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RESEARCH

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A larger radius of the medial femoral posterior condyle is a risk factor for medial meniscus posterior root tears

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Abstract

Background Studies have shown an association between medial meniscus posterior root tears (MMPRT) and morphologic characteristics of the bone. However, the association between distal femoral bone morphology and MMPRT, particularly the medial femoral posterior condyle, is poorly understood. Our study aimed to determine the association between the morphologic characteristics of the medial posterior femoral condyle and MMPRT.

Methods A retrospective case-control study was performed from January 2021 to January 2022. After screening based on the inclusion and exclusion criteria, two matched groups were analyzed: the MMPRT group and the isolated lateral meniscus tears group. The hip-knee-ankle angle (HKA) and Kellgren-Lawrence grade (KLG) were measured on radiographs; the medial tibial slope angle (MTSA), medial tibial plateau depth (MTPD), and radius of the medial femoral posterior condyle (RMFPC) were measured on magnetic resonance imaging (MRI) in both groups. The area under the curve (AUC) and the best cutoff value for predicting MMPRT were calculated by using receiver operating characteristic (ROC) curve analysis.

Results The final analysis included a total of 174 patients (87 MMPRT patients and 87 controls). Significant differences were shown in the RMFPC (17.6 ± 1.0 vs. 16.2 ± 1.0, $p < 0.01$) and MTSA (6.4 ± 2.0 vs. 4.0 ± 1.3, $p < 0.01$), which were larger than those of the control group. The MTPD (1.8 ± 0.6 vs. 2.9 ± 0.7, $p < 0.01$) and HKA (175.4 ± 2.2 vs. 179.0 ± 2.7, $p < 0.01$) of the injury group were significantly different from the control group, and both were lower than the control group. However, between the MMPRT and control groups on the KLG (2.3 ± 0.6 vs. 2.2 ± 0.6, $p = 0.209$), there was no statistically significant difference. Among them, the RMFPC cutoff value was calculated to be 16.8 mm by ROC curve analysis, and the sensitivity and specificity were both 81.61%.

Conclusions This study demonstrated that larger RMFPC, MTSA, smaller MTPD, and HKA were all associated with MMPRT, and RMFPC ≥ 16.8 mm was considered as a significant risk factor for MMPRT.

Keywords Medial meniscus posterior root tears, Medial femoral condyle, Risk factor, MRI

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Background

Converting axial stress to hoop stress is one of the capabilities of the meniscus [1]. At the same time, the distinctive wedge-shaped structure deepens the tibial plateau and improves knee joint stability [2]. Medial meniscus posterior root tears (MMPRT) alter the kinematics and contact pressures of the knee joint, which accelerates the onset of osteoarthritis and is biomechanically similar to total meniscectomy [3]. As a result, MMPRT has attracted attention.

A previous study showed that a greater varus mechanical axis angle, high body mass index (BMI), and female sex were risk factors of MMPRT [4]. Obviously, these risk factors, which do not reflect the geometry of the knee, are not a good explanation for the fact that MMPRT is more likely to occur when climbing stairs or squatting, especially when MMPRT is accompanied by a popping sound [5, 6]. Therefore, previous studies have reported that certain anatomic characteristics, such as a shallower medial tibial plateau concavity, a larger medial tibial plateau to femoral condyle dimension, and a steeper posterior slope may contribute to the risk factors associated with MMPRT [5, 7]. However, the above studies neglected the distal femoral morphological characteristics, especially the femoral posterior condyle with an independent radius during knee flexion [8, 9]. The posterior condyle of medial femur limits anterior tibial translation by creating a buttress effect with the posterior horn of the medial meniscus [3]. While the knee is flexing, hoop stress in the meniscus is increased due to increased contact between the femoral posterior condyle and the meniscus. Thus, the risk of MMPRT may be increased when the posterior horn of the meniscus is compressed by the larger medial posterior condyle of the femur.

The object of this study was to determine the association between the morphological characteristics of the medial femoral posterior condyle and MMPRT. It was hypothesized that an increased size of the medial femoral posterior condyle could be a risk factor for MMPRT.

Methods and materials

Study design

The institutional review board of our hospital supported this study, and a retrospective case-control study was designed. The medical records of those who were scanned using magnetic resonance imaging (MRI) for knee discomfort at our hospital from January 2021 to January 2022 were retrospectively analyzed. A total of 941 patients met the inclusion criteria and were divided into two groups: (1) patients with complete MMPRT and (2) patients with isolated lateral meniscus tears.

