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RESEARCH

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Anterior cruciate ligament tissue stiffness and anterior tibial translation are increased in patients with medial meniscus posterior root tear

Yavuz Selim Karatekin[1*], Harun Altınayak[1], Ahmet Serhat Genç[1], Mirsad Yalçınkaya[2], Mehmet Seyfi Buruk[3] and Orhan Balta[4]

Abstract

Introduction To evaluate the structural and functional relationship between medial meniscus posterior root tear (MMPRT) and anterior cruciate ligament (ACL), the aim was to assess the structure and elasticity of the ACL in patients with MMPRT and to measure tibial anterior translation.

Materials and Methods Between January and June 2024, 56 patients (study group) were diagnosed with unilateral MMPRT on magnetic resonance imaging (MRI) and 31 healthy volunteers (control group) were included in the study. While the tibial anterior translation of the patients was evaluated using the KT 1000 device, the structure and stiffness of the ACL were assessed with ultrasound shear wave elastography (SWE). The tibial slope measurement was taken at 30 degrees of knee flexion on true lateral radiographs where the femoral condyles overlapped.

Results A total of 87 participants were included in the study, consisting of 31 volunteers (25 females, 6 males) and 56 patients diagnosed with MMPRT (48 females, 8 males). The average SWE values of the ACL were compared between the study group (26.6 ± 8.9 kPa) and the control group (21.2 ± 5.7 kPa), with the study group demonstrating a significantly higher value (p: 0.004). In patients with MMPRT, the measurements of anterior translation using the KT 1000 device were an average of 6.19 ± 1.4 mm in the affected knees and 4.9 ± 0.78 mm in the unaffected knees. The comparison revealed a significantly greater anterior translation in the knees with MMPRT ($p < 0.05$). Multivariable regression analysis demonstrated a significant positive relationship between ACL SWE values and tibial slope (β = 1.11; CI, 0.24–1.99; P: 0.01).

Conclusions Greater tibial anterior translation was observed on the side with MMPRT in the patients. There is a correlation between MMPRT and the stiffness of the ACL, which exhibits a higher elastic modulus. Additionally, an increase in tibial slope significantly affects the stiffness of the ACL.

Level of evidence Level III, retrospective cohort study.

*Correspondence:
Yavuz Selim Karatekin
yavuzselimkaratekin@gmail.com

Full list of author information is available at the end of the article

Keywords Anterior cruciate ligament, Medial meniscus posterior root tear, Tibial slope, Anterior tibial translation, Degeneration, Shear wave elastography

Introduction

MMPRT weakens the hoop stress resistance during axial loading by causing meniscal extrusion. This condition leads to an increase in the contact area and pressure on the joint surface, ultimately resulting in joint degeneration [1, 2]. Interest in this topic increased after a biomechanical study demonstrated that there is no difference in tibiofemoral pressures between MMPRT and total meniscectomy [3]. Numerous studies have been conducted on etiology, and several factors such as increased tibial slope, genu varum, and the angulation of the medial femoral condyle have been identified as risk factors for MMPRT [4–6]. In addition to these risk factors, there are also studies examining the relationship between ACL insufficiency and the isolated posterior root region of the medial meniscus. These studies generally emphasize that anterior translation is increased in knees with MMPRT [7–9]. However, while these studies generally focus on ACL function, the relationship between ACL structure (degeneration and elasticity) and MMPRT has not been fully clarified.

SWE is a non-invasive, quantitative method used to measure the elasticity of soft tissues such as muscles and tendons. This ultrasound-based measurement method is based on the principle of measuring sound wave velocity in soft tissues and provides information about tissue stiffness and degeneration [10]. Studies emphasize that it provides information about the tissue stiffness and quality of tendons and ligaments [10–13]. Therefore, SWE can be used to provide information about the stiffness, quality, and degeneration of ACL tissue [12, 14].

