

T2 Relaxation Time Changes in the Distal Femoral Condylar Cartilage of Children and Young Adults with Discoid Meniscus

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Haesung Yoon¹, Hyun Ji Lim¹, Jisoo Kim¹, Kun-Bo Park², Hyun Woo Kim², and Mi-Jung Lee¹

Abstract

Objective. To investigate compositional changes in the distal femoral condylar cartilage (FCC) of children and young adults with and without discoid meniscus by T2 relaxation time mapping. **Design.** We retrospectively reviewed knee magnetic resonance images including sagittal T2 maps of distal FCC performed in patients with or without discoid meniscus. Combined meniscal pathology such as degeneration or tears was also reviewed. Regions of interest were selected, and T2 relaxation time profiles were generated according to medial and lateral and FCC and according to weight-bearing and non-weight-bearing FCC. Nonparametric comparison tests using median values were performed. **Results.** Seventy-nine knees from 73 patients (2–20 years) including 45 knees with lateral discoid meniscus (discoid group) were studied. T2 values of FCC showed negative correlation with age in both the discoid and nondiscoid groups ($P < 0.01$), except for medial weight-bearing FCC. In the discoid group, T2 relaxation times of lateral weight-bearing FCC (median, 46.5 ms) were lower than those of lateral non-weight-bearing (median, 53.2 ms; $P < 0.001$) and medial weight-bearing (median, 50.5 ms; $P = 0.012$) FCC. Lateral weight-bearing FCC also showed lower T2 values than other areas in patients with meniscal pathology in the discoid group. However, T2 relaxation times did not differ between the discoid and nondiscoid groups in patients without meniscal pathology. **Conclusions.** Children and young adults with discoid meniscus have lower T2 relaxation times in lateral weight-bearing FCC compared with non-weight-bearing or medial FCC, suggesting compositional changes have occurred in these patients.

Keywords

T2 mapping, discoid meniscus, children

Introduction

Discoid meniscus is an intra-articular knee disorder that typically presents in children and adolescents.¹ Its natural history depends on the type of anomaly and the presence of symptoms. Discoid meniscus has been reported as occurring in 1.5%–17% of the lateral meniscus and 0.1%–0.3% of the medial meniscus^{2,3} and incidences are higher in Asian countries.¹ Compared with the normal meniscus, a discoid meniscus displays significant disorganization of the circular collagen network, which may result in high rates of tears and degenerative lesions.⁴ Also, intrameniscal mucoid degeneration is common with discoid meniscus.^{5,6} A symptomatic discoid meniscus might require surgical treatment if an associated tear results in pain, clicking, or limited range of motion.^{5,7} Discoid meniscus can also be associated with osteochondral lesions of the ipsilateral femoral condyle regardless of the state of the meniscus.^{8,9}

Quantitative magnetic resonance imaging (MRI) techniques including T2 mapping, T1 rho imaging, delayed gadolinium-enhanced MRI of the cartilage, and sodium MRI have been employed to directly examine articular cartilage. These sequences provide a tool for the early diagnosis

¹Department of Radiology and Research Institute of Radiological Science, Severance Hospital, Yonsei University College of Medicine, Seoul, Korea

²Division of Pediatric Orthopaedic Surgery, Severance Children's Hospital, Yonsei University College of Medicine, Seoul, Korea

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Corresponding Author:

Mi-Jung Lee, Department of Radiology and Research Institute of Radiological Science, Severance Hospital, Yonsei University College of Medicine, 50-1, Yonsei-Ro, Seodaemun-gu, Seoul 03722, Korea.
Email: mjl1213@yuhs.ac



Table 1. Summary of Sequence Parameters for Conventional Knee MRI for Morphologic Evaluation.

