Diagn Interv Radiol 2025; DOI: 10.4274/dir.2025.253386

MUSCULOSKELETAL IMAGING

ORIGINAL ARTICLE

Association of patellofemoral malalignment with early trochlear and patellar chondromalacia: a prospective T2* mapping study

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PURPOSE

To investigate the association between patellofemoral malalignment and early-stage trochlear and patellar chondromalacia using the T2* mapping method.

METHODS

Seventy-five patients were included in the study and divided into two groups based on the presence (patient group) or absence (control group) of patellofemoral malalignment on magnetic resonance imaging. The T2* mapping measurements were evaluated by dividing patellar and trochlear cartilage into 12 quadrants on sagittal slices. The groups were first compared based on the mean T2* relaxation times of the cartilage. Subsequently, the 12 quadrants were compared individually between the two groups. Cut-off values were calculated for the quadrants, with significant differences observed.

RESULTS

The patient group included 39 patients, and the control group included 36 patients. There was no significant difference between the groups in terms of mean T2* relaxation values for the trochlear and patellar cartilage. However, in the separate comparison of the 12 quadrants, T2* relaxation values in the upper-outer–outer (P1, T1) and upper-outer–inner (P2, T2) quadrants of both the trochlear and patellar cartilage were found to be statistically significantly higher in the patient group. Similarly, significant cut-off values were identified for the T1, P1, and P2 quadrants.

CONCLUSION

Early chondromalacia can be quantitatively detected using T2* mapping. In patients with elevated T2* relaxation values in the superior–lateral regions of the patellar and trochlear cartilage, patellofemoral malalignment should be considered in the etiology.

CLINICAL SIGNIFICANCE

Chondromalacia caused by patellofemoral malalignment may exhibit an asymmetric onset, with the superior–lateral quadrant as the initial site of cartilage damage in both trochlear and patellar cartilage.

KEYWORDS

Cartilage, malalignment, mapping, patella, trochlea

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Received 08 April 2025; revision requested 24 May 2025; accepted 14 July 2025.

Epub: 18.08.2025

Publication date:

DOI: 10.4274/dir.2025.253386

Patellofemoral malalignment is a common cause of anterior knee pain in the young population. The normal alignment of the patella with the trochlear groove (TG) is a critical factor in load bearing, and malalignment (displacement of the patella from its expected trajectory within the knee joint) can lead to chondromalacia, synovial proliferation, and subchondral bone changes from a young age.[1,2] Early diagnosis and preventive interventions play a key role in avoiding irreversible cartilage damage. Therefore, it is important to monitor and thoroughly examine patients with patellofemoral malalignment from an early stage for potential cartilage damage.

You may cite this article as: Süner U, Çilengir AH, Bulut T, Gürsoy M, Önder Y, Dirim Mete B. Association of patellofemoral malalignment with early trochlear and patellar chondromalacia: a prospective T2* mapping study. *Diagn Interv Radiol.* 18 August 2025 DOI: 10.4274/dir.2025.253386 [Epub Ahead of Print].

It is accepted that cartilage damage can be reversible in the early stages or that its progression can be halted with preventive interventions.[3] Thus, for disease prevention or effective treatment, cartilage degeneration must be reliably detected at the earliest stage. However, with conventional magnetic resonance imaging (MRI), early detection is generally not possible. Standard sequences provide only morphological information about cartilage. This limitation exists because changes in water content within degenerated cartilage are minimal in the early stages, and the sensitivity of standard sequences to detect these changes is low.[4,5] Furthermore, due to their macromolecular structure, both proteoglycan and collagen protons have very short T2 relaxation times, making direct MRI measurement difficult.[5-7] As a result, quantitative MRI techniques such as T2 and T2* mapping have gained importance in this field.[8,9] These mapping methods provide quantitative information about cartilage composition by evaluating changes in extracellular matrix components.[10]

In recent years, most studies examining the association between patellofemoral malalignment and chondromalacia have focused on patellar cartilage, often overlooking trochlear cartilage.[11-13] Similarly, studies using T2 and T2* mapping have generally evaluated tibiofemoral and patellar cartilage, with limited attention to trochlear cartilage.[14-21] However, in cases of patellofemoral malalignment, the trochlear cartilage can also be affected and may contribute to anterior knee pain even in the absence of patellar cartilage damage. To the best of our knowledge, no previous study has examined the association between patellofemoral malalignment and early-stage damage to both patellar and trochlear cartilage using T2* mapping.