As a result of our literature review, there are very few studies investigating the relationship between MMPRT and ACL degeneration, elasticity, and structural properties [5]. The failure of either structure (the medial meniscus posterior root or ACL) to fulfill its function results in a disruption of load distribution, which may subsequently initiate a degenerative process in the other structure. Our hypothesis is that there is a relationship between MMPRT and the degeneration and structural changes of the ACL, even when the integrity of the ACL is preserved. Therefore, the objectives of this study are (1) to evaluate the structure and elasticity of the ACL using SWE in patients with MMPRT, and (2) to assess the functional relationship between MMPRT and the ACL by measuring tibial anterior translation using the KT 1000 device [15].

Materials and methods

This study was initiated after obtaining approval from the regional ethics committee (ID number of the approval: GOKAEK 2024/12/14), and informed consent was obtained from all individuals included in the study. A retrospective study was designed to compare the SWE values of ACL and KT1000 device measurements between two groups: healthy volunteers and patients diagnosed with MMPRT. Between January and June 2024, patients over the age of 18 who underwent knee MRI at our institution were reviewed through the electronic medical record system. As a result of this review, 138 patients with a diagnosis of MMPRT on MRI were identified.

The inclusion criteria were defined as (1) unilateral MMPRT and (2) a duration of symptoms longer than 3 months. The exclusion criteria were (1) advanced osteoarthritis on direct radiographs (Kellgren-Lawrence grade 3–4), (2) concomitant ligament injuries such as ACL rupture, (3) presence of inflammatory arthritis, (4) history of prior knee surgery, (5) knee flexion limitations, and (6) patients with inaccessible data. A total of 56 patients meeting the specified criteria and agreeing to participate (study group) and 31 healthy volunteers (control group) were included in the study (Fig. 1).

Clinical evaluation

Demographic data such as age, gender, and body mass index (BMI) were recorded retrospectively. MRI was performed on the contralateral knees of all patients included in the study to confirm the absence of root tears. The tibial anterior translation of both knees was assessed using the KT 1000 device with the knee in 30 degrees of flexion, similar to previous studies, and the results were recorded in millimeters (mm) [16]. The clinical outcomes of the patients were evaluated using the Tegner Lysholm Knee Scoring Scale (TLKSS) and the International Knee Documentation Committee Score (IKDCS).

Radiographic evaluation

KL grading system was applied to the anteroposterior knee radiographs to assess the severity of arthritis [17]. While the patients were standing, anteroposterior radiographs encompassing the entire lower extremity were used to measure the Medial Proximal Tibial Angle (MPTA) and the Hip-Knee-Ankle Angle (HKAA). MPTA was calculated as the angle formed medially between the proximal tibial joint orientation line and the mechanical axis of the tibia. HKAA was measured as the angle between the mechanical axis of the femur (a line drawn from the center of the femoral head to the midpoint of

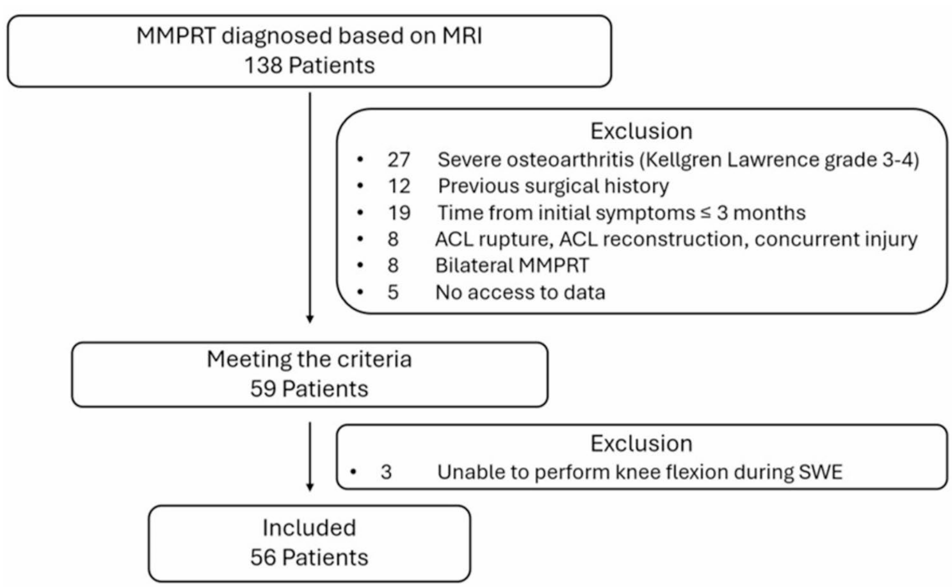

Fig. 1 Flowchart Depicting Patient Selection. MRI: Magnetic resonance imaging, MMPRT: Medial meniscus posterior root tear, SWE: Shear wave elastography, ACL: Anterior cruciate ligament

the femoral notch at the knee joint) and the mechanical axis of the tibia (a line drawn from the center of the ankle to the midpoint of the tibia at the level of the knee joint).