	Axial T2 FSE	Axial, Coronal T2 Fat-Suppressed FSE	Sagittal T1 FSE	Fat-Suppressed Proton Density-Weighted 3D FSE
TR/TE	2,500/100	2,500/60	625/10	1,600/32
Matrix size (mm)	384 × 306	384 × 306	384 × 306	320 × 320
Field of view (cm)	14	14	14	16
Slice thickness (mm)	3	3	3	0.5
Gap	0.3	0.3	0.3	0
No. of excitations	1	1	1	1

MRI = magnetic resonance imaging; FSE = fast-spin echo; TR = repetition time; TE = echo time.

of irreversible articular cartilage damage, which is of great significance in the treatment of cartilage-related diseases.^{10,11} T2 relaxation time is a time constant measured by MRI that reflects the molecular motion of protons in water and is determined by water content, tissue matrix anisotropy, and composition. Mean T2 relaxation times are highly sensitive to the anisotropy of collagen fibers in cartilage.^{12,13} We selected T2 mapping for this study because it has been previously used to detect early changes in cartilage composition that can precede gross morphologic damage¹⁴ and that are also related to external pressure.¹⁵ T2 mapping has been applied to the patellar cartilage of children and adolescents to assess skeletal maturation, with a sequential decrease in T2 relaxation time being observed.¹⁶ Also, T2 relaxation times were significantly longer in a group with patellar-femoral instability, which directly reflected severity in low-grade cartilage damage.¹⁷ There was one study regarding T2 relaxation times of discoid lateral meniscus before and after arthroscopic surgery in pediatric and young adult patients which showed that substantial changes occurred during the early postoperative and recovery period after reshaping surgery.¹⁸ However, there are limited studies about cartilage change in discoid meniscus patients, especially in children. We hypothesized that, if a discoid meniscus is present, there may be compositional changes in the adjacent cartilage from the narrow joint space and that different pressure may be applied compared with a normal meniscus. Therefore, the aim of this study was to investigate compositional changes in the distal femoral condylar cartilage (FCC) of children and young adults with and without discoid meniscus through T2 relaxation time mapping.

Methods

Patient Enrollment and Review

This study was approved as a retrospective study by the Institutional Review Board of Severance Hospital (4-2021-0730). The requirement to obtain informed consent was waived. Since April 2016, T2 mapping is routinely performed in patients who undergo knee MRI in our institution. Patients who were 20 years old or older, had previous trauma or were

suspected to have arthritis or tumors were excluded. Sex and age at the time of MRI were recorded. We also reviewed medical records for reports on patient symptoms and other pathology including a meniscal lesion or osteochondral lesion in the knee. We also assessed progression during the follow-up interval and operative findings if surgery was performed.

Image Acquisition

MRI was performed on an Achieva 3.0 T MR scanner (Philips Medical System, Best, The Netherlands) using a 8-channel SENSE knee coil (Philips). The knee MRI protocol included T2 mapping after routine conventional MRI for 20 minutes with the patients in the supine position with knees in full extension and ankles kept in the neutral position. For morphological evaluation of the meniscus and cartilage, we used the routine imaging sequence summarized in **Table 1**. The T2 map consisted of a sagittal multi-echo spine-echo (SE) T2-weighted sequence performed with a repetition time (TR) of 2500 ms, 6 echo times (TE) of 13, 26, 39, 52, 65, and 78 ms, a slice thickness of 3 mm, a field of view of 160 mm × 160 mm, a pixel matrix of 320 × 320, and a total acquisition time of 7 minutes 56 seconds.

MRI Data Analysis

On anatomical imaging of the knee, the presence of discoid meniscus and combined meniscal pathologies such as degeneration or tears were reviewed in consensus by 2 pediatric radiologists subspecializing in pediatric musculoskeletal imaging.

T2 maps were analyzed using an advanced cartilage analysis application (IntelliSpace Portal, Philips Healthcare, The Netherlands) by 2 pediatric radiologists. To measure intra- and inter-observer reliabilities for the T2 relaxation times of the articular cartilage, measurements were performed at 2 separate times, 4 weeks apart. In the analysis program, a least-squares regression weighted by the variance of the estimates of the signal intensity was used.¹⁹ T2 maps of the articular cartilage of the knee joint, with a color scale ranging between 1 and 81 ms, were created from the T2 mapping source data.