The main hypothesis of this study is that patellofemoral malalignment is an etiological factor in both patellar and trochlear chondromalacia and that the chondromalacia caused by this malalignment exhibits an asymmetric onset on both joint surfaces from an early age. Another hypothesis is that this asymmetric chondromalacia can be detected at an early stage in both the patella and trochlea using T2* mapping.

Main points

- Patellofemoral malalignment is a key cause of chondromalacia.
- Early chondromalacia in patellofemoral malalignment typically involves the superolateral portions of patellar and trochlear cartilage.
- Early detection of chondromalacia using T2* mapping may improve treatment success.

In line with these hypotheses, one of the aims of the study is to investigate the association between patellofemoral malalignment and early-stage chondromalacia of trochlear and patellar cartilage using T2* mapping in young adults. Another aim is to determine which regions of the cartilage is first affected by chondromalacia.

Methods

Participants

This prospective study was approved by the İzmir Katip Çelebi University Faculty of Medicine Clinical Researches Ethics Committee (date: 12.09.2019, number: 88). Between January 2023 and January 2024, 524 patients who presented to the orthopedics and traumatology department with complaints of anterior knee pain and were suspected of having patellar malalignment based on physical examination by two orthopedists were included in the study (Figure 1). Exclusion criteria included being under 18 or over 40 years of age, a history of trauma or surgery in the knee region, any rheumatologic disease, or evidence of osteoarthritis on knee radiographs. A power analysis was conducted to determine the sample size, calculating that at least 36 patients per group (72 in total) would be required. The study was planned to conclude once this minimum number was reached in each group.

From the 524 patients prospectively evaluated, the following were excluded: those under 18 years (n = 62), over 40 years (n = 308), with a history of trauma (n = 23) or surgery (n = 20) in the knee region, with any rheumatologic disease (n = 12), and with osteoarthritic findings on knee radiographs (n = 12). The age range of 18–40 years was selected to eliminate the influence of pediatric cartilage and age-related degenerative changes on the results. Additionally, cases with traumatic, postoperative, rheumatologic, or osteoarthritic cartilage changes were excluded to avoid confounding effects.

A routine knee MRI and T2* mapping protocol was performed using a 3T MRI scanner (Magnetom Lumina, Siemens Healthineers, Erlangen, Germany) on the 87 patients who met the inclusion criteria (Supplementary Table 1). Four patients were excluded due to motion artifacts that rendered the MRI scans non-diagnostic. Furthermore, since the primary aim of the study was to detect early-stage chondromalacia in young adults and given that the optimal T2* relaxation time measurement is not feasible in the presence of full-thickness or near full-thickness cartilage defects due to the partial volume effect of synovial fluid within the mapping area, eight patients with high-grade (stage 3 or 4) chondromalacia were excluded.[22] This ensured a homogeneous study cohort and alignment with the study's objectives.

Patellofemoral instability magnetic resonance imaging parameters

A total of 75 patients underwent morphological evaluation using standard MRI sequences. Parameters identified in the literature for diagnosing patellofemoral malalignment–including the Insall–Salvati index, lateral patellofemoral angle, lateral trochlear inclination angle, trochlear sulcus depth, trochlear sulcus angle, tibial tubercle (TT)–TG distance, and medial trochlea/lateral trochlea length ratio–were measured. Patients were divided into two groups, those with patellofemoral malalignment (patient group) and those without (control group), based on the cut-off values established in the literature (Table 1). These measurements were performed using validated techniques described in the Supplementary Material 1.[23-28] Patients presenting with anterior knee pain and physical examination findings consistent with patellofemoral malalignment were classified into the malalignment group if one or more of these MRI-based morphological parameters were present.

Cartilage T2* relaxation measurement

Next, T2* relaxation measurements were performed on sagittal slices with a thickness of 3 mm. In the T2* mapping sequences, the trochlear and patellar cartilage was manually divided on sagittal images into superior, middle, and inferior thirds along the vertical axis and into medial–medial, medial–lateral, lateral–medial, and lateral–lateral quadrants along the horizontal axis, yielding a total of 12 quadrants for each structure (Table 2). This approach allowed a comprehensive sampling of both the patellar and trochlear cartilage.

