side[39,40].

In quantitative terms, there was a correlation between the areas of contact of the medial meniscus in the frontal and sagittal views, and the heights at the tibial periphery; with the cartilage volume. The less were the contacts and heights, the less the cartilage volumes although this does not signify cause and effect. It does however indicate that decreased cartilage volume is associated with a meniscus which is in less contact with the cartilage and has a diminishing protective role.

In a previous study[40] meniscal coverage and height in the frontal plane were compared against cartilage loss over a specific time period. It was pointed out that meniscal subluxation resulted in reduced contact and height, and demonstrated a strong association between meniscal damage, diagnosed on the MRI scan, and cartilage loss. Other authors have documented meniscal extrusion as OA progressed[14–17,40,41]. The implication was that cartilage damage such as horizontal cleavage lesions reduced the load-bearing and protective role of the medial meniscus by reducing radial stiffness. In our study it was interesting that the highest correlation between cartilage volume and the meniscal parameters was on the anterior meniscus. This could imply cartilage damage occurring near heel strike, a similar view being proposed previously[41,42].

In summary we showed that, in our series of cases with a full range of OA severities, reduced cartilage volumes on the femur and tibia were associated with reduced meniscal contact and height, in both frontal and sagittal views. In addition, in agreement with previous studies, the thickness maps indicated that loss of medial cartilage occurred

predominantly in areas which were not contacting the meniscus. In cases of severe OA the full thickness wear lesions extended to the medial edge, suggesting that the meniscus subluxed or lost substance as the loss of cartilage progressed. We concluded that the more the cartilage loss, the less was the meniscus able to carry out a load-bearing or protective function in preventing wear progression.

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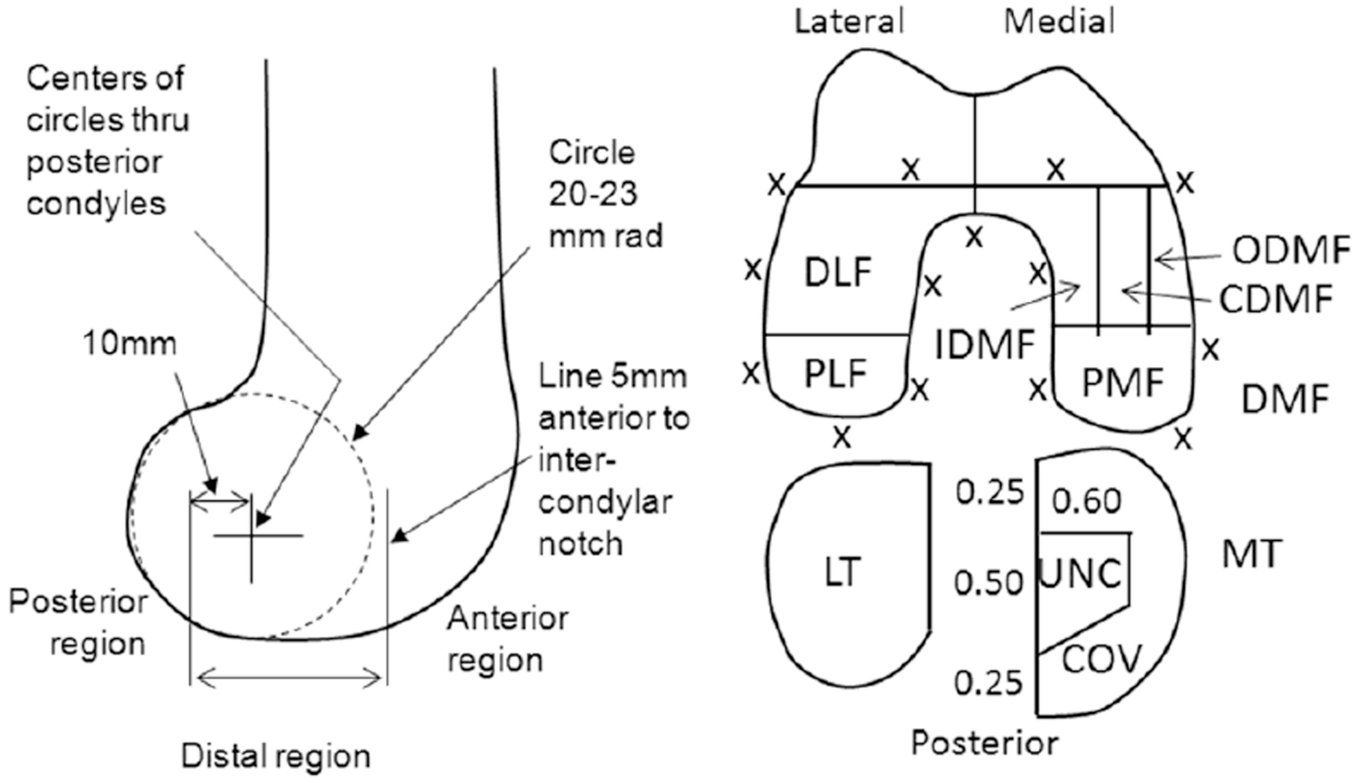