The tibial slope measurement was performed with the knee in 30 degrees of flexion on true lateral radiographs, where the femoral condyles overlap, following the method described by Utzschneider et al. [18]. The tibial axis was determined by drawing a line through the exact midpoints of the anterior and posterior tibial cortices at 5 cm and 15 cm distal to the knee joint line. The tibial slope was then defined as the angle between the line drawn along the medial tibial plateau and the perpendicular line to the tibial axis.

SWE technique and measurements

All SWE and B-mode ultrasound evaluations were carried out using a digital ultrasound/SWE device (Mindray, Resona R9) with a linear transducer operating at a frequency of 9 – 3 MHz. Patients were positioned in the semisupine position with the knee flexed to 110 degrees, and the ultrasound examination was initiated in B-mode. A goniometer was utilized to standardize the knee flexion measurements. The ACL was defined as a linear structure located between the patella and the anterior aspect of the tibia, posterior to Hoffa's fat pad, and visible in the distal one-third in the oblique sagittal plane. The probe was positioned parallel to the ACL fibers in the longitudinal axis, and the assessment of the ACL ligament segment was performed in the oblique sagittal plane. Initially, the ACL was visualized in B mode, with the distal one-third segment being highlighted. Subsequently, a 2 mm region of interest (ROI) was placed within the distal segment of the ACL for measurement. During the SWE measurements, data provided by the device were recorded in kilopascals (kPa). Each measurement was repeated at three different points on the visible ACL segment and analyses were performed by averaging the measurement values (Fig. 2).

Statistical analysis

All radiological measurements were performed by two board-certified radiologists (M.Y. and M.S.B.) experienced in musculoskeletal radiology on a best-agreement basis. Additionally, the diagnosis of MMPRT was confirmed by two radiologists at different times. If either radiologist deemed the MMPRT diagnosis uncertain, the patient was excluded from the study. To determine interobserver reproducibility, additional measurements were conducted independently by two observers on a randomly selected group of 20 individuals and interclass correlation coefficients (ICCs) were calculated. The ICCs for SWE measurements were $r = 0.836$, for HKA angle measurements it was $r = 0.741$, and for the tibial slope it was $r = 0.801$, indicating high interobserver reliability across measurements. To determine the sample size, the effect size was calculated as 0.675. With a significance level of 0.05 and a power of 0.80, the minimum required sample size for each group was determined to be 28. Taking into account a 10% margin of error, the study was planned with at least 31 participants per group.

Statistical analyses were conducted using SPSS software version 22 (SPSS Inc., IBM, Armonk, NY). Categorical variables are presented as frequencies, while continuous numeric variables are expressed as means