After identifying the four main quadrants along the horizontal axis, a sagittal slice passing through the center of each quadrant was selected separately for the patellar and trochlear cartilage (yielding eight sagittal slices in total). A region of interest (ROI) was then manually placed at the center of the superior, middle, and inferior thirds of each

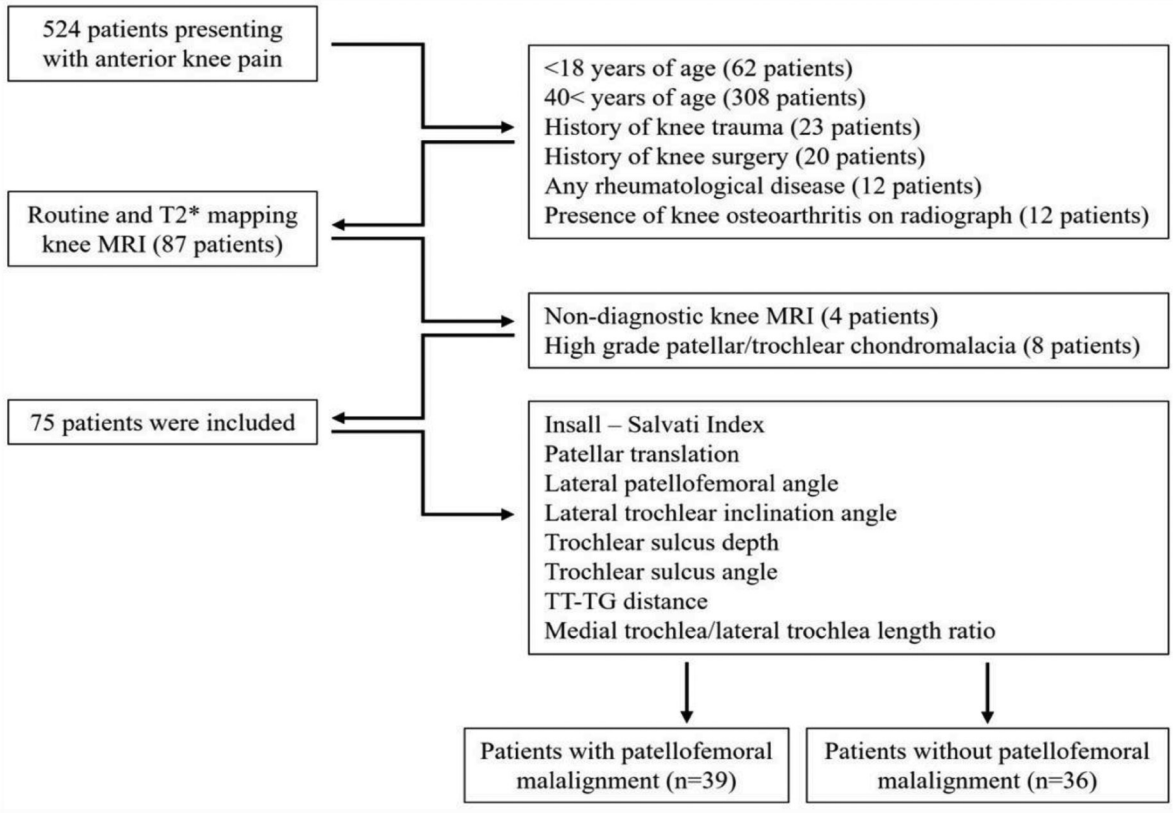

Figure 1. Study flowchart. MRI, magnetic resonance imaging; TT-TG, tibial tubercle-trochlear groove.

Table 1. Patellofemoral malalignment magnetic resonance imaging measurements and values associated with patellofemoral malalignment

Patellofemoral malalignment MRI measurements	Values associated with patellofemoral malalignment
Insall–Salvati index	>1.2
Lateral patellofemoral angle	<8°
Lateral trochlear inclination angle	<11°
Trochlear sulcus depth	<3 mm
Trochlear sulcus angle	>144°
TT–TG distance	>15 mm
Medial trochlea/lateral trochlea ratio	<40%

MRI, magnetic resonance imaging; TT–TG: tibial tubercle–trochlear groove.

selected sagittal slice, and T2* relaxation values were recorded (Figure 2). Measurements were performed using the Siemens syngo. via (Siemens Healthcare, Erlangen, Germany) software on the MRI workstation. To minimize sampling error, small and similarly sized ROIs were used whenever possible, and high magnification was employed to avoid interfaces with synovial effusion and subchondral bone.[29]

All measurements were performed in consensus by two radiologists, one with 10 years of experience and another with 24 years of experience in musculoskeletal radiology. To reduce measurement errors and potential bias, morphological assessments and T2* relaxation measurements were conducted in separate sessions, spaced 1 month apart.

