pISSN 2384-1095
eISSN 2384-1109

iMRI 2021;25:93-100 https://doi.org/10.13104/imri.2021.25.2.93

iMRI
Investigative Magnetic Resonance Imaging

Original Article

Bone Microarchitecture at the Femoral Attachment of the Posterior Cruciate Ligament (PCL) by Texture Analysis of Magnetic Resonance Imaging (MRI) in Patients with PCL Injury: an Indirect Reflection of Ligament Integrity

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Received: September 10, 2020
Revised: November 19, 2020
Accepted: December 11, 2020

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Purpose: (1) To evaluate the trabecular pattern at the femoral attachment of the posterior cruciate ligament (PCL) in patients with a PCL injury; (2) to analyze bone microarchitecture by applying gray level co-occurrence matrix (GLCM)-based texture analysis; and (3) to determine if there is a significant relationship between bone microarchitecture and posterior instability.
Materials and Methods: The study included 96 patients with PCL tears. Trabecular patterns were evaluated on T2-weighted MRI qualitatively, and were evaluated by GLCM texture analysis quantitatively. The grades of posterior drawer test (PDT) and the degrees of posterior displacement on stress radiographs were recorded. The 96 patients were classified into two groups: acute and chronic injury. And 27 patients with no PCL injury were enrolled for control. Pearson's correlation coefficient and one-way ANOVA with Bonferroni test were conducted for statistical analyses. This protocol was approved by the Institutional Review Board.
Results: A thick and anisotropic trabecular bone pattern was apparent in normal or acute injury (n = 57/61;93.4%), but was not prominent in chronic injury and posterior instability (n = 31/35;88.6%). Grades of PDT and degrees of posterior displacement on stress radiograph were not correlated with texture parameters. However, the texture analysis parameters of chronic injury were significantly different from those of acute injury and control groups ($P < 0.05$).
Conclusion: The trabecular pattern and texture analysis parameters are useful in predicting posterior instability in patients with PCL injury. Evaluation of the bone microarchitecture resulting from altered biomechanics could advance the understanding of PCL function and improve the detection of PCL injury.

Keywords: Magnetic resonance imaging; Knee; Ligament

INTRODUCTION

Posterior cruciate ligament (PCL) injuries are much less common than other ligament injuries, accounting for only 3-23% of all knee ligament injuries in the general population (1). Accurate diagnosis and prompt treatment are important because an injured and unrepaired PCL can lead to chronic instability and early osteoarthritis of the knee. However, PCL injuries may be underdiagnosed, because patients with PCL injury are often asymptomatic, and the spectrum of magnetic resonance imaging (MRI) findings in PCL injuries varies (2). In the chronic phase, the torn and granulated PCL retains continuity between the tibia and femur, but shows attenuated ligament caliber or buckled contour on MRI; although discontinuity of the PCL is a primary diagnostic sign, it is not always seen on MRI. Furthermore, the diagnostic accuracy of MRI in chronic PCL tears is only 23% (3); therefore, MRI alone could be not helpful in patients with chronic PCL injuries.

For accurate evaluation of the PCL, medical examination with stress is required. The posterior drawer test is most accurate in the clinical diagnosis of PCL tears, and posterior knee stress radiography can be helpful to evaluate posterior instability. However, MRI with posterior stress is not clinically feasible with available systems.

Bone is a dynamic organ that undergoes consistent osteoblastic and osteolytic activity to adapt to environmental mechanical demands. According to Wolff's law (4-6), this homeostasis of bone is an important process in the dynamic coupling of bone formation and resorption cells that function at the trabecular surface (7, 8). This adaptation to tensile or compressive forces leads to microlevel changes in trabecular bone organization relating to length, orientation, and connectivity (9). At the femoral attachment of the PCL, trabecular bone is linear and thick, an adaptation to the tensile demands influenced by the PCL. We hypothesized that trabecular bone with no tensile activity at the PCL femoral attachment site would be thinned and sometimes disappear.