Figure 1.
Definition of the regions for analysis of cartilage volume.
DLF=distal lateral femur; IDMF=inner distal medial femur, CDMF=central, ODMF=outer; DMF=distal medial femur=sum of IDMF,CDMF,ODMF; PMF=posterior medial femur. The area bounded by xxx was used for normalization of the volume data in the different regions. LT=lateral tibia; UNC=uncovered medial, COV=covered medial, MT=medial tibia=sum of UNC and COV.

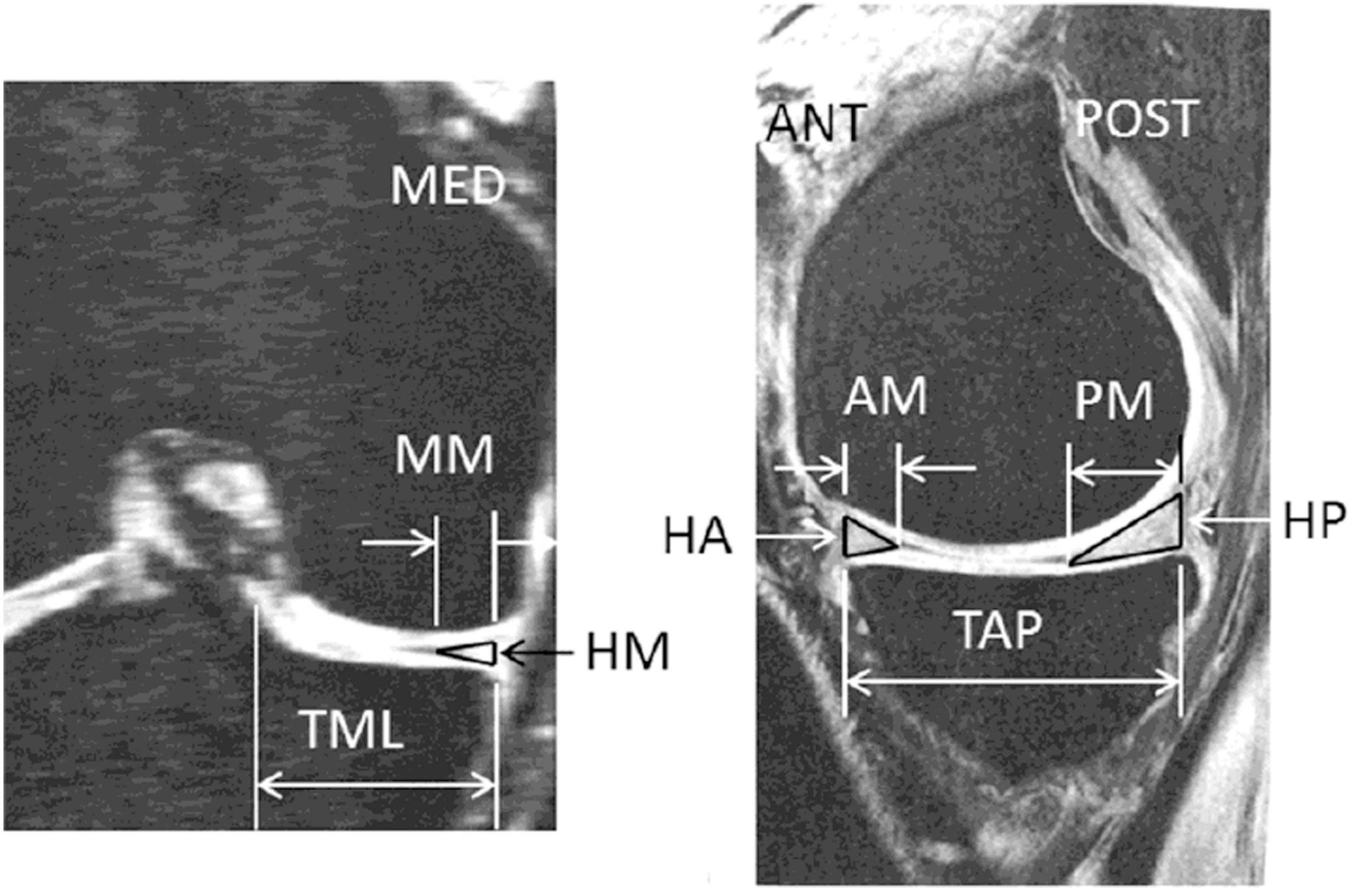

Figure 2.
Definition of the parameters for analysis of the medial meniscus. The proportionate lengths of meniscal contact are defined as MM/TML, AM/TAP and PM/TAP. Heights HM, HA and HP are measured at the extremities of the tibial condyle.