Statistical analysis

To calculate the sample size, G*Power 3.1 (Heinrich Heine University, Düsseldorf, Germany) software was used. The study by Subhawong et al.[30] served as the basis for this calculation. Based on the patient and control group average values reported in that study, with an α value of 0.05 and power of 0.8, the total sample size was calculated as 72, with 36 in each group.

Statistical analyses were performed using IBM SPSS Statistics Standard Concurrent User V27 (IBM Corp., Armonk, New York, USA). Descriptive statistics were presented as count (n), percentage (%), mean ± standard deviation (SD), median, minimum, and maximum values. The normality of numerical variables was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using the Levene test.

Group comparisons were performed using the independent two-sample t-test, as the data met the assumptions for parametric testing. The receiver operating characteristic (ROC) analysis method was used to evaluate the area under the curve (AUC). Repeated measures analysis of variance (ANOVA) was used to compare measurement values, mixed design ANOVA was used to compare values between groups, and Bonferroni correction was applied for main effect comparisons in the mixed design ANOVA. A *P* value of <0.05 was considered statistically significant.

Results

Among the 75 patients included in the study, 39 had MRI findings of patellofemoral malalignment (patient group), whereas the remaining 36 did not show such findings (control group). The patient group comprised 17 men and 22 women, and the control group contained 16 men and 20 women. The mean age of the patient group

Table 2. T2* relaxation measurement areas of the trochlear and patellar cartilage

Trochlea quadrant	Region description	Patella quadrant	Region description
T1	Upper-lateral–lateral quadrant	P1	Upper-lateral–lateral quadrant
T2	Upper-lateral–medial quadrant	P2	Upper-lateral–medial quadrant
T3	Upper-medial–lateral quadrant	P3	Upper-medial–lateral quadrant
T4	Upper-medial–medial quadrant	P4	Upper-medial–medial quadrant
T5	Mid-lateral–lateral quadrant	P5	Mid-lateral–lateral quadrant
T6	Mid-lateral–medial quadrant	P6	Mid-lateral–medial quadrant
T7	Mid-medial–lateral quadrant	P7	Mid-medial–lateral quadrant
T8	Mid-medial–medial quadrant	P8	Mid-medial–medial quadrant
T9	Lower-lateral–lateral quadrant	P9	Lower-lateral–lateral quadrant
T10	Lower-lateral–medial quadrant	P10	Lower-lateral–medial quadrant
T11	Lower-medial–lateral quadrant	P11	Lower-medial–lateral quadrant
T12	Lower-medial–medial quadrant	P12	Lower-medial–medial quadrant

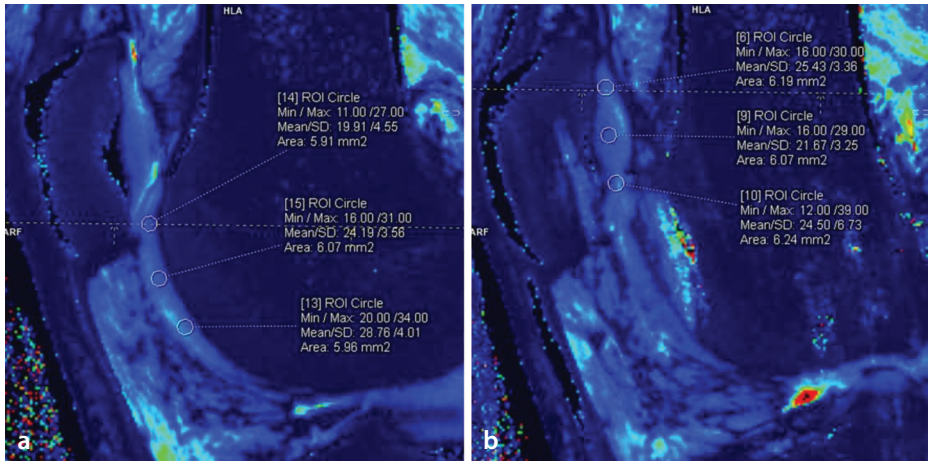

Figure 2. Trochlear **(a)** and patellar **(b)** cartilage T2* relaxation time measurements. ROI, region of interest; SD, standard deviation.

was 27.69 years (range: 19–40; SD: ±6.39), whereas the control group had a mean age of 28.17 years (range: 19–39; SD: ±6.58). The mean body mass index (BMI) was 24.38 (SD: ±3.01) in the patient group and 24.68 (SD: ±3.73) in the control group. No statistically significant differences were found between the groups regarding gender, age, or BMI ($P = 0.949$, $P = 0.680$, and $P = 0.725$, respectively).