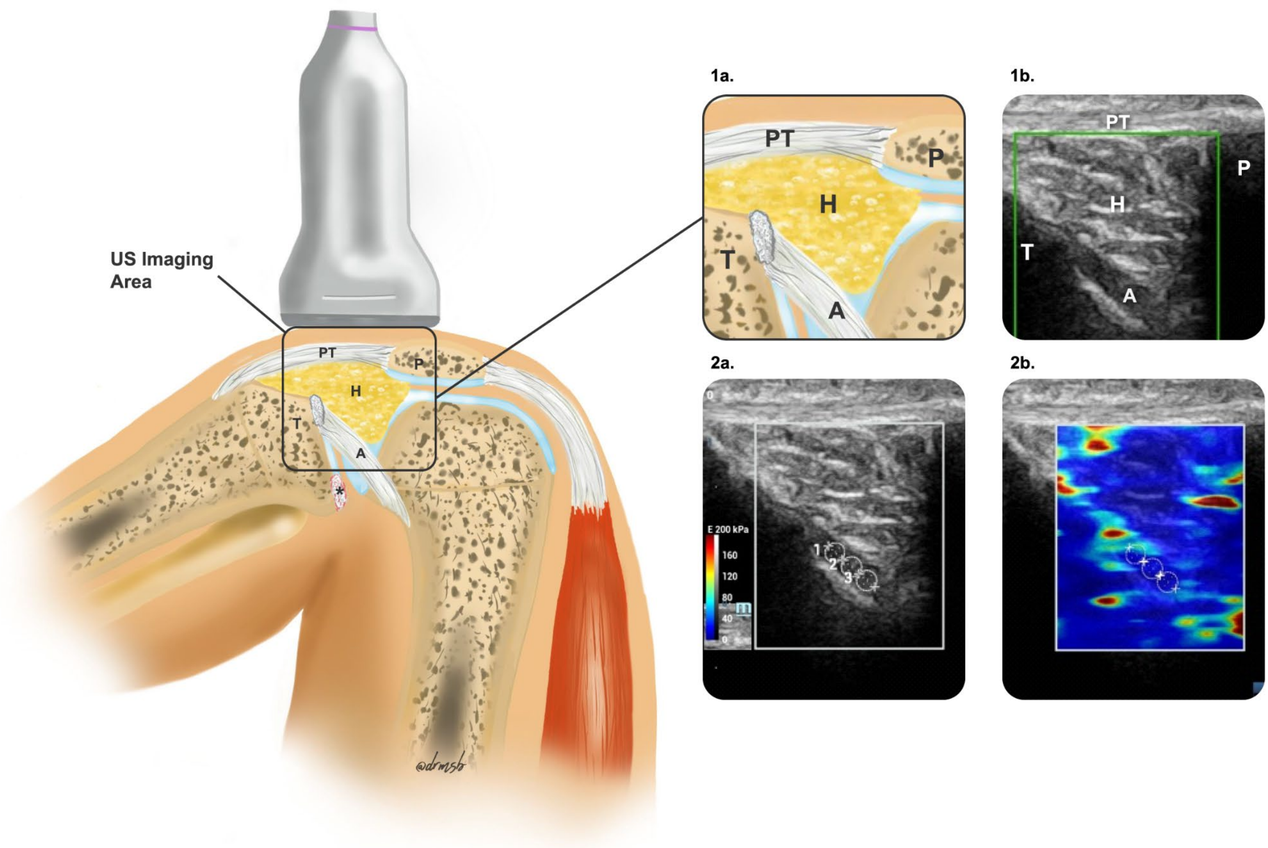

Fig. 2 Demonstration of knee ultrasound shear wave elastography application. PT: patellar tendon, H: Hoffa fat pad, P: patella, T: tibia, A: anterior cruciate ligament. Figure 1a and b: Localization of anatomical regions in the ultrasound images. The distal portion of the ACL is observed between the patella and tibia, posterior to the Hoffa fat pad. Figure 2**a** and **b**: Consecutive ROIs (Regions of Interest) used in elastography measurements and the elastography measurements on the ACL are observed

Table 1 Comparison of side and gender between study and Control Groups, and descriptive statistics of clinical scores

	Group	Female	Male	Total	*P* value
Gender	**Volunteer**	25 (80.6%)	6 (19.4%)	31	0.3797
	MMPRT	48 (85.7%)	8 (14.3%)	56	
	Group	**Right**	**Left**	**Total**	**P value**
Side	**Volunteer**	16 (51.6%)	15 (48.4%)	31	0.279
	MMPRT	23 (41%)	33 (59%)	56	
	MMPRT (n)	**Mean**	**Minimum**	**Maximum**	**SD**
TLKSS	56	64,3	23	64.3	14.7
IKDCS	56	54.8	24.1	54.8	12.5

Pearson Chi-Square test, MMPRT: medial meniscus posterior root tear, TLKSS: tegner lysholm knee scoring scale, IKDCS: international knee Documentation Committee score, SD: Standart deviation

with their corresponding standard deviations. The Kolmogorov-Smirnov test was employed to assess the equality of variances and to evaluate the normality of distribution for all variables. An independent-samples t-test was conducted to compare the means between the groups. Multivariable regression analysis was used to determine the relationship between SWE value and other parameters. Gender and side categorical variables were analyzed using the Chi-square test. P values below 0.05 were considered statistically significant.