Quantitative texture analysis of the bone microarchitecture pattern is a property assessed by MRI (10, 11). In a clinical setting, texture analysis is a non-invasive technique for characterization of the trabecular architecture in post-processing of images, and can be utilized for objective quantitative assessment of the parameters of contrast, correlation, and energy (uniformity) of the region of interest (ROI) of images. The application of texture analysis to the PCL femoral attachment would be both non-invasive and quantitatively useful. Texture analysis parameters, contrast, inverse difference moment (IDM), angular second moment (ASM), entropy, and correlation were used to characterize the structure of the spatial relationships on grayscale. However, there are few reports on trabecular bone at the PCL femoral attachment site.

The purpose of the present study was (1) to evaluate the trabecular pattern at the femoral attachment of the PCL on MRI in patients with a history of PCL injury; (2) to analyze bone microarchitecture at the femoral attachment of the PCL by applying gray level co-occurrence matrix (GLCM)-based texture analysis; and (3) to determine if there is a significant relationship between bone microarchitecture and posterior instability in patients with PCL tears on routine knee MRI, by comparing the texture values between normal and instability groups.

MATERIALS AND METHODS

Study Population

This retrospective study was approved by the Institutional Review Board. We retrospectively identified a study population with PCL tears between January 2010 and February 2015 from the database of our hospital information system. Inclusion criteria were (1) patients with a recorded sprain of the PCL (ICD-10 code S83.52) as the primary or secondary diagnosis, and (2) patients who had knee MRI in our hospital. We searched for the following words in context: PCL tear, tear of PCL, tear of the PCL, PCL sprain, sprain of the PCL, sprain of PCL, PCL rupture, rupture of PCL, and rupture of the PCL. Exclusion criteria were clinically suspected septic arthritis (n = 4), history of knee operation (n = 2), age under 15 years (n = 2), poor image quality due to metallic artifact (n = 2), PCL degeneration on second MRI review (n = 5), no available posterior drawer test or stress radiograph (n = 3), and no applicable posterior drawer test or stress radiograph due to an acute traumatic condition (n = 6). Based on the time of injury (6 months) according to medical records, the study population was classified into two groups: the acute injury group and the chronic injury with posterior instability group.

The 27 patients with no PCL injury were enrolled for control group: patients who had undergone the knee MRI from January 2015 to March 2015. Inclusion criteria for control groups were: (1) age between 18 and 39 years; (2) no injury of ACL or PCL; and (3) no deformity of distal femur. The MRI findings and diagnosis of the 27 patients were: low-grade chondromalacia (n = 5), high grade chondromalacia (n = 3), medial meniscus tear (n = 3), lateral meniscus tear (n = 3), discoid lateral meniscus (n = 1), patellar tendinopathy (n = 4), ganglion (n = 2), MCL sprain grade 1 (n = 2), no internal structure abnormality (n = 2), muscle strain (n = 1), and soft tissue contusion without internal structure abnormality (n = 1). On demographic comparison, age and gender were compared between the groups.

Instability Information from Medical Records and Stress Radiographs

The medical records provided the results of posterior drawer tests. The posterior drawer tests were performed by fellowship-trained arthroscopic orthopedic surgeons. The degrees of posterior displacement on posterior stress radiographs were measured by the consensus of a fellowship-trained musculoskeletal radiologist and a fellowship-trained arthroscopic orthopedic surgeon.

MRI Protocol

All knee MRI scans were performed on 3T MR scanners (MR750 and MR750w: GE Healthcare, Milwaukee, WI, USA; MAGNETOM Trio: Siemens, Erlangen, Germany; Achieva or Achieva Tx: Philips Healthcare, Best, The Netherlands). The knee MR images were scanned in routine position with an eight-channel dedicated knee coil (Philips Healthcare; InVivo, Gainesville, FL, USA) or a 16-channel GEM flex-M or GEM flex-S coil (GE Healthcare). The routine knee MRI sequence consisted of T2-weighted sagittal, T1-weighted axial, fat-saturated T2-weighted axial, fat-saturated T2-weighted coronal, and fat-saturated intermediate-weighted three-dimensional fast spin echo (FSE) isovoxel MR images. The typical MR parameters of FSE T2-weighted sagittal MR images are repetition time/echo time, 2783-5420/83-100 msec; matrix size, 640-449 x 640-449; field of view (FOV), 14-16 cm; slice thickness, 3 mm; slice gap, 0.3 mm; flip angle, 90-160; echo train length (ETL), 15-17; number of excitation (NEX), 1-2 (Table 1). MR parameters (FOV, matrix size, NEX) were compared between the groups.