An overall average T2* relaxation value for both the trochlea and patella was calculated by averaging the detailed T2* relaxation values from the 12 quadrants. When comparing these average T2* relaxation values without quadrant differentiation, no statistically significant differences were observed between the groups (Table 3).

Next, T2* relaxation values obtained by dividing the trochlear and patellar cartilage into 12 quadrants in the sagittal plane were compared. According to the results, T2* relaxation values in the superior-lateral–lateral (T1, P1) and superior-lateral–medial (T2, P2) quadrants of both the trochlear and patellar cartilage were significantly higher in the patient group ($P = 0.013$, $P = 0.001$, $P = 0.017$, and $P = 0.044$, respectively) (Tables 4 and 5).

Additionally, a ROC analysis was conducted to determine cut-off values for T2* relaxation in the 12 defined quadrants (Supplementary Tables 2 and 3). The evaluation revealed that the AUC was statistically significant for the P1, P2, and T1 quadrants. When assessing T2* relaxation values in these quadrants, values in the T1, P1, and P2 quadrants were significantly higher in the patient group. It was also possible to determine a diagnostic cut-off value for each of these regions. The threshold values were calculated as above 21.7 milliseconds for T1, above 24.1 milliseconds for P1, and above 24.3 milliseconds for P2 (Supplementary Table 4).

Discussion

In this study, we evaluated the association between patellofemoral malalignment and early-stage trochlear and patellar chondromalacia using T2* mapping. There was no difference in the average T2* relaxation values of the trochlear and patellar cartilage between the two groups, with and without MRI findings of patellofemoral malalignment. However, when the T2* relaxation values of the 12 quadrants were compared individually, values in the superior-lateral–lateral quadrant (P1, T1) and superior-lateral–medial quadrant (P2, T2) of both the trochlear and patellar cartilage were significantly higher in the patient group. These results suggest that chondromalacia caused by patellofemoral malalignment may exhibit an asymmetric onset, with the superior-lateral quadrant as the initial site of cartilage damage in both the trochlear and patellar cartilage.

It is well established that early-stage cartilage degeneration can be reversible or its progression halted through various interventions, including pharmacotherapy, lifestyle changes, or realignment surgery.[3] Therefore, reliable early detection of cartilage degeneration is critical for successful treatment. Standard sequences (T1 weighted, T2 weighted, and proton density) only provide information about cartilage morphology and have relatively low sensitivity for detecting early degeneration.[5] Quantitative MRI techniques, such as T2 and T2* mapping, have gained increasing importance for early cartilage assessment.[8,9] In particular, T2 mapping is used to evaluate water content and collagen fiber orientation within cartilage and is widely applied in clinical practice.[31] By contrast, T2* mapping similarly assesses cartilage water content but has the advantage of

Table 3. Comparison of mean T2* relaxation values (milliseconds) of the trochlear and patellar cartilage in groups with patellofemoral malalignment

Patellofemoral malalignment	Trochlear cartilage (mean ± SD)	Patellar cartilage (mean ± SD)
Yes	22.18 ± 3.59	22.52 ± 3.15
No	20.78 ± 3.47	21.63 ± 2.06
P value	0.094	0.163

SD, standard deviation.

Table 4. Comparison of trochlear cartilage T2* relaxation values (milliseconds) between groups

Quadrant	Patellofemoral malalignment		*P* value
	No	Yes	
T1	17.60 ± 4.17	20.53 ± 5.54	**0.013**
T2	19.38 ± 5.99	22.60 ± 6.04	**0.017**
T3	23.31 ± 6.18	25.60 ± 6.68	0.132
T4	16.25 ± 4.92	18.54 ± 5.86	0.074
T5	24.88 ± 4.72	26.52 ± 6.91	0.242
T6	25.59 ± 5.34	25.88 ± 5.38	0.818
T7	24.80 ± 7.92	27.31 ± 5.77	0.122
T8	20.73 ± 5.47	22.20 ± 5.32	0.247
T9	18.18 ± 5.96	19.89 ± 6.88	0.260
T10	19.94 ± 6.46	19.09 ± 5.66	0.548
T11	18.36 ± 5.54	19.23 ± 5.41	0.496
T12	18.38 ± 5.94	18.77 ± 5.16	0.762

Values are presented as mean ± standard deviation. The values written in bold are statistically significant.