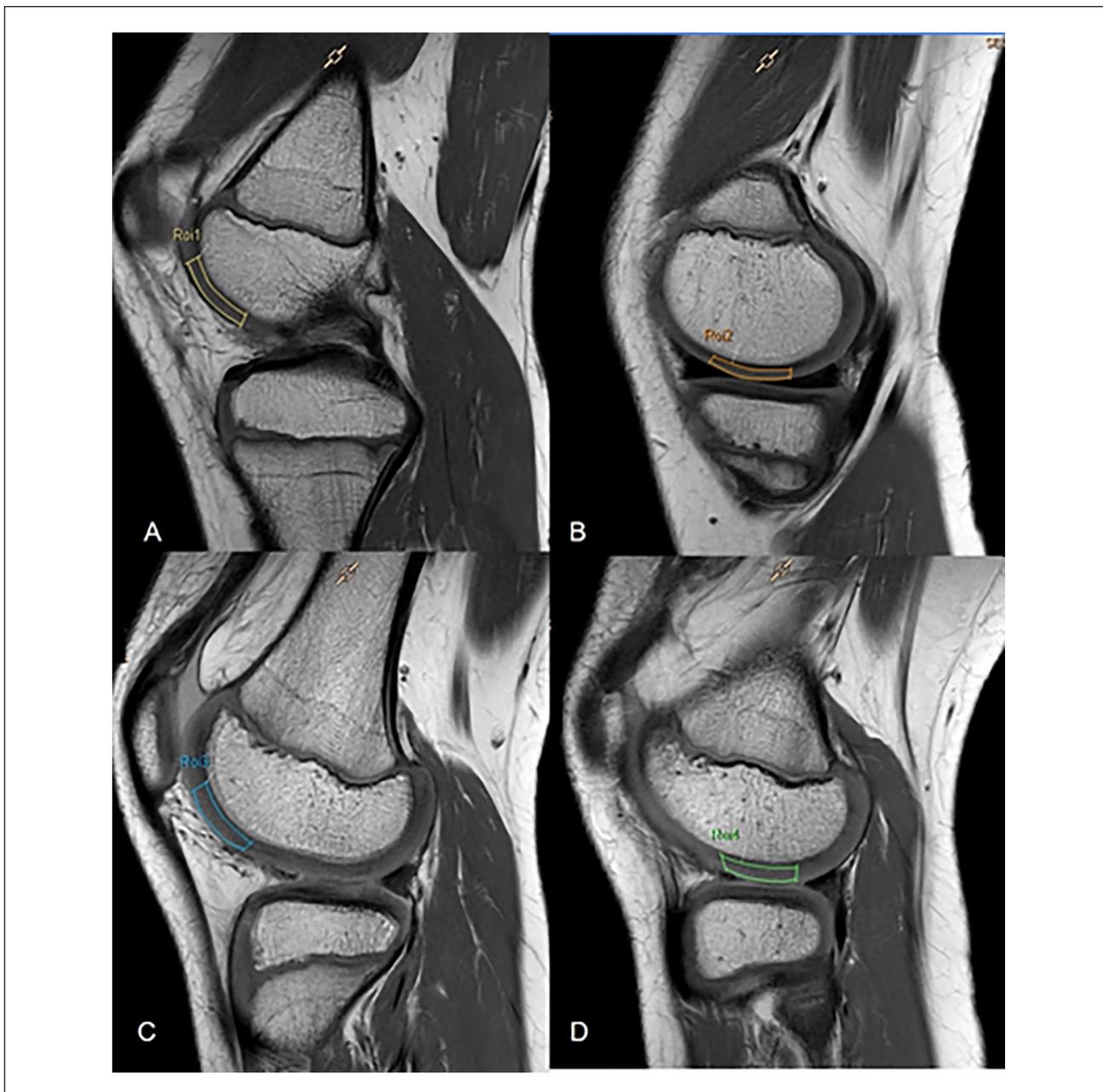


Figure 1. Representative images of T2 mapping in weight-bearing and non-weight-bearing portions of the medial and lateral femoral condyles. The maximum area of the distal femoral condylar cartilage for T2 mapping is drawn in the (A) medial non-weight-bearing (yellow box), (B) medial weight-bearing (orange box), (C) lateral non-weight-bearing (blue box), and (D) lateral weight-bearing (green box) portions.

Regions of interest (ROIs) were drawn manually at both medial and lateral FCC (Fig. 1). According to the nomenclature suggested by Eckstein *et al.*,²⁰ the central portion of medial and lateral FCC was considered the weight-bearing portion²¹ and we additionally analyzed the anterior third portion of the medial and lateral FCC as the non-weight-bearing portion. The posterior third FCC was not analyzed because this cartilage can be both weight-bearing and non-weight-bearing

depending on knee flexion. Therefore, the FCC T2 relaxation times were measured for both the weight-bearing and anterior non-weight-bearing portions. A total of 4 T2 relaxation times were measured from the medial and lateral FCC in each patient. We drew the ROIs for T2 mapping as large as possible for the FCC areas and did not include the surrounding subchondral bone and noncartilaginous components such as synovium and fat in the joint space.