MRI Analyses

FSE T2-weighted MR images were assessed by a fellowship-trained musculoskeletal radiologist with 10 years of MRI experience. Trabecular patterns on T2-weighted MR images were evaluated qualitatively by a musculoskeletal radiologist. The trabecular patterns at the PCL femoral attachment were classified as with or without apparent thick, prominent, anisotropic, trabecular bone. For quantitative evaluation, GLCM-based texture analysis was performed in parallel orientation along the bone-PCL interface direction using ImageJ (National Institutes of Health, Bethesda, MD, USA) and GLCM Texture Analyzer plugin v0.4 (http://rsb.info.nih.gov/ij/plugins/texture.html) (12): (1) load DICOM sagittal MRI image of best visualized PCL attachment; (2) rotate the image along the course of the PCL attachment to analyze in parallel orientation along the bone-PCL interface direction; (3) convert to 8-bit indexed images with automated window level/width; (4) draw an approximately 50 mm^2 square-shape ROI (Fig. 1) ; and (5) perform the GLCM texture analysis. The following texture analysis parameters were recorded: contrast, inverse difference moment (IDM), angular second moment (ASM), entropy, and correlation. The parameters were calculated as follows:

(1) Contrast group

$$\text{Contrast}=\sum_{n=0}^{G-1} n^2 \left\{ \sum_{i=1}^{G} \sum_{j=1}^{G} P(i,j) \right\}, |i-j|=n$$

$$\text{Inverse difference moment (IDM)}= \sum_{i=0}^{G-1} \sum_{j=0}^{G-1} \frac{1}{1+(i-j)^2} P(i,j)$$

(2) Orderliness group

$$\text{Angular second moment (ASM)}= \sum_{i=0}^{G-1} \sum_{j=0}^{G-1} \{P(i,j)\}^2$$

$$\text{Entropy}= -\sum_{i=0}^{G-1} \sum_{j=0}^{G-1} P(i,j) \times \log((P(i,j))$$

Table 1. Parameters for Magnetic Resonance Imaging (MRI) Sequences

TR (repetition time)	2783-5420 msec
TE (echo time)	83-100 msec
Matrix size	384-512 × 326-384
FOV	14-16 cm
Slice thickness	3 mm
Slice gap	0.3 mm
Flip angle	90-160°
ETL	15-17
NEX	1-2

ETL = echo train length; FOV = field of view; NEX = number of excitations

(3) Statistical group

$$\text{Correlation}=\sum_{i=0}^{G-1}\sum_{j=0}^{G-1}\frac{\{i\times j\}\times P(i,j)-\{\mu x\times \mu y\}}{\sigma x\times \sigma y}$$

G is the number of gray levels used. μ is the mean value of P.

μx, μy, σx and σy are the means and standard deviations of Px and Py.

Statistical analyses

Age, gender and MR parameters (FOV, matrix size, NEX) were compared between the groups. Age, FOV, matrix size were compared between the groups using the one-way ANOVA with post-hoc analysis using the Bonferroni test, and NEX, gender were compared with Chi-squared test.

Pearson's correlation coefficient was used to compare the degree of instability shown by the posterior drawer test and posterior stress view, with the texture analysis parameters. The texture parameters were compared between the groups using the one-way ANOVA with post-hoc analysis using the Bonferroni test. All analyses were performed using statistical software (R package 3.1.2; http://cran.r-project.org). P values < 0.05 were considered statistically significant.