Results

A total of 87 participants were included in the study, consisting of 31 volunteers (control group: 25 females, 6 males) and 56 patients diagnosed with MMPRT (study group: 48 females, 8 males) (Table 1). The average age of the study group was 51.6 (SD ± 4.8), while the average

Table 2 Comparison of quantitative data between groups

	Group	*N*	Mean	SD	*P* value
Age (years)	**Volunteer**	31	50.5	5.5	0.358
	MMPRT	56	51.6	4.8	
BMI (kg/m^2)	**Volunteer**	31	28.5	2.7	0.179
	MMPRT	56	29.5	3.2	
SWE-value (kPa)	**Volunteer**	31	21.2	5.7	**0.004**
	MMPRT	56	26.6	8.9	
HKA (°)	**Volunteer**	31	176.1	1.8	0.767
	MMPRT	56	175.9	2.1	
MPTA (°)	**Volunteer**	31	86.81	1.5	0.740
	MMPRT	56	86.3	1.8	
Tibial slope (°)	**Volunteer**	31	8.6	2.5	0.425
	MMPRT	56	9.1	2.9	

independent-samples t-test. SWE: Shear Wave Elastografi, kg/m^2: kilogram/square meters, kPa: kilopascals, (°): degree, SD: Standart deviation, BMI: Body mass index, MPTA: Medial proximal tibial angle, HKA: Hip knee ankle angle

Table 3 Comparison of the sides affected and unaffected by MMPRT in patients

	MMPRT	*N*	Mean	SD	*P* value
KT 1000 (mm)	**Non-Tear**	56	4.9	0.78	**< 0.01**
	Tear	56	6.19	1.4	

Independent samples test. mm: millimeter, SD: Standart deviation

age of the control group was 50.5 (SD ± 5.5) (Table 2). In the study group, there were 23 right-sided and 33 left-sided participants, while the control group comprised 16 right-sided and 15 left-sided participants (Table 1). No significant differences were found between the study and control groups in terms of gender, side, and age ($p > 0.05$). The average clinical scores for the patients were measured as follows: TLKSS: 64.3 (SD ± 14.7) and IKDCS: 54.8 (SD ± 12.5) (Table 1).

The average SWE values of the ACL were compared between the study group (26.6 ± 8.9 kPa) and the control group (21.2 ± 5.7 kPa), with the study group demonstrating a significantly higher value (p: 0.004) (Table 2). In the comparison between the groups, no significant differences were found for BMI (study group average: 29.5 ± 3.2 kg/m², control group average: 28.5 ± 2.7 kg/m²), HKA (study group average: 175.9° ± 2.1, control group average: 176.1° ± 1.8), MPTA (study group average: 86.3° ± 1.8, control group average: 86.81° ± 1.5), and tibial slope (study group average: 9.1° ± 2.9, control group average: 8.6° ± 2.5) ($p > 0.05$) (Table 2).

In patients with MMPRT, the measurements of anterior translation using the KT 1000 device were an average of 6.19 ± 1.4 mm in the affected knees and 4.9 ± 0.78 mm in the unaffected knees. The comparison revealed a significantly greater anterior translation in the knees with MMPRT ($p < 0.05$) (Table 3). Multivariable regression analysis demonstrated a significant positive relationship between ACL SWE values and tibial slope (β = 1.11; CI, 0.24–1.99; P: 0.01) (Table 4).

Discussion

The most significant finding of this study is that patients with MMPRT exhibit a stiffer ACL with a higher elastic modulus. Additionally, greater tibial anterior translation was observed on the MMPRT-affected side compared to the healthy side. Furthermore, it was found that the increase in tibial slope significantly affects the stiffness of the ACL.