Table 2. T2 Values of Knee Cartilage in the Discoid and Nondiscoid Group.

		Age (years)	Sex (M: F)	T2 Values (ms)			
				Medial Femoral Condyle		Lateral Femoral Condyle	
				Weight-Bearing Portion	Non-Weight-Bearing Portion	Weight-Bearing Portion	Non-Weight-Bearing Portion
Discoid group	All (<i>n</i> = 45)	11.0 (4.0-20.0)	26:19	50.5 (32.6-77.4)	51.9 (31.3-83.4)	46.5 (24.9-74.6)	53.2 (27.5-79.8)
	With meniscal pathology (<i>n</i> = 27)	10.0 (5.0-20.0)	15:12	51.2 (32.6-74.2)	53.1 (31.7-83.4)	48.4 (24.9-59.9)	55.1 (27.5-79.8)
	Without meniscal pathology (<i>n</i> = 18)	12.0 (4.0-20.0)	11:7	48.8 (32.7-77.4)	49.8 (31.3-65.2)	45.1 (36.7-74.6)	51.2 (33.6-77.1)
Nondiscoid group	All (<i>n</i> = 34)	11.0 (2.0-18.0)	12:22	50.3 (34.2-77.3)	49.6 (33.1-77.1)	49.1 (31.7-67.8)	48.9 (35.8-69.6)

The values are medians (ranges) except for sex.

Statistical Analysis

Descriptive analyses were performed for clinical findings such as disease side, symptoms, and follow-up duration. The Mann-Whitney *U* test was used to test the T2 differences between groups. Two-way analysis of variance (ANOVA) and the Wilcoxon signed rank test were used to test within individuals. Spearman's correlation analysis was performed for age. Intraclass correlation coefficients were assessed by 2 pediatric radiologists to measure the intra- and inter-observer reliabilities for T2 relaxation times. Agreement strength was interpreted as follows: 0.80, almost perfect; 0.61 to 0.80, substantial; 0.41 to 0.60, moderate; 0.21 to 0.40, fair; and ≤ 0.20 , slight. Values of $P < 0.05$ were considered to indicate statistical significance. Data handling and statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA) and MedCalc version 20.008 (MedCalc Software Ltd, Ostend, Belgium).

Results

Patient Characteristics

A total of 73 patients were included in the study. Our study group consisted of 36 males and 37 females with a median age of 11 years (age range, 2-20 years) at the time of MRI. Among these patients, 6 underwent both right and left knee MRI. There were a total of 79 cases including 45 cases with lateral discoid meniscus (discoid group) and 34 cases without discoid meniscus (nondiscoid group). There was no medial discoid meniscus in the discoid group. Among the 45 cases of the discoid group, 27 had pathology such as degeneration (*n* = 11) or tears (*n* = 16) including 9 complex tears and 4 horizontal tears in the discoid meniscus.

Common symptoms were knee pain (*n* = 63), limited motion (*n* = 7), or clicking sound during knee motion (*n* = 3). Physical examinations performed by pediatric orthopedic surgeons found no remarkable findings in 31 patients (19 in the discoid group and 12 in the nondiscoid

group), positive McMurray tests in 29 (19 in the discoid group and 10 in the nondiscoid group), tenderness in 22, and joint effusion in 4 patients. The median follow-up duration was 6.0 months (range, 0-53 months), during which surgery was performed on 20 knees for meniscal tears (*n* = 17), osteochondral lesions (*n* = 2), and corrective osteotomy for patella dislocation (*n* = 1). Osteochondral lesions were detected in 2 patients, both in the discoid group, and were confirmed during surgery.

T2 Changes of FCC Compared between the Discoid and Nondiscoid Groups

There was excellent agreement between the inter- and intra-observer assessments for all measurements (**Supplementary Table 1**).

Age was not different between the discoid and nondiscoid groups (median, 11.0 vs 11.0 years; $P = 0.968$). T2 values of the medial and lateral FCC were not different between the discoid and nondiscoid groups (**Table 2**). Comparing male and female patients, the medial and lateral FCC T2 values were not different between the discoid and nondiscoid groups (all, $P > 0.05$).