Table 5. Comparison of patellar cartilage T2* relaxation values (milliseconds) between groups

Quadrant	Patellofemoral malalignment		*P* value
	No	Yes	
P1	23.22 ± 4.37	27.03 ± 4.91	**0.001**
P2	23.96 ± 4.51	26.49 ± 5.92	**0.044**
P3	23.11 ± 5.32	23.34 ± 4.30	0.840
P4	19.46 ± 3.04	20.32 ± 4.37	0.322
P5	22.52 ± 5.02	23.14 ± 7.27	0.674
P6	23.33 ± 6.10	24.28 ± 5.89	0.498
P7	22.31 ± 4.12	21.83 ± 4.42	0.629
P8	19.64 ± 4.1	19.98 ± 5.87	0.775
P9	20.29 ± 3.68	19.58 ± 5.12	0.499
P10	22.14 ± 3.39	23.22 ± 5.57	0.323
P11	20.40 ± 4.04	21.91 ± 4.74	0.149
P12	19.29 ± 4.16	19.20 ± 4.89	0.930

Values are presented as mean ± standard deviation. The values written in bold are statistically significant.

a shorter acquisition time compared with T2 mapping. Additionally, T2* mapping is more sensitive to local magnetic field inhomogeneities, making it more effective for detecting early-stage changes.[14,32]

In addition, T1 rho mapping, which is sensitive to proteoglycan content, can indicate early degeneration but is limited by longer acquisition times and reduced scanner compatibility.[33] Delayed gadolinium-enhanced MRI of cartilage measures glycosaminoglycan concentrations using a contrast agent and can detect early glycosaminoglycan loss. However, its use is limited by the need for contrast injection and prolonged imaging duration.[33]

Quantitative T2* mapping has been reported as an effective technique for assessing cartilage compositional integrity.[14] Compared with T2 mapping, T2* mapping is more sensitive to subtle changes in tissue composition due to its sensitivity to local field inhomogeneities, which have dephasing effects.[14,32] It also provides a high signal-to-noise ratio and high spatial resolution, with relatively short scan times.[16] Mars et al.[34] concluded that T2* mapping was superior to T2 mapping for detecting cartilage injury.

Therefore, T2* mapping is considered more sensitive for detecting changes within cartilage tissue. However, its role across different stages of cartilage degeneration remains incompletely defined. There is evidence that T2* mapping is useful for identifying early-stage degeneration in cartilage areas that exhibit elevated T2* relaxation times compared with normal cartilage.[14] However, no previous studies have identified the specific anatomical regions where early cartilage damage begins in the patella and trochlea.

The most significant difference between our study and previous studies in the literature is that we performed detailed measurements by dividing the trochlear and patellar cartilage into 12 quadrants to detect heterogeneous changes. This aspect of our study is superior to others in the literature. Only Ruiz Santiago et al.[9] used a similar quadrant division method; however, the main purpose of their study was to determine the relationship between cartilage T2 values and the current staging of chondromalacia, which is not the subject of our research.

In our study, when comparing the average T2* relaxation values of the trochlea and patella in the sagittal plane between the patient and control groups, no statistically significant difference was found. However, when detailed T2* relaxation measurements were made by dividing the trochlea and patella into 12 quadrants, statistically significant results were obtained in specific quadrants. Similar to our findings, Kim et al.[35] reported that the involvement of lateral patellar facet cartilage was statistically significantly higher in the patellofemoral malalignment group. Additionally, in our study, T2* relaxation values in the lateral quadrants (P1, P2) of the patellar cartilage were higher in the patellofemoral malalignment group. Furthermore, T2* relaxation values in the lateral quadrants (T1, T2) of the trochlear cartilage, similar to the patella, were also significantly higher in our study. Various mechanisms may explain this. One explanation is that in patients with patellofemoral malalignment, the contact area between the patella and the TG decreases during flexion, leading to increased maximum patellofemoral contact pressure.[36] Additionally, when the TT–TG distance increases, the patella shifts laterally, which especially increases patellofemoral joint stress on the lateral side.[37] These changes in load transfer may explain the greater occurrence of chondromalacia on the lateral side.

Consistent with these mechanisms, our study also found statistically significant T2* relaxation values in the lateral quadrants and statistically significant results in the ROC analysis. These findings indicate that chondromalacia caused by patellofemoral malalignment exhibits an asymmetric onset and is more prevalent on the lateral joint surfaces of both the patella and trochlea. Therefore, evaluating the trochlear and patellar cartilage by dividing it into quadrants, rather than relying on average values, using the T2* mapping method is more sensitive and meaningful for assessing early-stage chondromalacia.