Our inclusion criteria included the following: complete MMPRT or isolated lateral meniscus tear, over 18 years old, BMI between 18 and 26 kg/m^2, and taking an MRI scan for knee pain in our hospital. After excluding prior knee injury, concomitant ligament injury (such as anterior cruciate ligament injury), osteonecrosis, missing radiographs of the entire lower limb, and signs of patellofemoral dysplasia, there were 87 patients with complete MMPRT in the final research group. For the control group, we selected 87 patients with isolated lateral meniscus tears whose demographic data (including sex, age, and BMI) were similar to that of the study group. The patient enrollment flowchart of this study is shown in Fig. 1. Since demographics such as age, sex, and BMI were considered risk factors for MMPRT, a propensity score matching (PSM) was performed to reduce the effect of confounding factors. The MMPRT group and control group were matched at a ratio of 1:1 using the nearest neighbor method, without replacement, with a caliper of 0.2. Matching variables included age, sex, and BMI in the logistic regression model of PSM. In this study, the control group we selected were patients with isolated lateral meniscus tears and no medial meniscus tears; the study group were patients with MMPRT and no lateral meniscus tears. It has been shown that certain osteomorphological features of the knee are risk factors for MMPRT, the majority of which are degenerative tears [4, 5, 7]. However, no studies have shown that certain osteomorphological features of the knee are risk factors for isolated lateral meniscus tears, which are mostly caused by acute trauma [10, 11]. Therefore, it was justified to compare patients with MMPRT and patients with isolated lateral meniscus tears as two different populations. Meanwhile, the studies by Hwang et al. and Chung et al. also selected non-healthy individuals as the control group [4, 5]. MMPRT was defined as a complete separation of the posterior root of the medial meniscus from the posterior horn or a radial meniscus root injury within 10 mm of the tibial plateau attachment on MRI [5, 12]. The MRI of patients in both the control and study groups were read and diagnosed as MMPRT or isolated lateral meniscus tears by senior radiologists and experienced surgeons.

Measurement methods

All patients underwent standing hip-knee-ankle radiographs and MRI (SIEMENS MAGNETOM Avanto 1.5T) in our hospital. Measurements included hip-knee-ankle angle (HKA), Kellgren-Lawrence grade (KLG), medial tibial plateau depth (MTPD), radius of the medial femoral posterior condyle circle (RMFPC), and medial tibial slope angle (MTSA). HKA and KLG were obtained on radiographs, while RMFPC, MTSA, and MTPD were measured on MRI. With MRI, T1-weighted images (TR/TE 580/9.30 ms), proton density-weighted images (TR/TE 3000/37 ms) were obtained. FOV was 16 cm, matrix