Chronic ACL insufficiency is associated with medial meniscus tears [19]. One of the most important

Table 4 Multivariable regression analysis

				95% CI				
Dependent variables	**Variables**	**Regression Coefficient (β)**	**SE**	**Lower**	**Upper**	***P* value**	***R*^{2}**	
SWE-value (kPa)	**Tibial slope**	1.11	0.43	0.24	1.99	**0.01**		0.532
	HKA	-0.92	0.92	-2.79	0.93	0.32		
	MPTA	0.35	1.01	-1.70	2.41	0.72		
	IKDCS	0.12	0.18	-0.23	0.49	0.48		
	TLKSS	-0.03	0.16	-0.35	0.29	0.83		
	BMI	0.64	0.41	-0.2	1.49	0.13		
	Age	0.09	0.27	-0.46	0.64	0.74		

Multivariable regression analysis, SWE: Shear wave elastografi, TLKSS: Tegner Lysholm knee scoring scale, IKDCS: International knee documentation committee score, SE: standard errors, CI: confidence interval, BMI: Body mass index, MPTA: Medial proximal tibial angle, HKA: Hip knee ankle angle structures that limit anterior tibial translation in ACL insufficiency is the medial meniscus [20, 21]. In their study, Papageorgiou et al. [22] emphasized that the load borne by the medial meniscus can double in the absence of the ACL. Additionally, they demonstrated that after ACL reconstruction, load distribution is regulated, and the load on the medial meniscus returns to its original state. Recently, various authors have investigated the relationship between the isolated posterior root region of the medial meniscus and the ACL in relation to tibial translation load [7, 8]. In their study on human cadaver knees, Ueki et al. [9] demonstrated that there is increased anterior translation in knees with MMPRT following ACL reconstruction. In a comprehensive biomechanical study, Allaire et al. [3] examined joint contact pressure and knee kinematics in cadaver knees with created MMPRT. They emphasize that tibial translation significantly increases in specimens with MMPRT and returns to the level of the healthy knee after root repair. In MRI studies, Okazaki et al. [8] showed that the pathologically stretched ACL in patients with MMPRT decreased after root repair. They highlight that this result is attributed to the restoration of the secondary stabilizing effect of the medial meniscus following root repair. In our study, tibial anterior translation was assessed using the KT-1000 device, and the increased tibial anterior translation in patients with MMPRT is consistent with the literature, indicating that the medial meniscus posterior root plays an active role in stabilization.

While most existing studies examine the relationship between ACL and MMPRT from a functional perspective, there are very few publications that investigate this relationship from a structural standpoint [5, 23]. In their study, Kodama et al. [5] noted that ACL degeneration is more prominent in patients with MMPRT. Kijima et al. [12] emphasized that the degenerated coracoacromial ligament exhibited a higher elastic modulus. They explained that this is due to mechanical factors causing the coracoacromial ligament to stretch and stiffen as a result of degeneration. In our study, the higher SWE values of the ACL in patients with MMPRT indicate that the ACL is structurally stiffer. This finding can be interpreted as indicating a higher degree of ACL degeneration in patients with MMPRT, supporting our hypothesis. There may be two reasons for this. The first reason is that ACL degeneration may lead to insufficient resistance against tibial anterior translation and rotational forces, resulting in increased load on the medial meniscus posterior root region, which can contribute to the development of MMPRT. The second reason is the initiation of a compensatory degenerative process in the ACL due to increased loading after the occurrence of MMPRT (Fig. 3). In their study, Kodama et al. [5] emphasized that the evaluation of patients with MMPRT was conducted within the first three months after the onset of symptoms, and therefore, the ACL degeneration process associated with MMPRT could not begin within such a short period. Therefore, they suggest that ACL degeneration occurred prior to the onset of MMPRT. In our study, patients were evaluated three months after the onset of symptoms to allow for a more thorough functional examination. Therefore, it may not be possible to make this distinction in our study.