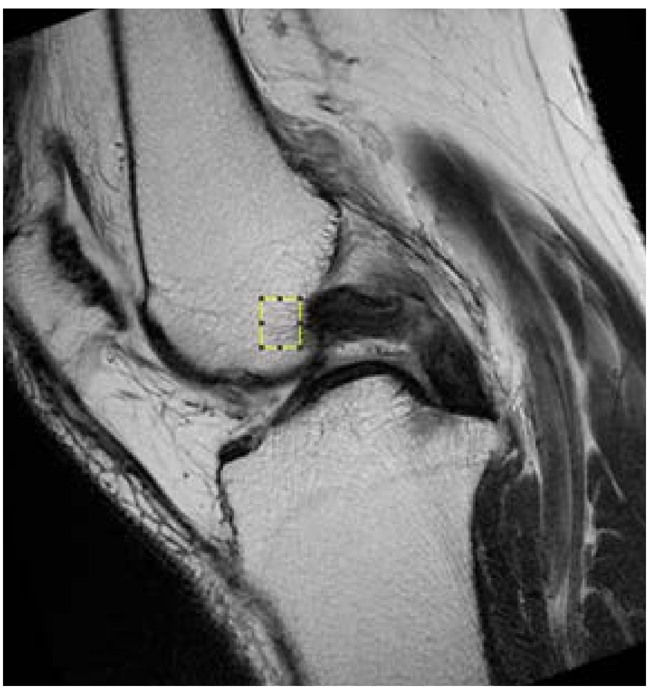


Fig. 1. Magnetic resonance (MR) image indicating a rectangular-shaped region-of-interest (ROI) measuring approximately 50 mm^2 at the bone, just near the posterior cruciate ligament (PCL) femoral attachment site.

RESULTS

Ninety-six patients with PCL injury who underwent a knee MRI between January 2010 and February 2015 were included and evaluated. Sixty-five patients were male, and 31 were female. The mean age was 40.7 years (range: 15-89). We assessed 51 right and 45 left knees.

On demographic comparison, age was significantly different between the control group and chronic injury group, but there was no significant difference among the groups for gender (Table 2). On MR parameter comparison, there was no significant difference among the groups for FOV, matrix size, NEX (Table 3).

On qualitative evaluation with conventional MR image, a thick, prominent, anisotropic, trabecular bone pattern was apparent at the PCL femoral attachment in 57 of 61 (93.4%) normal or acutely injured patients, but was not prominent in 31 of 35 patients with chronic injury and posterior instability 31 of 35 (88.6%) (Fig. 2).

On quantitative evaluation with texture analysis, the posterior drawer test grades and the degrees of displacement on posterior stress radiographs did not

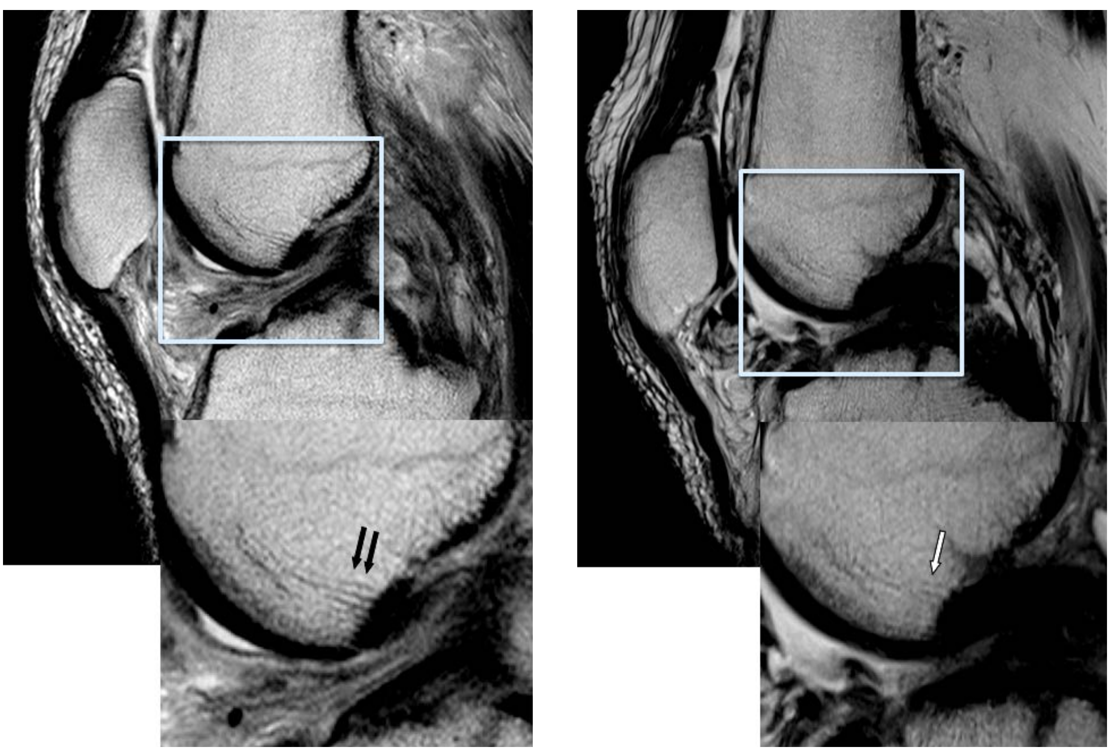
Table 2. Comparison of Age (Mean ± SD) and Gender