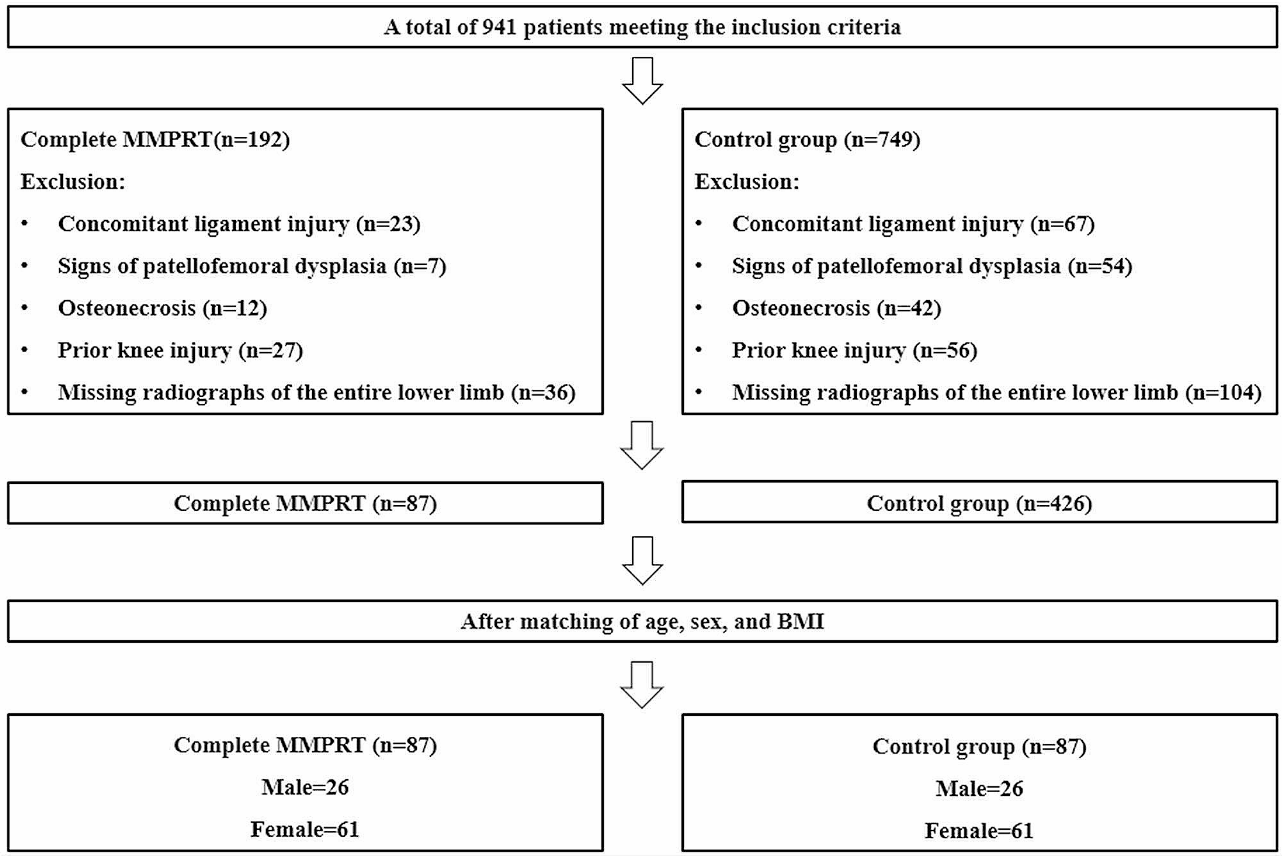

Fig. 1 Flowchart of patient enrollment. MMPRT, medial meniscus posterior root tears

was 320×320 pixels, and slice thickness was 4 mm with a gap of 0.4 mm.

The measurement of the angle formed by the mechanical axes of the femur and tibia in radiographic images of the entire lower limb was defined as the HKA [13]. KLG was also obtained from the plain radiographs and graded as follows: 0 indicated normal, 1 indicated doubtful joint space narrowing and possible osteophytic lipping, 2 indicated definite osteophytes and definite joint space narrowing, 3 indicated moderate multiple osteophytes, definite joint space narrowing, some sclerosis, and possible bone contour deformity, or 4 indicated large osteophytes, marked joint space narrowing, severe sclerosis, and definite bone contour deformity [4, 14].

MTSA and MTPD were measured using MRI, following the method described by Hudek [15] and Hashemi [16]. The first step was to identify the proximal tibial anatomical axis. The posterior cruciate ligament insertion and intercondylar eminence were visible, and the posterior and anterior cortices of the tibia were both concave on the central sagittal slice. Both the distal and proximal circles were fitted inside and tangent to the anterior and posterior boundaries of the cortex, and the proximal circle was tangent to the proximal cortex. The anatomical axis of the proximal tibia is represented by the line connecting the centers of both circles. The MTSA is the acute angle formed by the line perpendicular to the anatomical axis of the proximal tibia and the line connecting the highest points of the posterior and anterior cortical margins of the medial tibial plateau (Fig. 2a and b). This

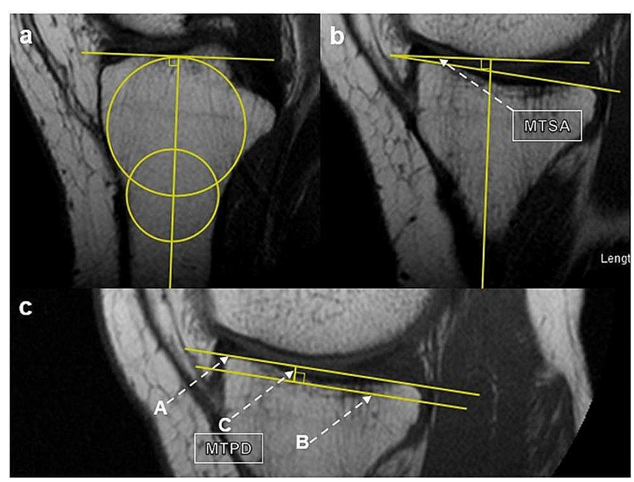

Fig. 2 Schematic diagram of MTSA (**a**, **b**) and MTPD (**c**) measurement methods. (**a**) To determine the anatomical axis of the tibia. (**b**) The arrow indicated MTSA. (**c**) The arrow indicated that the C line was MTPD. *MTSA* Medial tibial slope angle, *MTPD* Medial tibial plateau depth