When considering age, T2 values of FCC showed negative correlations in lateral weight-bearing ($\rho = -0.501$, $P = 0.003$ in the nondiscoid group and $\rho = -0.397$, $P = 0.007$ in the discoid group), lateral non-weight-bearing ($\rho = -0.607$, $P < 0.001$ in the nondiscoid group and $\rho = -0.467$, $P = 0.001$ in the discoid group), and medial non-weight-bearing ($\rho = -0.492$, $P = 0.003$ in the nondiscoid group and $\rho = -0.505$, $P < 0.001$ in the discoid group) condyles (**Fig. 2**). T2 relaxation times of medial weight-bearing FCC showed no correlation with age in either the discoid ($P = 0.658$) or nondiscoid ($P = 0.058$) group.

When comparing right and left knees, T2 values of the left medial non-weight-bearing FCC were lower in the nondiscoid group (median 44.8 vs 53.0 ms, $P = 0.002$). In the discoid group, the left medial weight-bearing FCC times were lower

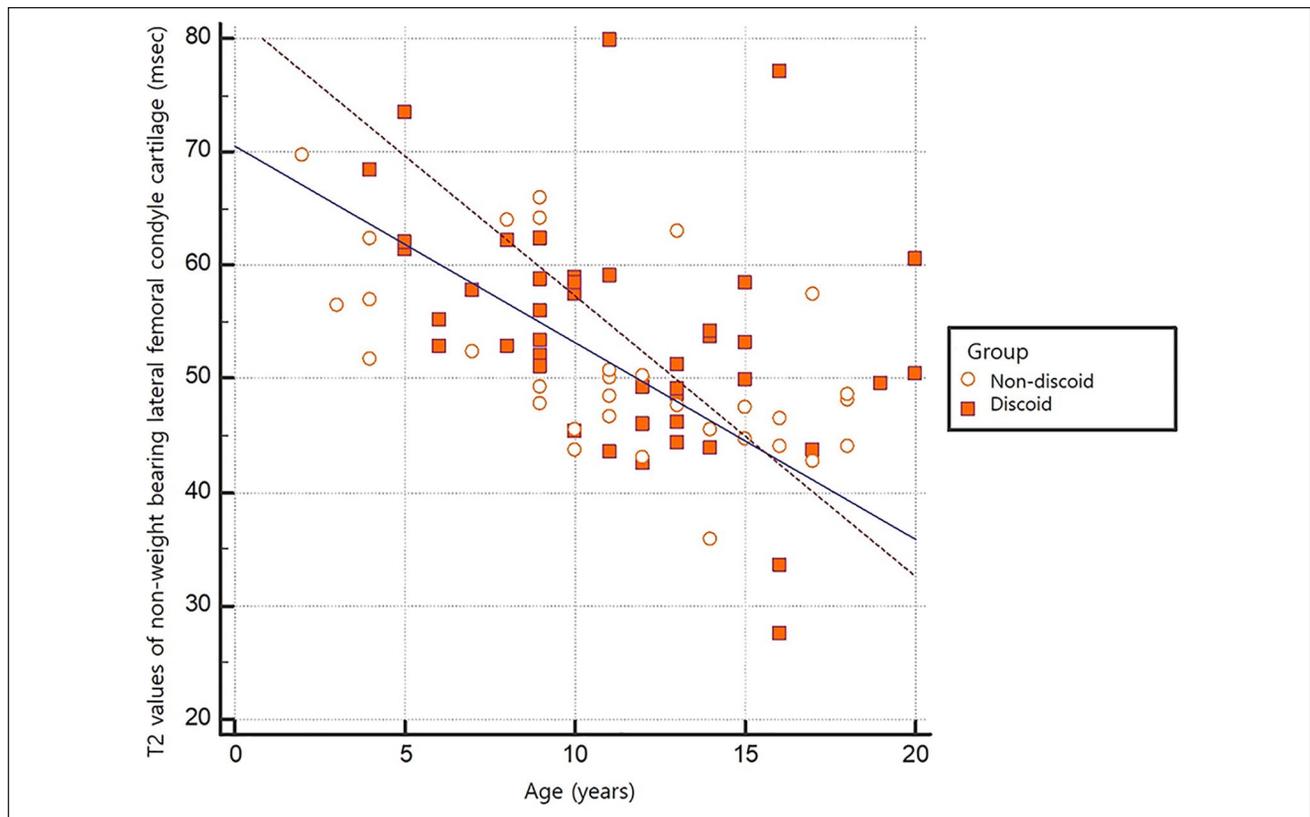


Figure 2. A scatter plot correlating age and T2 values of the femoral condylar cartilage. The discoid and nondiscoid group both showed negative correlation between age and T2 values of the femoral condylar cartilage. This graph only shows the T2 values of lateral non-weight-bearing femoral condylar cartilage ($\rho = -0.607$, $P < 0.001$ in the nondiscoid group and $\rho = -0.467$, $P = 0.001$ in the discoid group).

(median 47.9 vs 53.4 ms, $P = 0.004$). However, the T2 values of other areas were not different between the 2 groups.

Intra-Individual Comparisons

In the discoid group, there was a significant difference between the T2 values of different areas on 2-way ANOVA ($P = 0.005$). In paired comparison analyses, T2 values differed between the weight-bearing and non-weight-bearing portions of the lateral FCC (median, 46.5 vs 53.2 ms; $P < 0.001$). Also, lateral