	Control	Acute injury	Chronic injury	P value in post-hoc	Overall P value
Age	29.67 ± 6.25	39.03 ± 19.16		0.051	0.006
		39.03 ± 19.16	43.54 ± 17.64	0.619	
	29.67 ± 6.25		43.54 ± 17.64	0.005	
Gender					0.542
Male	16	43	22		
Female	11	18	13		

Table 3. **Comparison of MR Parameters; FOV and Matrix Size (Mean ± SD), and NEX**

	Control	Acute injury	Chronic injury	P value in post-hoc	Overall P value
FOV	14.11 ± 0.42	14.38 ± 0.76		0.214	0.122
		14.38 ± 0.76	14.17 ± 0.51	0.383	
	14.11 ± 0.42		14.17 ± 0.51	1.000	
Matrix size	509.67 ± 12.12	508.43 ± 24.63		1.000	0.959
		508.43 ± 24.63	508.40 ± 14.84	1.000	
	509.67 ± 12.12		508.40 ± 14.84	1.000	
NEX					0.053
1	16	20	12		
2	11	41	23		

FOV = field of view; NEX = number of excitation



a b

Fig. 2. (A) The thick, prominent, anisotropic trabecular bone pattern at the posterior cruciate ligament (PCL) femoral attachment site is apparent in the acute injury group (black arrows). (B) In contrast, the trabecular pattern is less prominent and smoothened in the chronic injury group (white arrow).

correlate with the texture parameters of ASM, contrast, correlation, IDM, and entropy (P = 0.893, 0.594, 0.944, 0.833, and 0.193, respectively ; all are $P > 0.05$). However, ASM, contrast, correlation, IDM, and entropy were significantly different between the acute and chronic groups (Table 4 and Fig. 3).