method is not influenced by the length of the proximal tibia and has been shown to have the greatest repeatability when measuring the tibial plateau slope on sagittal MRI [17]. The measurement of MTPD was performed in the same plane as the measurement of MTSA. First, utilize the A line to connect the apexes of the posterior and anterior cortical edges of the tibial plateau. The B line was positioned tangentially to the deepest point of the subchondral bone, maintaining a parallel orientation to the A line. The perpendicular distance C line between the A line and B line was measured to represent the MTPD (Fig. 2c) [16]. RMFPC was measured according to the method used by Howell [9] in his study. The best-fitting circle representing the medial femoral posterior condyle was drawn on the four adjacent nonorthogonal sagittal scan planes using a circle-fitting technique. The RMFPC was then determined by calculating the average of the radii in the four contiguous planes (Fig. 3). The study showed that the subchondral bone of the lateral and medial femoral condyles had a separate transverse axis

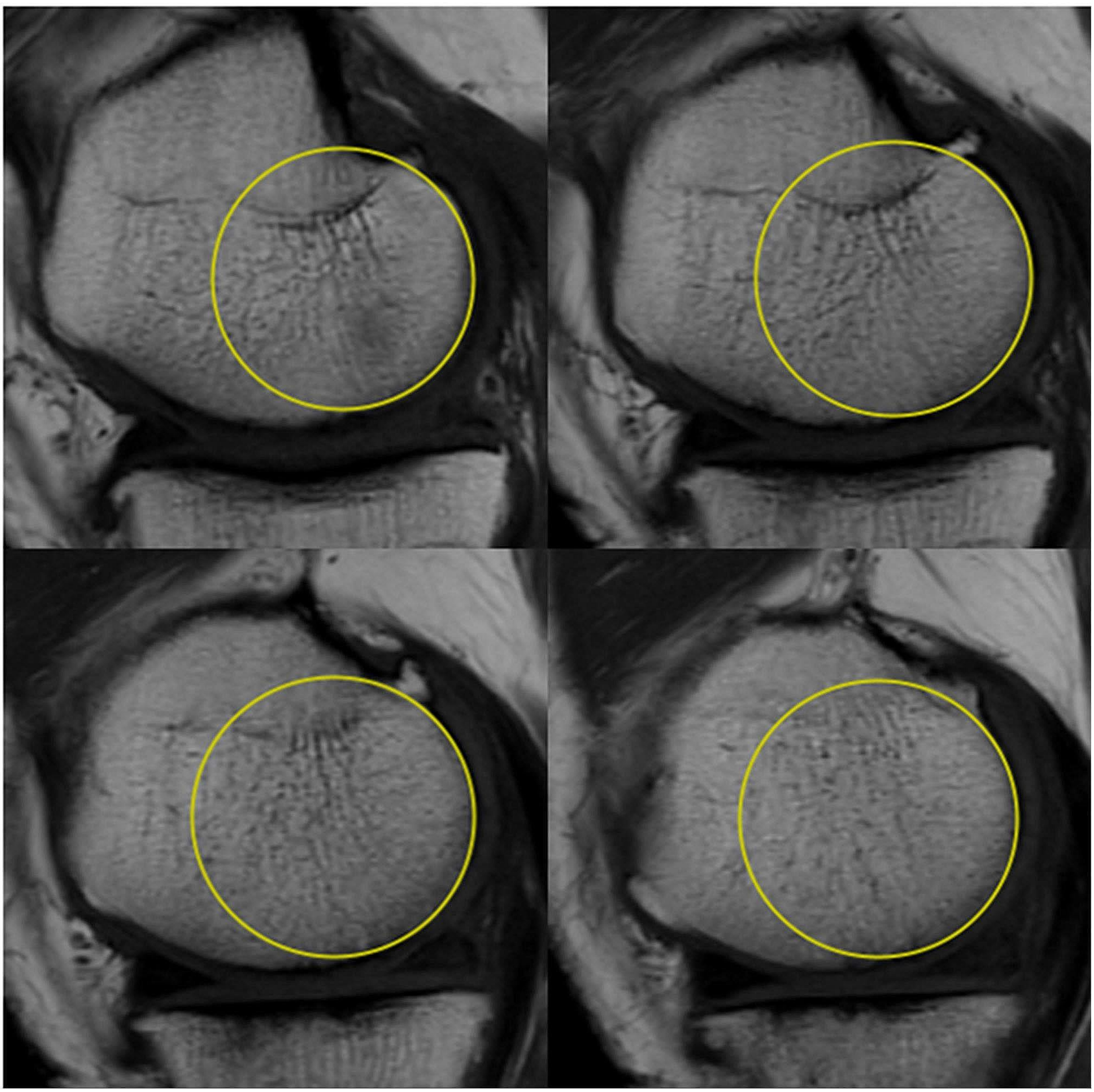

Fig. 3 RMFPC was the average of the radii on the four adjacent images. The best-fitting circles (yellow circle) of the medial femoral condyle were shown. *RMFPC* Radius of medial femoral posterior condyle circle