weight-bearing FCC demonstrated lower T2 relaxation times compared with medial weight-bearing (50.5 ms; $P = 0.012$) and medial non-weight-bearing (51.9 ms; $P = 0.006$) FCC in the discoid group (**Fig. 3A**). However, there was no difference in T2 relaxation times between these areas in the nondiscoid group ($P = 0.437$).

T2 Value Changes of FCC Compared between Patients with and without Meniscal Pathology in the Discoid Group

There was a significant difference between the T2 values of areas on 2-way ANOVA in patients with meniscal pathology in the discoid group ($P = 0.005$). T2 values of the lateral

FCC differed between the weight-bearing and non-weight-bearing portions (median, 48.4 vs 55.1 ms; $P < 0.001$). Also, lateral weight-bearing FCC demonstrated lower T2 relaxation times compared with medial weight-bearing (51.2 ms; $P = 0.015$) and medial non-weight-bearing (53.1 ms; $P = 0.004$) FCC (**Fig. 3B**). However, there were no differences in T2 relaxation times between the FCC areas in patients without meniscal pathology in the discoid group ($P = 0.372$).

Discussion

In this retrospective study, T2 relaxation time mapping was applied to children and young adults with discoid meniscus to investigate compositional changes in distal femoral cartilage. T2 relaxation times were negatively correlated with age in children and young adults. Lateral weight-bearing FCC demonstrated lower T2 relaxation values compared with other areas in the discoid group, even in the group with meniscal pathology. However, there was no difference in T2 relaxation values between the different areas of FCC in the nondiscoid group or between patients without meniscal pathology in the discoid group.

Our study found no significant sex-dependent differences in the T2 relaxation time values of FCC, although the