SWE is an imaging method that provides real-time dynamic evaluation and demonstrates quantitative mechanical properties, such as the stiffness of tissues like muscles, tendons, and ligaments. Many studies have emphasized that SWE provides information about tissue stiffness, degeneration, and quality [10, 12, 14, 24–27]. Spalazzi et al. [14] have demonstrated that elastography is a method that can be used to assess the mechanical properties of the ACL. In our study, the high SWE values of the ACL were considered an indirect indicator of ACL degeneration. Cellular changes and structural irregularities during ACL degeneration can alter the mechanical properties of the ligament, leading to functional instability in the knee [28, 29]. ACL degeneration histopathologically leads to chondrocyte metaplasia, calcification, fibrous tissue formation, collagen disorganization, and myofibroblast formation [28, 30]. Additionally, although the ACL is a synovial membrane, it is an intra-articular ligament that partially interacts with synovial fluid through diffusion [31, 32]. Changes in the mediators of synovial fluid due to factors such as trauma and arthritis in the knee can also influence ACL degeneration [29, 33–37]. It is emphasized that MMPRT occurs acutely following trauma during knee flexion in young patients, while it develops as a result of degeneration in middle-aged to older individuals [38–40]. Therefore, MMPRT can contribute to ACL degeneration not only mechanically but also through the mediators it creates in the synovial fluid.

An increase in tibial slope is known to lead to anterior translation of the tibia, resulting in insufficiency of stabilizing structures and an increase in anteroposterior instability [7, 41–43]. In their biomechanical study conducted on cadavers, Samuelsen et al. [7] demonstrated that an increase in tibial slope leads to an increased load on the ACL reconstruction graft, and this force increase is even more pronounced in the presence of MMPRT. Various studies in the literature report that both MMPRT and ACL degeneration are associated with tibial slope [5, 6, 44]. In our study, a linear relationship was observed between the increase in tibial slope and ACL SWE values through regression analysis. An increase in slope can elevate the anterior translation load, resulting in greater stress on the ACL, which may lead to the ligament becoming structurally stiffer and more degenerated.

It is known that there is a relationship between MMPRT and genu varum, BMI, and gender [4]. In our