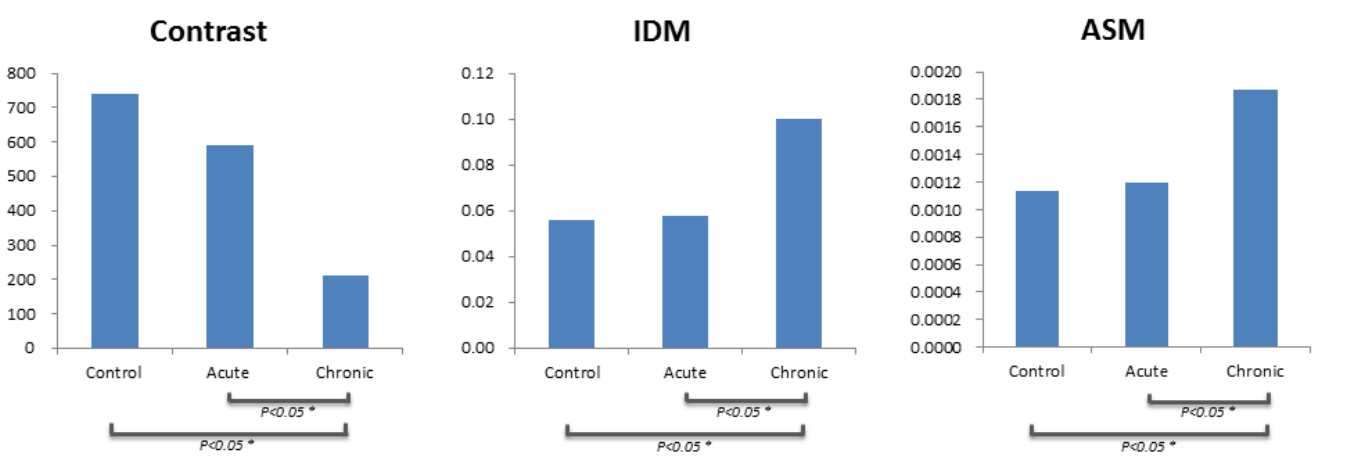
DISCUSSION

Cortical and cancellous bones are continuously remodeled throughout life by osteoclastic and osteoblastic activity. Several models include Wolff's law of remodeling in response to mechanical stress (4-6), piezoelectric

Table 4. Comparison of Texture Analysis Parameters (Mean ± SD)

	Control	Acute injury	Chronic injury	P value in post-hoc	Overall P value
ASM	0.0011 ± 0.0004	0.0012 ± 0.0006		0.77	< 0.05**
		0.0012 ± 0.0006	0.0019 ± 0.0005	< 0.05*	
	0.0011 ± 0.0004		0.0019 ± 0.0005	< 0.05*	
Contrast	738.38 ± 431.49	601.32 ± 377.75		0.234	< 0.05**
		601.32 ± 377.75	213.92 ± 151.89	< 0.05*	
	738.38 ± 431.49		213.92 ± 151.89	< 0.05*	
Correlation	0.0006 ± 0.0003	0.0007 ± 0.0004		0.714	< 0.05**
		0.0007 ± 0.0004	0.0024 ± 0.0013	< 0.05*	
	0.0006 ± 0.0003		0.0024 ± 0.0013	< 0.05*	
IDM	0.0558 ± 0.0209	0.0579 ± 0.0199		0.932	0.011**
		0.0579 ± 0.0199	0.1001 ± 0.0321	< 0.05*	
	0.0558 ± 0.0209		0.1001 ± 0.0321	< 0.05*	
Entropy	6.7190 ± 0.4295	6.6849 ± 0.5460		0.940	0.007**
		6.6849 ± 0.5460	6.4297 ± 0.2291	0.019*	
	6.7190 ± 0.4295		6.4297 ± 0.2291	0.028*	

ASM = angular second moment; IDM = inverse difference moment



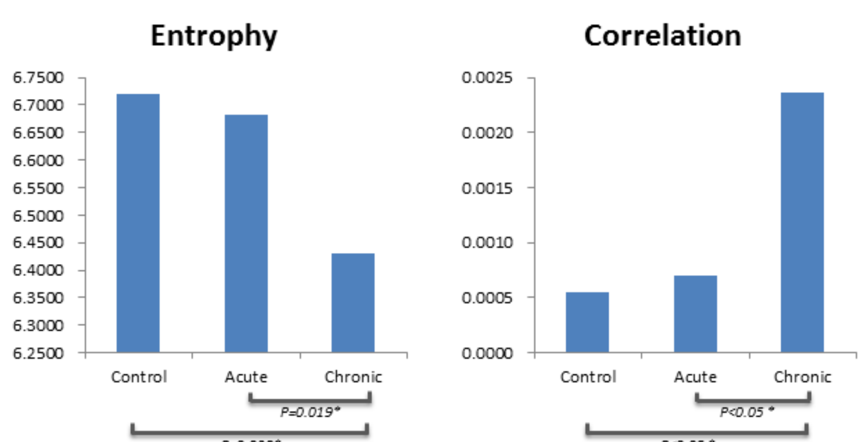


Fig. 3. The graphs compare the texture parameters of contrast, inverse difference moment (IDM), angular second moment (ASM), entropy, and correlation. ASM, contrast, correlation, and IDM show a significant difference between the acute and chronic groups ($P < 0.05$), although there was no significant difference between the acute and control groups ($P > 0.05$).