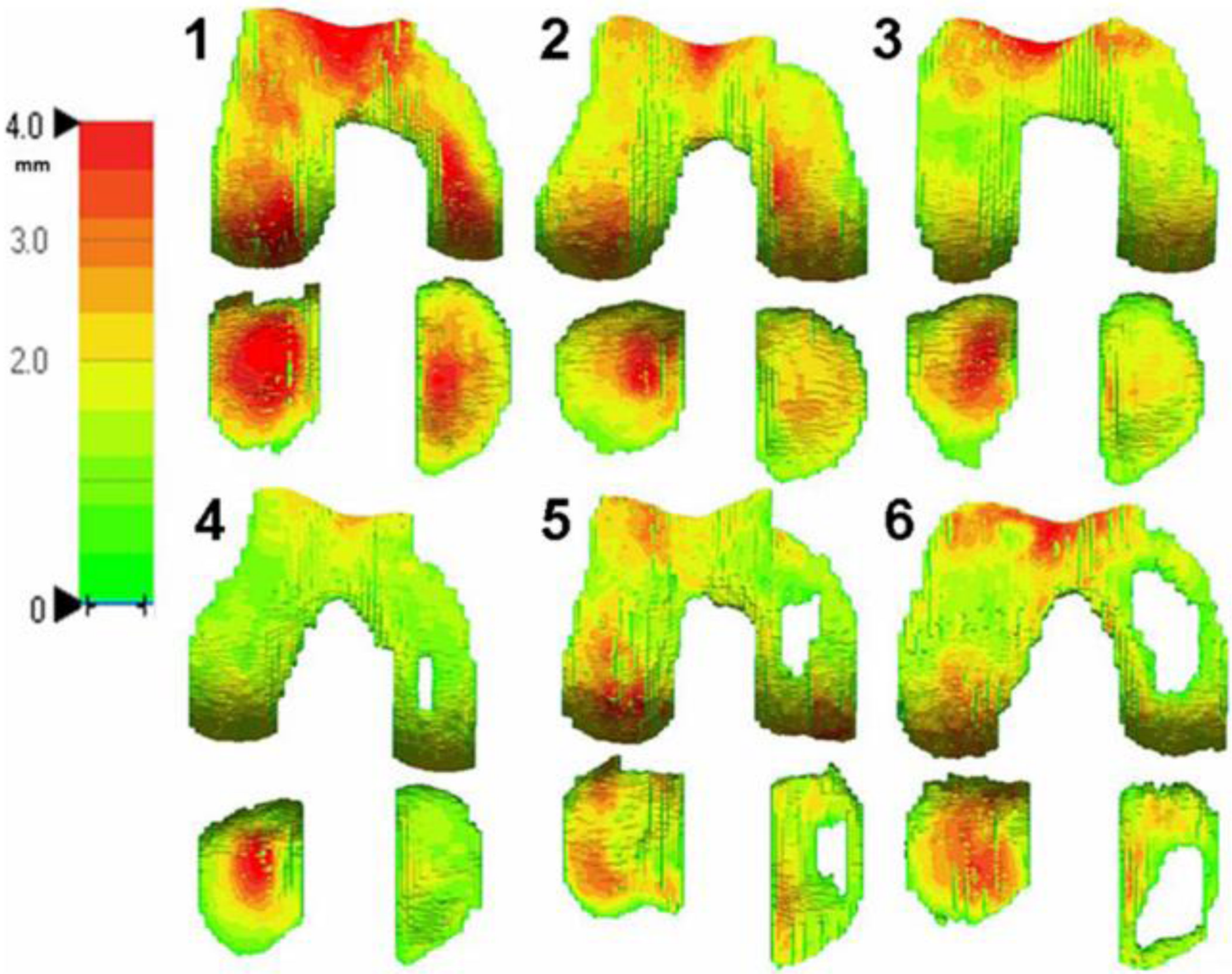

Figure 3.

Selected group of 6 cases showing increasing severity of the cartilage wear on the femur and tibia. 1='normal' case, 6=severe wear. The color coding depicts the thickness of the cartilage.

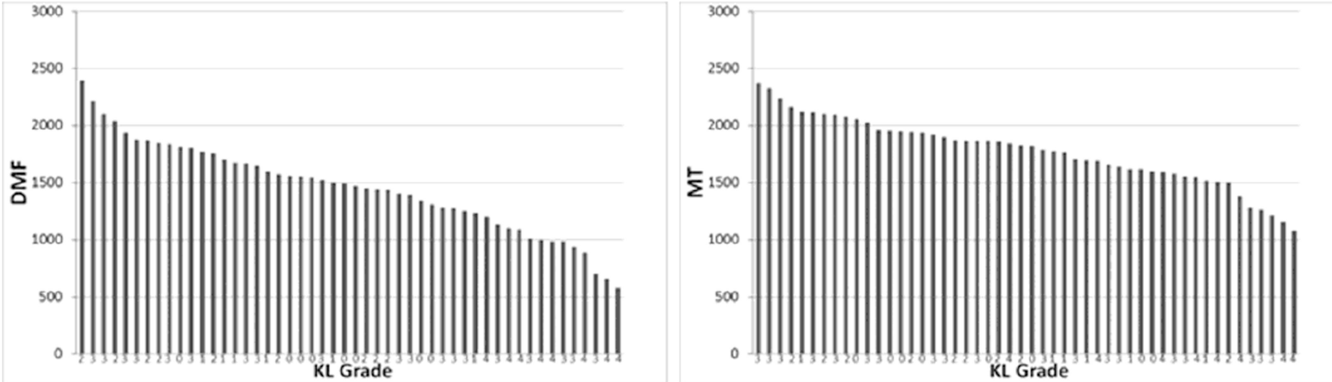

Figure 4.
a (left). The values or normalised DMF for the 50 OA cases plotted in order of decreasing value. For reference, the KL grades are noted below each case.
b (right). The values of normalised MT for the 50 OA cases plotted in order of decreasing value. There is not an exact correspondence of cases between DMF and MT.