Another statistical analysis in our study involved conducting ROC analysis to determine cut-off values for the presence of chondromalacia in all quadrants of both the trochlea and patella. Accordingly, it was found that cut-off values could be determined for specific quadrants in the sagittal plane. In particular, T2* mapping measurements in the T1, P1, and P2 quadrants revealed statistically significant relaxation values and allowed for the determination of cut-off values in the ROC analysis.

Therefore, we believe it is meaningful to focus on the T1 and P1 quadrants for measurements and to consider the results obtained from these regions. Although a cut-off value could also be determined for the P2 quadrant in the ROC analysis, the practical and memorable nature of obtaining significant results in both the T2* relaxation values and ROC analysis for the T1 and P1 areas may facilitate easier measurement and clinical application. For cut-off values to be practically applicable in clinical settings, they need to be verified through further studies. Thus, rather than proposing the cut-off values identified in our study as definitive criteria, we recommend that quadrants where cut-off values can be determined be evaluated more carefully when assessing early-stage chondromalacia. This approach will help alert clinicians to areas that require focused attention and support more effective follow-up.

Similarly, Fulkerson et al.[38] noted that different regions of the patellar cartilage are not equally affected by chondromalacia and that different mechanisms are responsible for damage in different regions. He reported that lateral patellar facet cartilage damage is associated with chronic patellar tilt, whereas medial facet cartilage damage is linked to patellar dislocation. Therefore, in clinical evaluations, both T2* relaxation values and the patient's morphological MRI findings and clinical history should be considered.

Our study has some limitations. The main limitation is that, despite dividing the trochlea and patella into 12 quadrants and measuring from the midpoint of each quadrant to detect heterogeneous chondromalacia distribution, exact standardization may not be achieved for measurement localization in each patient. Chondromalacia in each quadrant may not occur precisely in the center but may develop at the edges.

Second, in our study, T2* relaxation value measurements were performed only on sagittal slices for both the patella and trochlea, without including axial or coronal slices. Given the imaging planes, the rationale for performing T2* relaxation measurements in the sagittal plane for both trochlear and patellar chondromalacia was to ensure more accurate assessment, particularly for the trochlea, which has a steep orientation. Sagittal plane acquisition allows evaluation of the articular cartilage perpendicular to the shearing forces acting on the joint. Anatomically, measurements taken in other planes may not yield accurate results for the trochlea. Additionally, the relatively thick slice thickness of T2* mapping compared with cartilage thickness in other planes may contribute to inaccuracies. These factors may lead to the incorrect calculation of T2* relaxation values due to the partial volume effect from non-cartilage structures.[22] Therefore, we believe sagittal plane measurements are more reliable than those taken in the axial or coronal planes, especially for the trochlea. However, evaluation and comparison across slices in axial and coronal planes could contribute to standardizing the most appropriate measurement plane.

All patients in our study were symptomatic with anterior knee pain; however, the absence of an objective scoring system to quantify symptom severity may be considered a third limitation. As a general limitation of imaging-based studies, there was no histopathological verification of chondromalacia. Nonetheless, given the presence of well-defined and widely accepted diagnostic criteria, invasive procedures are no longer preferred or routinely used in current clinical practice and research. Although T2* value measurements in our study were performed by consensus between two radiologists experienced in musculoskeletal radiology, intra-observer and inter-observer agreement were not assessed.

In conclusion, in the presence of patellofemoral malalignment, both patellar and trochlear cartilage can be examined more specifically by dividing them into quadrants

rather than using a general assessment. Early chondromalacia can be detected by quantitatively assessing the superior-lateral sections of the patellar and trochlear cartilage using T2* mapping. Additionally, in patients with high T2* relaxation values identified in the superior-lateral sections of the patellar and trochlear cartilage, patellofemoral malalignment should be primarily considered as the etiology of chondromalacia. Thus, T2* mapping may serve as a valuable non-invasive imaging tool for the early diagnosis and monitoring of cartilage degeneration in patients with patellofemoral malalignment.

Footnotes

Conflict of interest disclosure

The author declared no conflicts of interest.

Funding

İzmir Katip Çelebi University Scientific Research Projects Coordination (project number: 2022-TDU-TIPF-0012).

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Supplementary Material 1.