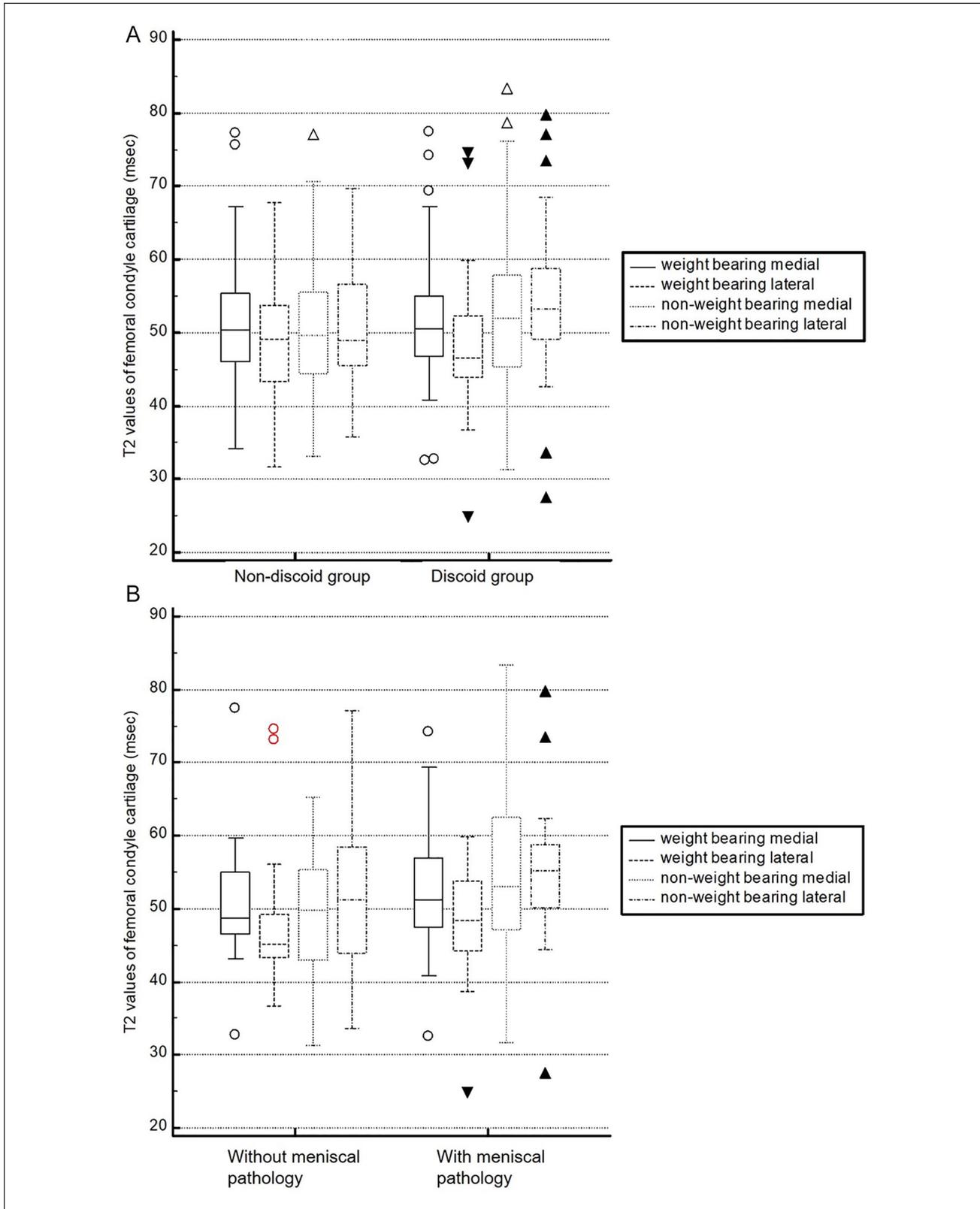


Figure 3. Box plots to compare T2 values. The graphs show T2 values of femoral condylar cartilage in the medial weight-bearing, lateral weight-bearing, medial non-weight-bearing medial, and lateral non-weight-bearing areas. **(A)** When comparing the discoid and nondiscoid group, only the discoid group had lower T2 values in the lateral weight-bearing portion compared with other areas ($P < 0.02$). **(B)** When comparing the discoid group with and without meniscal pathology, the T2 value of the lateral weight-bearing portion was lower than the other portions, but only in patients with meniscal pathology ($P < 0.02$).

relation between the 2 variables is still controversial. This is consistent with a previously published study on cartilage T2 relaxation time in the pediatric knee joint.²² However, our finding contrasts to that of a previous study involving patellar cartilage in children and young adults in which male subjects had significantly higher cartilage T2 relaxation time values compared with female subjects.¹⁶ This difference was explained by how skeletal maturation proceeds at different rates depending on sex. However, the past study focused on patellar cartilage and showed a wider range of patient age. In our study, T2 relaxation time values showed negative correlation with age in lateral weight-bearing, lateral non-weight-bearing, and medial non-weight-bearing FCC in both the nondiscoid and discoid groups. This is consistent with previous studies showing age- and maturation-dependent decreases in T2 relaxation time in patellar and knee joint cartilage.^{16,22,23} Similar results have been found in studies that compared hemophilia and healthy group patients, with T2 relaxation times showing a negative correlation with age in nearly all regions except for medial weight-bearing knees.²⁴ The negative correlation between T2 relaxation time values and age might be due to a combination of factors: the higher concentration of collagen and proteoglycans decreasing the amount of free water in juvenile cartilage,²⁵ physiologic reduction of water content around the joints during skeletal maturation,²³ and loss of unossified epiphyseal hyaline cartilage.^{16,26}