ranging from 10° to 160°, along with a consistent singular radius of curvature [18]. In the non-orthogonal sagittal plane (sagittal kinematic plane), the medial and lateral condyles of the femoral were thus projected as a circle [9].

The images in this study were obtained from our PACS system using medical measurement software to digitally measure (Weasis v3.7.0; University Hospital of Geneva), which could draw circles of any diameter at any position and overlay them all at a fixed position of the entire image series.

Two blinded orthopedic surgeons with clinical experience performed all measurements and repeated measurements 1 month later. The evaluation of interobserver and intraobserver consistency and reliability was conducted using the intraclass correlation coefficient (ICC). It was considered poor for ICC values < 0.8, good for values between 0.8 and 0.9, and excellent for values > 0.9. The ICCs for the HKA were 0.91 (95% CI, 0.86–0.96) and 0.89 (95% CI, 0.81–0.94) for the intraobserver reliability and for the interobserver reliability. The ICCs for the KLG were 0.89 (95% CI, 0.87–0.92) and 0.88 (95% CI, 0.83–0.91) for the intraobserver reliability and for the interobserver reliability. The ICCs for the RMFPC were 0.90 (95% CI, 0.83–0.96) and 0.88 (95% CI, 0.78–0.94) for the intraobserver reliability and for the interobserver reliability. The ICCs for the MTSA were 0.88 (95% CI, 0.82–0.93) and 0.86 (95% CI, 0.76–0.92) for the intraobserver reliability and for the interobserver reliability. The ICCs for the MTPD were 0.91 (95% CI, 0.83–0.95) and 0.87 (95% CI, 0.78–0.92) for the intraobserver reliability and for the interobserver reliability. These high ICC values indicated that the measurements taken by two independent observers were highly reliable and reproducible.

Statistical analyses

Continuous variables were retained to one decimal place and expressed as the mean ± standard deviation. The analysis of data was performed by using SPSS software (version 25.0, IBM Corp., Armonk, N.Y., USA). This study focused on the relationship between RMFPC and MMPRT. The paired sample t-test or Wilcoxon signed rank test was used to examine significant differences between the two groups based on the normality of the continuous variables (HKA, RMFPC, MTSA, and MTPD) after pairing sex, age, and BMI. For the ordinal categorical variable (KLG), the Marginal Homogeneity test was performed to detect significant differences. It was set at a significance level of $p < 0.05$. For the measurement with significant differences, we calculated the odds ratio (OR) with 95% confidence intervals (CI) to determine whether it was a risk factor for MMPRT. The optimal cutoff value for detecting MMPRT and the association between the indicator with significant differences (e.g., HKA, MTSA) and MMPRT were determined through receiver operating characteristic (ROC) curve analysis. The optimal cutoff with the best sensitivity and specificity was obtained at the maximum Youden index.

Table 1 Demographic data of the patients

	MMPRT (*n* = 87)	Control (*n* = 87)	*P* values
Age(years)	59.8 ± 7.6	59.8 ± 7.8	0.904
Male/female	26/61	26/61	1
Height(cm)	162.9 ± 7.0	163.6 ± 6.6	0.394
Weight(kg)	65.0 ± 5.8	65.2 ± 5.5	0.585
BMI(kg/m^2)	24.4 ± 0.6	24.3 ± 0.6	0.472

Data for age, height, weight, and BMI were expressed as mean ± standard deviation

Table 2 Comparison of significant differences between injury group and control group

	MMPRT (*n* = 87)	Control (*n* = 87)	*P* values
HKA(deg)	175.4 ± 2.2	179.0 ± 2.7	< 0.01*
KLG	2.3 ± 0.6	2.2 ± 0.6	0.209
RMFPC(mm)	17.6 ± 1.0	16.2 ± 1.0	< 0.01*
MTSA(deg)	6.4 ± 2.0	4.0 ± 1.3	< 0.01*
MTPD(deg)	1.8 ± 0.6	2.9 ± 0.7	< 0.01*