Patellofemoral instability magnetic resonance imaging parameters

- Insall-Salvati index: The ratio of the patellar tendon length to the patella height was measured on the midsagittal magnetic resonance imaging (MRI) slice. The distance between the apex of the patella and the tibial tuberosity along the inner contour of the patellar tendon was measured for patellar tendon length, and the maximum craniocaudal dimension of the patella was measured for patella height.
- Lateral patellofemoral angle: Measured on the axial image passing through the mid-point of the patella, it is the angle between the tangent line of the anterior femoral condyle and the patellar lateral facet joint line.
- Lateral trochlear inclination angle: Determined by measuring the angle between the lateral femoral trochlea axis and the posterior condylar tangent line on the first cranial slice where the trochlear cartilage is fully visualized.
- Trochlear sulcus depth: Calculated by subtracting the distance between the trochlear groove and the posterior condylar tangent line from the average distance between the most anterior points of the medial and lateral facets and the posterior condylar tangent line. This measurement is performed approximately 3 cm proximal to the tibiofemoral joint line.
- Trochlear sulcus angle: The angle between the medial and lateral facets, measured on the first cranial axial MRI slice where the trochlear cartilage is visualized.
- Tibial tubercle–trochlear groove distance: The mediolateral distance between the deepest point of the trochlear groove and the midpoint of the tibial tuberosity, measured by superimposing the axial slices where both points are visible.
- Medial trochlea/lateral trochlea length ratio: Calculated by multiplying the ratio of the medial trochlea facet length to the lateral trochlea facet length by 100, measured on the axial slice 3 cm proximal to the tibiofemoral joint line.

Supplementary Table 1. Acquisition parameters

	T1 weigted coronal	PD FS coronal	PD FS sagittal	PD FS axial	Sagittal T2* mapping
TR (msec)	390	3180	4250	3490	1220
TE (msec)	12	35	36	35	4.36, 11.9, 19.44, 26.98, 34.52
NEX	1	1	1	1	1
Flip angle	150	150	180	129	60
Slice thickness (mm)	3	3	3	3	3
Matrix	324 × 432	300 × 400	300 × 400	288 × 384	384 × 384
FOV (mm)	160	160	160	160	160

FS, fat suppressed; NEX, number of excitations; PD, proton density; TE, echo time; TR, repetition time; FOV, field of view.

Supplementary Table 2. Trochlear cartilage receiver operating characteristic analysis

Quadrant	AUC	SE	*P*	Asymptomatic 95% CI	
				Lower bound	Upper bound
T1	0.644	0.064	**0.024**	0.524	0.752
T2	0.554	0.067	0.425	0.422	0.686
T3	0.592	0.067	0.169	0.461	0.722
T4	0.610	0.066	0.097	0.480	0.739
T5	0.585	0.067	0.207	0.453	0.717
T6	0.495	0.068	0.935	0.361	0.628
T7	0.580	0.069	0.245	0.445	0.714
T8	0.586	0.069	0.215	0.450	0.722
T9	0.616	0.067	0.081	0.485	0.747
T10	0.451	0.068	0.469	0.318	0.584
T11	0.532	0.068	0.635	0.399	0.665
T12	0.551	0.068	0.457	0.417	0.684

The value written in bold are statistically significant. AUC, area under the curve; CI, confidence interval; SE, standard error.

Supplementary Table 3. Patellar cartilage receiver operating characteristic analysis

Quadrant	AUC	SE	*P*	Asymptomatic 95% CI	
				Lower bound	Upper bound
P1	0.731	0.060	**<0.001**	0.615	0.827
P2	0.632	0.065	**0.044**	0.511	0.741
P3	0.521	0.068	0.756	0.387	0.655
P4	0.547	0.069	0.494	0.413	0.681
P5	0.535	0.068	0.606	0.402	0.669
P6	0.574	0.068	0.272	0.442	0.707
P7	0.481	0.068	0.778	0.348	0.614
P8	0.519	0.068	0.783	0.386	0.651
P9	0.447	0.067	0.428	0.314	0.579
P10	0.565	0.067	0.336	0.433	0.697
P11	0.578	0067	0.239	0.448	0.709
P12	0.480	0.068	0.771	0.347	0.613

The values written in bold are statistically significant. AUC, area under the curve; CI: confidence interval; SE, standard error.

Supplementary Table 4. Cut-off T2* relaxation values (milliseconds) determined for the T1, P1, and P2 quadrants

Quadrants	Cut-off	AUC	SE	*P*	Asymptomatic 95% CI		Sensitivity	Specificity
					Lower bound	Upper bound		
T1	>21.7	0.644	0.064	0.024	0.524	0.752	35.90	91.43
P1	>24.1	0.731	0.060	<0.001	0.615	0.827	79.49	62.86
P2	>24.3	0.632	0.065	0.044	0.511	0.741	64.10	62.86

AUC, area under the curve, CI, confidence interval; SE, standard error.