remodeling in response to electrical charge (13), and the Hueter-Volkmann law theorizing that bone remodels in small packets of cells known as basic multicellular units (14). In this regard, cancellous bone remodels more according to Wolff's law; increasing mechanical stress increases bone gain. According to Wolff's law, bone is a dynamic organ, in which homeostasis depends upon tension or loading conditions corresponding to mechanical stress within the bone (4, 5). In particular, the turnover of trabecular bone is greater than that of cortical bone, and trabecular bone is more susceptible to failure because of the higher turnover rate. This loading condition creates a specific pattern of thick, prominent, anisotropic trabecular bone at the femoral attachment site of the PCL. This specific pattern can disappear under conditions of lack of tension or loading from the PCL because the specific prominent anisotropic trabecular patterns resulted from the tension or loading of the PCL. These resulting patterns of bone dynamics could be useful in interpretation of musculoskeletal images related to tendon or ligament pathology. We thought that trabecular bone would be diminished with decreased function of the PCL.

Diagnostic performance could be problematic in evaluation of chronic PCL tears, because the granulated PCL is visualized as low signal intensity on T2-weighted MR images. With no clinical history, a radiologist can miss a tear of the PCL in radiologic reading room without any knowledge of clinical history. To overcome this limitation, some authors have reported that the ratio of the lateral femoral condylar width to the PCL length can be a useful index (15). However, this method might be inaccurate, because the knee position can change in the current widely-used quadrature knee coils, depending on a patient's height or size.

On qualitative review, we found that the specific, prominent, anisotropic trabecular patterns differed between the acute and chronic (more than 6 months) injury groups with posterior instability (Fig. 2). This is because bone remodeling has not yet occurred in the acute phase; therefore, the specific patterns are retained. After a period of time, bone remodeling progresses, and the trabecular pattern changes. For more accurate quantitative evaluation of the trabecular pattern, we applied texture analysis to the femoral attachment site of the PCL. This quantitative analysis of the texture analysis can detect subtle differences in images.

For more accurate quantitative evaluation of the trabecular pattern, we applied texture analysis to the femoral attachment site of the PCL. This quantitative analysis of the texture analysis can detect subtle differences in images. We adopted the GLCM method (12), which is widely utilized for quantitative medical image analysis. To minimize the variation of knee position, the MR images were rotated to parallel the PCL course; texture analysis parameters could be affected by image rotation.

Age, gender, and MR parameters including FOV, matrix size, and NEX may affect the texture analysis. We evaluated if there was significant difference among the groups. Only the age was significant different between control group and chronic injury group. It might be because normal findings are more frequent in the young patients, and chronic injury is possibly more frequent in the old patients. There was no significant difference among the groups for FOV, matrix size, NEX, gender. Therefore, the influence of these factors to texture analysis among the groups might be minimal.

Our method for the evaluation of bone microarchitecture is strengthened by prevention of posterior tibial translation by the PCL. One of clinically used test for detection of injury to the PCL is the posterior drawer test, although physical examination is often inconclusive for a PCL tear (16). Our study was limited to changes in bone microarchitecture resulting from PCL tears and the related posterior instability. We believe this approach could be extended to include the attachments of ligaments or tendons.

There are several limitations to this study. First, we extracted the texture parameters from T2-weighted two-dimensional FSE MR images which can nicely demonstrate trabecular bone patterns. In the near future, we believe the features derived from three-dimensional texture analysis might be evaluated for improved performance over two-dimensional approaches. Secondly, we did not perform radiologic-pathologic correlations. The evaluation of bone microarchitecture could provide important diagnostic information. Therefore, a future study of the bone microarchitecture and texture analysis is needed. Third, texture parameters could depend on SNR, CNR and voxel size from MR images. Fourth, in control group, some have pathologic findings such as chondromalacia or meniscus tear with possibility of affecting bone microarchitecture. Fifth, we analyzed only the PCL femoral attachment. Further analysis of the PCL tibial attachment might be needed to evaluate the relationship with the PCL injury.

In conclusion, the trabecular pattern and texture analysis parameters are useful in predicting posterior instability in patients with PCL injury. Evaluation of the bone microarchitecture resulting from altered biomechanics could advance the understanding of PCL function and improve the detection of PCL injury.

Acknowledgment

This work was supported by a National Research Foundation (NRF) grant funded by the Korea government, Ministry of Science and ICT (MSIP, 2018R1A2B6009076).

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