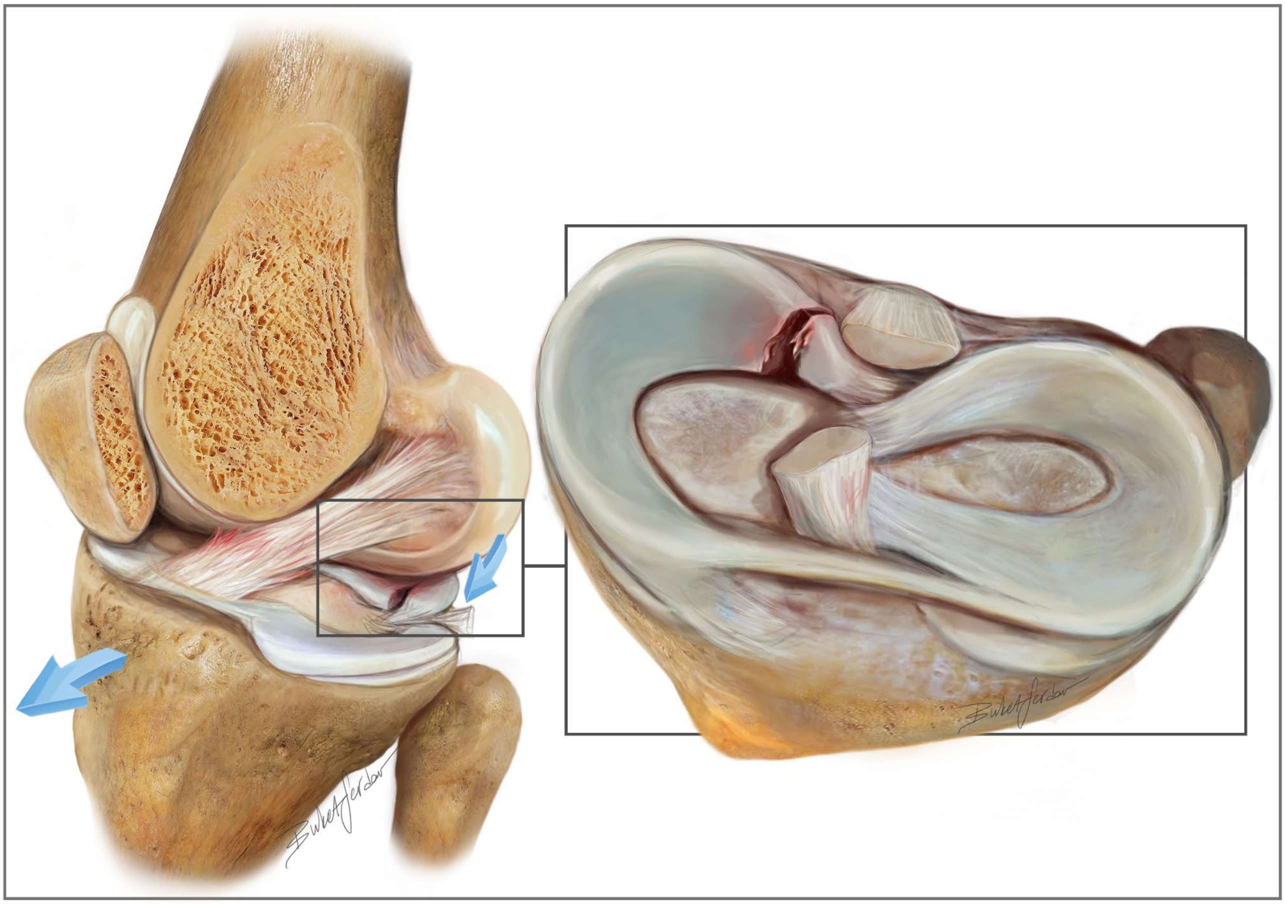

Fig. 3 Illustration of the relationship between the anterior cruciate ligament and medial meniscus posterior root tear. In knees with medial meniscus posterior root tear, the anterior cruciate ligament is more degenerated and stiffer, with increased anterior tibial translation

study, the patient population is predominantly female, and the BMI results are consistent with being overweight, nearing the obesity threshold. To evaluate genu varum, both the MPTA and HKA angles fall within normal ranges, but they are close to the varus threshold. These findings are roughly consistent with the literature, and we believe that our study reflects the general population. To the best of our knowledge, our study is the first to evaluate the structure and elasticity of the ACL in patients with MMPRT.

Limitations

This study has several limitations. The first limitation is that the study is retrospective, and the sample size is relatively small; however, the statistical power was sufficient. Secondly, the diagnosis of MMPRT and ACL degeneration could not be confirmed arthroscopically in all patients. However, the diagnosis of MMPRT via MRI shows a high correlation with arthroscopic examination [45]. Thirdly, the ligament's flexibility and stiffness may vary individually among the participants included in the study, potentially affecting the SWE values. Fourthly, the most significant limitation of this study is the lack of histopathological validation of the structural changes in the ACL. Future studies are needed to fully elucidate the relationship between ACL degeneration and structural changes with MMPRT.

Conclusions

Greater tibial anterior translation was observed on the side with MMPRT in the patients. There is a correlation between MMPRT and the stiffness of the ACL, which exhibits a higher elastic modulus. Additionally, an increase in tibial slope significantly affects the stiffness of the ACL.

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Author contributions
Conceptualization: Y.S.K., H.A. Methodology: Y.S.K, H.A, A.S.G., M.Y., M.S.B. Formal analysis and investigation: Y.S.K., H.A., A.S.G., M.Y., M.S.B., O.B. Writing - original draft preparation: Y.S.K., H.A., M.Y., M.S.B. Writing - review and editing: Y.S.K., H.A., M.Y., M.S.B., O.B. Funding acquisition: Y.S.K., H.A., A.S.Gç, M.Y., M.S.B., O.B. Resources: Y.S.K., H.A., M.Y. Supervision: Y.S.K., H.A.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval
Ethical approval for this study was obtained from the University of Health Sciences, Samsun Training and Research Hospital, Scientific Research Ethics Committee. Informed consent was obtained from patients to use all patient information. Research protocol code: GOKAEK 2024/12/14.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Orthopaedics and Traumatology, Samsun Education and Research Hospital, Samsun, Turkey
[2]Faculty of Medicine, Department of Radiology, Samsun University, Samsun, Turkey
[3]Department of Radiology, Samsun Education and Research Hospital, Samsun, Turkey
[4]Faculty of Medicine, Department of Orthopaedics and Traumatology, Gaziosmanpasa University, Tokat, Turkey

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