A paired sample t-test was applied for *RMFPC*, and nonparametric tests were performed for *HKA*, *KLG*, *MTSA*, and *MTPD*

*Significant difference

G*Power (3.1.9.2, Kiel, Germany) was used to conduct a power analysis to determine the sample size based on a power of 0.95, an effect size (Cohen's d) of 0.7, and an α error of 0.05. The sample size calculation estimated that 110 patients (55 per group) were required for the present study. In this study, 174 patients (87 in each group) were enrolled, which met the required sample size. A post hoc power analysis was also performed to calculate whether the sample size had sufficient statistical power. The effect sizes for HKA, RMFPC, MTSA, and MTPD were 1.46, 1.40, 1.42, and 1.69, respectively. The calculated means and standard deviations of the measurements with significant differences were used to determine these effect sizes [19]. With an α error of 0.05, the effect size obtained and the final sample size, post hoc power analyses revealed that the statistical power for HKA, RMFPC, MTSA, and MTPD was 100%. Sufficient statistical power was achieved based on the final sample size of this study.

Results

Table 1 presents the demographic characteristics (including age, sex, height, weight, and BMI) of the two groups, showing no difference between them. The results of the radiographic and MRI measurements and statistical analysis are summarized in Table 2. The paired sample t-test or nonparametric test indicated that there was no significant difference in KLG between the MMPRT group and the control group. However, significant differences were observed between the two groups in terms of HKA, RMFPC, MTPD, and MTSA. Among them, RMFPC and MTSA exhibited greater values in the knees with MMPRT compared to the control group, whereas MTPD and HKA showed lower values in the knees with MMPRT than in the control group.

According to the ROC analysis (Fig. 4), the area under curve (AUC) of HKA was 0.884 (95% CI, 0.831–0.938). The cutoff of HKA at the maximum Youden index (0.6782) was 177.9° and predicted MMPRT with 78.16% sensitivity and 89.66% specificity. The smaller the HKA, the higher the risk of MMPRT (OR, 0.480; 95% CI, 0.334–0.691). The AUC of RMFPC was 0.841 (95% CI, 0.780–0.902). The cutoff of RMFPC at the maximum Youden index (0.6322) was 16.8 mm and predicted MMPRT with 81.61% sensitivity and 81.61% specificity. The larger the RMFPC, the greater the risk of MMPRT (OR, 3.870; 95% CI, 1.753–8.544). The AUC of MTSA was 0.852 (95% CI, 0.794–0.909). The cutoff of MTSA at the maximum Youden index (0.5517) was 4.8° and predicted MMPRT with 75.86% sensitivity and 79.31% specificity. The larger the MTSA, the greater the risk of MMPRT (OR, 2.775; 95% CI, 1.648–4.647). The AUC of MTPD was 0.890 (95% CI, 0.839–0.941). The cutoff of MTPD at the maximum Youden index (0.6552) was 2.0 mm and predicted MMPRT with 74.71% sensitivity and 90.80% specificity. The lower the MTPD, the greater the risk of MMPRT (OR, 0.095; 95% CI, 0.033–0.275).

Discussion

A significant finding from this study was that a larger RMFPC was an increased risk factor for an MMPRT. Measurement of the RMFPC could help identify patients at higher risk of MMPRT, which was consistent with the hypothesis of our study. The optimal cutoff value of RMFPC to predict MMPRT was 16.8 mm, with a sensitivity and specificity of both 81.61%, which could robustly identify patients with MMPRT. Besides, a larger HKA, MTSA, and shallower MTPD were also significantly correlated with MMPRT.

There is a strong connection exists between the posterior horn of the medial meniscus and the tibial plateau at the root of the medial meniscus. This connection resulted in restricted movement of the posterior horn of the medial meniscus, making it particularly susceptible to deterioration or tearing [20]. Hwang et al. [4] showed that increasing age, varus mechanical axis alignment, female sex, and higher BMI (similar to risk factors for osteoarthritis) were intrinsic risk factors for MMPRT. As the degree of meniscus degeneration increases, meniscus injury may occur during movement [4, 21]. In our study, we observed that the association between the varus mechanical axis and MMPRT was consistent with their findings. They denied the influence of posterior tibial slope on MMPRT, probably because they measured it on lateral radiographs rather than the medial tibial plateau on MRI. Studies on biomechanics have indicated that a steep MTSA can increase forward movement of the