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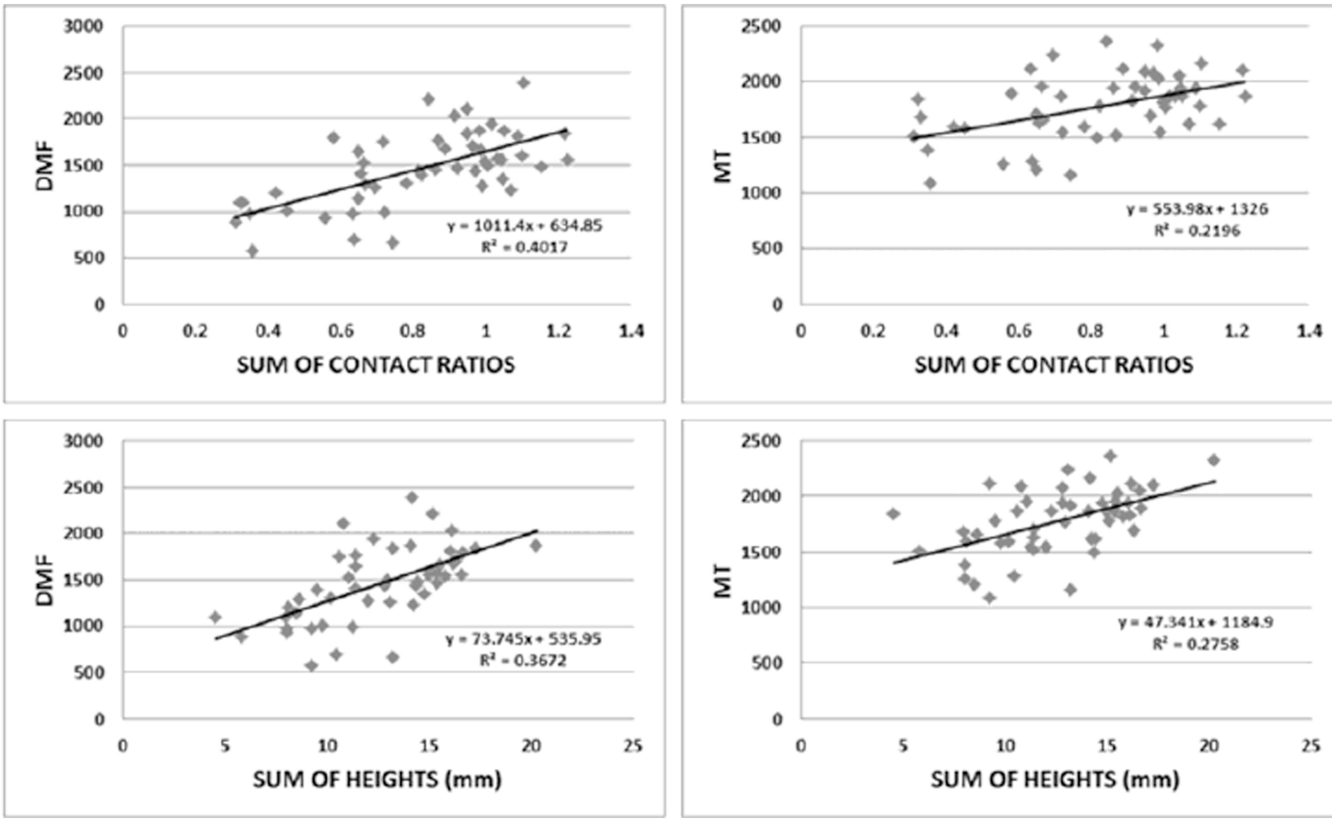

Figure 5.

a (top). Relations between normalised DMF (distal femoral volume) and normalised MT (proximal tibial volume) with the combined meniscus contact ratios.

b (bottom). Relations between normalised DMF (distal femoral volume) and normalised MT (proximal tibial volume) with the Sum of the Meniscal Heights.

Table 1

Relations between the cartilage volumes in different regions. For example the loss in the central region cDMF was 0.39 that of the loss in the entire distal femur region DMF with a high correlation (R2) of 0.86.

REGION RATIO	WEAR VOLUME RATIO	R2 VALUE
cDMF/DMF	0.39	0.86
iDMF/DMF	0.45	0.82
oDMF/DMF	0.16	0.53
MT/DMF	0.47	0.5
COV/MT	0.62	0.81
UNC/MT	0.38	0.60
PMF/DMF	0.66	0.42
DLF/DMF	0.33	0.17
LT/MT	0.26	0.02

Table 2

Correlation coefficients (R2) between cartilage volumes and meniscal parameters.

Y	X	R^2	Y	x	R^2
CONTACTS					
DMF	MM/TML	0.27	MT	MM/TML	0.16
DMF	AM/TAP	0.31	MT	AM/TAP	0.26
DMF	PM/TAP	0.29	MT	PM/TAP	0.09
DMF	SUM	0.40	MT	SUM	0.22
HEIGHTS					
DMF	HM	0.18	MT	HM	0.14
DMF	HA	0.44	MT	HA	0.30
DMF	HP	0.17	MT	HP	0.14
DMF	SUM	0.37	MT	SUM	0.28

DMF = Volume of cartilage of Distal Medial Femur. MT = Volume of cartilage of Proximal Medial Tibia.

The meniscal parameters are described in Figure 2.

SUM = Sum of Contact Ratios, as in Figure 5a; and Sum of Meniscal Heights, as in Figure 5b.