In our study, lateral weight-bearing FCC demonstrated lower T2 relaxation times compared with other areas of FCC in children and young adults with discoid meniscus, especially in patients with meniscal degeneration or tears. This is different from a previous healthy adult control study, which showed higher T2 relaxation times in all weight-bearing zones compared with non-weight-bearing zones.²⁷ The characteristics of juvenile cartilage might explain this discrepancy as collagen fibrils are in less organized zonal patterns in juvenile cartilage compared with adult cartilage.²⁸ The way weight affects the mechanical loading of the pediatric knee joint will influence the measured T2 relaxation time values. A previous study with healthy adolescent basketball players showed lower T2 relaxation values in medial weight-bearing compartment regions after a 30-minute run.²⁹ A previous study emphasized that the medial femoral condyle is the most common location of chronic cartilage lesions.¹⁵ Although we cannot assume any clinical associations between our findings to osteochondral lesions as the number of patients with these traits are too small, the discoid meniscus has been associated with osteochondral lesions in the ipsilateral femoral condyle regardless of the state of the meniscus in the past studies.^{8,9}

Decreased T2 relaxation times can reflect early cartilage degeneration. This was suggested in a previous study on children and adolescents that compared hemophilia patients and healthy controls.²⁴ However, other previous longitudinal juvenile idiopathic arthritis¹⁴ and patellofemoral instability¹⁶

studies show that increased T2 relaxation values indicate compositional change in cartilage.³⁰ More studies regarding T2 relaxation times in children and adolescent patients with various underlying diseases should be conducted to assess the compositional changes of T2 relaxation time.

Even though the history of T2 relaxation time mapping is long and has included pediatric patients since 2002,¹³ the reliability of its measurements needs to be tested before we can use them in clinical practice. A recent multicenter multi-vendor study of healthy adults demonstrated good to excellent longitudinal reproducibility.³¹ However, there were discrepancies in T2 values across centers. Therefore, a single cut-off value cannot be applied to all institutions.

We used bulk average measurement for cartilage T2 mapping compared with other researchers who used separate data from 3 layers (deep, middle, and superficial). Desrochers *et al.*³² demonstrated depth-dependent changes in knee cartilage T2 under compressive strain in a 7T MRI study. These researchers found that bulk T2 averaging masks important local variations. In pediatric hips, Lu *et al.*³³ evaluated acetabular cartilage using all layers and 3 layers equally divided. The acetabular cartilage T2 relaxation values increased from the deep layer to the superficial layer in healthy hips. However, the deep layer showed no difference between the dislocated hip and control T2 values despite significant differences in the other layers. Because cartilage thickness varies in children during maturation, measuring separate layers might produce greater variability. Further research is necessary on the diagnostic ability of T2 values for different layers associated with disease or pressure, if more sophisticated measurements are possible.

There are several limitations to this study. This was a retrospective study with a limited number of patients and the subjects were children and young adults of a wide age range. A selection bias might exist. Also we could not include pathologic results associated with FCC T2 value changes. There were only 2 patients with osteochondral lesions, and we could not evaluate the predictive effect of T2 values associated with this disease. Moreover, the nondiscoid group was not a true healthy control group even though we excluded patients with gross pathology on MRI. Further prospective research including contralateral normal knees, pathologic results, and long-term follow-up is needed. Furthermore, correlation with other quantitative MRI such as T1 rho imaging will confirm the clinical importance of T2 relaxation time mapping.

In conclusion, T2 relaxation time mapping demonstrated age-related changes in pediatric knee cartilage and showed lower T2 values in the lateral weight-bearing FCC of children and young adults with discoid meniscus, especially in patients with meniscal degeneration or tears. Further research is needed to explore the clinical utility of this technique for early disease detection or prognosis prediction.

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

Ethical approval was obtained from the Institutional Review Board of Severance Hospital (4-2021-0730).

Informed Consent

Obtaining informed consent was waived for the present study because this was a retrospective study.

ORCID iDs

Kun-Bo Park  <https://orcid.org/0000-0002-8839-4870>

Mi-Jung Lee  <https://orcid.org/0000-0003-3244-9171>

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