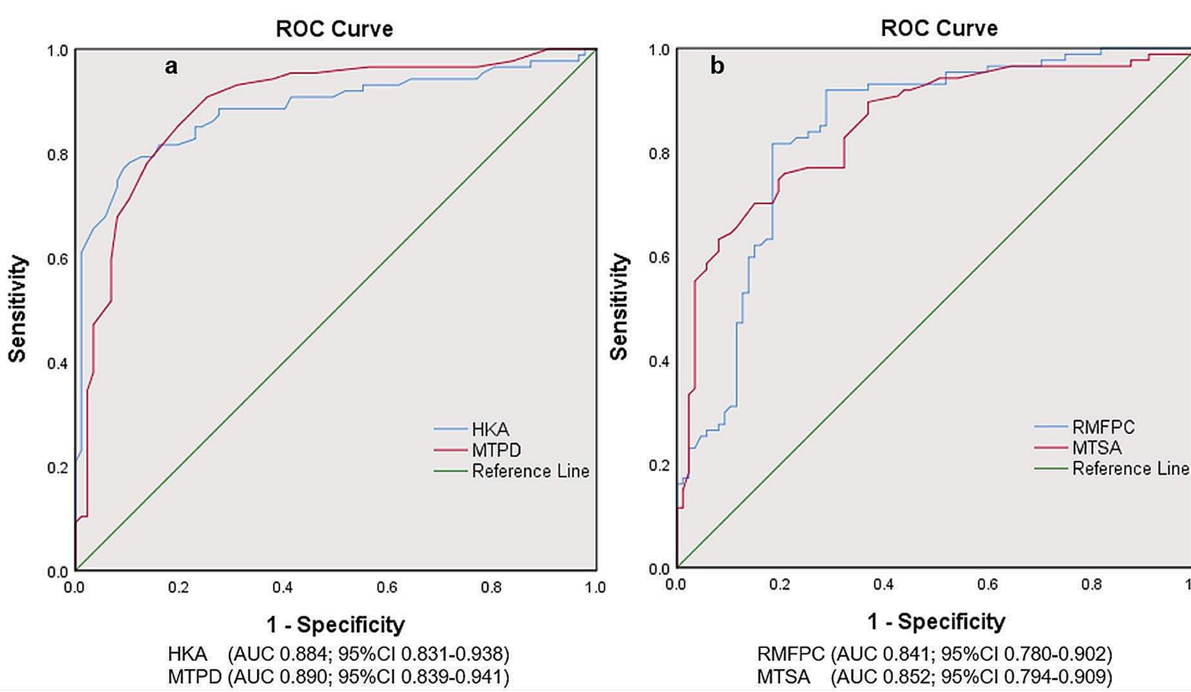

Fig. 4 Receiver operating characteristic curve analysis for measurements (**a**, **b**). *AUC* Area under the curve, *HKA* Hip-knee-ankle angle, *MTPD* Medial tibial plateau depth, *RMFPC* Radius of medial femoral posterior condyle circle, *MTSA* Medial tibial slope angle

tibia under pressure and exert more stress on the meniscus [22–27]. And the major pressure distributed in the medial compartment is concentrated on the posterior horn of the medial meniscus [28]. Also, because of the tight connection between the tibia and the meniscus, this means that the posterior horn of the medial meniscus can be used as a buttress to limit anterior displacement of the tibia against the medial posterior condyle of the femur [3]. Simultaneously, a deeper MTPD may restrict the mobility of the femoral condyles and increase the resistance to femoral displacement relative to the tibia to an extent [16]. According to Okazaki et al. [7], biomechanical alternations in the posterior roll of the femur result from a shallow MTPD and a steep MTSA. These changes may increase the risk of MMPRT by causing the posterior horn of the medial meniscus to be impinged. In addition, the mismatch between the tibia and the femur has also been considered a risk factor for MMPRT [29]. However, they have paid more attention to the morphology of the tibia and ignored the fact that the morphology of the femoral condyles has an equally significant role in knee kinematics, especially the medial femoral posterior condyle.

Our study found that patients with a larger RMFPC may have a higher risk of MMPRT. The mechanism of injury may be caused by increased force on the posterior root of the medial meniscus during flexion [3]. When under pressure, the meniscus can deform to convert an axial load into an annular stress [2]. Greater deformation and increased circular stresses are the effects of this, as the larger medial femoral posterior condyle makes greater contact with the posterior root of the medial meniscus. From 10° to 160°, the posterior condyle of the femur has a single radius and axis of motion [18]. And the larger the circle, the smaller its curvature, and the closer it tends to be to a straight line. The concave medial tibial plateau loses its ability to restrict the medial posterior femoral condyle when the contour radius of the medial femoral posterior condyle increases and its curvature decreases. As a result, there is an enhanced tendency for the femoral condyles to move posteriorly, which increases the forces on the posterior root of the medial meniscus and the risk of MMPRT. Furthermore, a medial posterior femoral condyle with a large radius may interfere with normal meniscal motion. Both the anterior and posterior horns of the medial meniscus are strongly adhered to the tibia [30]. In the meantime, the flexion and extension of the knee occur mainly between the meniscus and the femoral condyles, but the rotation of tibia in relation to the femur occurs mainly between the tibia and the meniscus [31, 32]. As a result, when the knee joint suddenly flexes and extends, the meniscus may have restricted mobility due to the discontinuity of the "screw homing" mechanism, and it may tear during the movement [32].

Some studies [33, 34] suggested a potential correlation between a narrow posterior open angle and injuries to the posterior portion of the medial meniscus. In addition, Suganuma et al. [34] suggested that bone decompression on the posterior segment of the medial meniscus (preoperative assessment using MRI to identify the extent of medial posterior femoral condyle resection) during medial meniscal repair had a better prognosis than arthroscopic meniscus repair using sutures alone. This approach improved knee functionality and provided greater accommodation for the medial meniscus, which could also indicate that the medial femoral posterior condyle played a significant role in the MMPRT. However, further biomechanical and kinematic analyses are needed to analyze it.

Among the indicators with significant differences, ROC curve analysis showed that RMFPC greater than 16.8 mm had high specificity and sensitivity as a diagnostic indicator, with a 3.89-fold increased risk of MMPRT (95% CI, 1.910–7.224). The rest of the indicators that exhibited significant differences were also associated with MMPRT, in agreement with the findings of previous research. This also indicates that there are risk factors of MMPRT in the localized bone morphology of the knee joint [5]. The main clinical significance of this research is to assist doctors in not only improving the identification of patients with MMPRT but also in recognizing individuals at a heightened risk for meniscal injury and implementing appropriate interventions.

This study has strengths and limitations. Previous studies have demonstrated that demographic factors are risk factors for MMPRT, and the use of a paired design with similar demographic characteristics excluded the influence of confounding factors on the present study to some extent. Age has been found to be significantly associated with KLG [35, 36], which also explains the lack of a statistically significant difference in KLG and MMPRT between the two groups in this study. The evaluation of knee joint morphological structures was limited to Asian patients, as the data were only obtained from the Third Hospital of Hebei Medical University. From the perspective of racial differences, the applicability of the results to the full range of racial groups may be limited. Using healthy controls rather than patients with isolated lateral meniscus tears, together with diagnosis by the arthroscopic gold standard, may provide more accurate results. MRI and full-length films of the lower extremities were required for all patients, which undoubtedly increased the cost and time of the study, but also ensured that the study data were comprehensive and reliable.

Conclusions

Larger RMFPC, steeper MTSA, and smaller MTPD and HKA were all associated with MMPRT and were all risk factors for MMPRT. And RMFPC≥16.8 mm was determined to be an important risk factor for MMPRT, which is of great importance for reducing the underdiagnosis of MMPRT and for intervention in high-risk groups.

Abbreviations

MMPRT	Medial meniscus posterior root tears
BMI	Body mass index
MRI	Magnetic resonance imaging
KLG	Kellgren-Lawrence grade
PSM	propensity score matching
HKA	Hip-knee-ankle angle
MTSA	Medial tibial slope angle
RMFPC	Radius of medial femoral posterior condyle circle
MTPD	Medial tibial plateau depth
ROC	Receiver operating characteristic
CI	Confidence intervals
AUC	Area under curve
ICC	Intraclass correlation coefficient
OR	Odds ratio

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Author contributions
The study was designed and conceptualized by JW and SG. Material preparation and data measurement were performed by JW, JG, and KP. The statistical analysis of data done by JW. The first version of the manuscript was written by JW. As the corresponding author, SG provided support for the study, made revisions to the manuscript, and gave approval to the final version. The submitted version was read and approved by all authors.

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Data availability
Full access to all raw data and materials throughout the study is available from the first author. (Junsen Wang, Junsen-Wang2019@outlook.com).

Declarations

Ethics approval and consent to participate
The Ethics Committee of the Third Hospital of Hebei Medical University approved this retrospective study in accordance with the Declaration of Helsinki. The data collected in this study were obtained with informed consent from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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