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Quantitative evaluation of postoperative status after meniscal repair using synthetic magnetic resonance imaging

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Abstract

Background Surgical treatment is the primary modality for meniscal tears, and assessment of recovery after meniscal surgery is important in the development of a patient's treatment plan. Synthetic MRI (SyMRI) can simultaneously provide an objective assessment of meniscal changes and contrast-weighted images for subjective evaluation. This study aimed to assess whether SyMRI, utilizing both qualitative and quantitative mapping, could accurately evaluate postoperative recovery status, using Lysholm scores as a reference.

Methods From July to November 2022, 49 patients undergoing arthroscopic meniscus tear repair were enrolled. Each underwent conventional MRI and sagittal SyMRI on a 3.0 T scanner preoperatively, and at 6 and 12 months postoperatively. All patients completed the Lysholm form before MRI. Twenty-seven patients completed all MRI sessions. Meniscal T1 and T2 relaxation times, as well as proton density (PD) values, were measured. One-way ANOVA assessed changes over time, while Pearson and Spearman correlation analyses evaluated associations with Lysholm scores and Stoller grades, respectively.

Results Only T2 relaxation times demonstrated significant differences across time points ($P < 0.001$). T2 relaxation times negatively correlated with Lysholm scores ($r = -0.772$, $P < 0.001$), while T1 relaxation times and PD values showed no significant correlations. Stoller grade also showed a significant negative correlation with Lysholm scores ($r = -0.409$, $P < 0.001$).

Conclusions SyMRI-derived T2 relaxation time may serve as a quantitative biomarker for assessing postoperative meniscal healing. By enabling the acquisition of multiple MRI parameters in a single, time-efficient scan, SyMRI offers a noninvasive and practical tool for evaluating postoperative meniscal status and guiding clinical decision-making.

Keywords Meniscus, Synthetic MRI, Quantitative MRI, MRI

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Introduction

The meniscus consists of the extracellular matrix (ECM), primarily composed of water and collagen [1]. Its primary function is to distribute the load across the knee joint by increasing congruency, thereby diminishing stress on the articular cartilage [2]. Additionally, the meniscus also plays secondary roles in shock absorption, stability, lubrication and proprioception of the knee joint [3, 4].

The meniscus injury commonly leads to knee joint pain, with an annual incidence of 60–70/100,000 [5]. These tears typically result from a combination of axial and rotational forces, leading to shear loads on the meniscus [6]. Treatment options for meniscal tears include total meniscectomy, meniscus repair, and non-operative approaches. However, total meniscectomy can expedite the onset of osteoarthritis [7, 8]. Young patients with meniscus tear often undergo meniscus repair to prevent osteoarthritis and restore mobility more effectively [9]. Not only does meniscal repair lead to improved clinical outcomes, but it also entails lower economic costs when compared with total meniscectomy or non-operative treatment [10, 11].

Second-look arthroscopy serves as the gold standard for assessing postoperative status following meniscal repair [12]. However, its invasive nature limits its use for postoperative follow-up. Magnetic resonance imaging (MRI) is a valuable diagnostic tool for meniscal tears, with reported diagnostic accuracy ranging from 88 to 92% [13]. While MRI is commonly utilized for analyzing menisci and articular cartilage non-invasively [13–16], its sensitivity and specificity in evaluating meniscal degeneration and meniscus postoperative status are relatively lower than magnetic resonance (MR) arthrography [17, 18]. Ciliz et al. [19] investigated 37 patients with prior meniscal surgery. Direct MR arthrography was found superior to conventional MRI in diagnosing recurrent meniscus tears, albeit requiring contrast material injection into the knee joint cavity [20, 21]. Indirect MR arthrography demonstrates enhanced accuracy, sensitivity, and specificity than conventional MRI for diagnosing recurrent meniscal tears [22]. However, it may also amplify signals from tissues both inside and outside the joint, potentially leading to false-positive diagnoses. Quantitative magnetic resonance imaging (qMRI) has emerged as a valuable tool for assessing tissue integrity and biochemical changes in musculoskeletal structures, including the meniscus. Techniques such as T2, T2*, and T1 mapping have been applied to evaluate meniscal degeneration, subclinical injury, and healing status. For instance, T2*-mapping at 7 T has demonstrated sensitivity in detecting intrasubstance degeneration in patients with posterior root tears [23], while T2 mapping has been shown to reflect meniscal healing after repair [24]. Additionally, MR relaxation times have correlated with histopathological findings in degenerated menisci [25], and ultra-short echo time (UTE)—T2* mapping has revealed subclinical meniscal injuries following ACL tears [26]. Despite the growing utility of these conventional qMRI techniques, their clinical application remains limited by relatively long acquisition times and the need for multiple pulse sequences.

Synthetic magnetic resonance imaging (SyMRI) technology utilizes a single scan employing multiple dynamic multiple echo (MDME), enabling the reconstruction of images with various contrasts [27]. Although SyMRI has been increasingly adopted for neuroimaging, its applications in the musculoskeletal system are still emerging. Recent studies have demonstrated its feasibility in evaluating osteoporosis [28], optimization of shoulder soft-tissue contrast [29], and synovitis [30]. In the context of meniscal imaging, our previous study demonstrated the utility of SyMRI for quantitatively evaluating meniscal injury at the time of diagnosis [31]. Additionally, Lee et al. reported the use of SyMRI for identifying meniscal tears with promising diagnostic performance [32]. However, no studies to date have explored the use of SyMRI in monitoring postoperative meniscal healing. Boudabbous et al. [33] observed a high concordance between SyMRI and conventional MRI in diagnosing knee joint diseases. SyMRI can quantify the T1, T2 relaxation time and PD of the tissue simultaneously, providing an objective assessment of meniscal changes and contrast-weighted images for subjective evaluation. In contrast, traditional qMRI methods—such as T2 mapping or UTE imaging—typically require separate sequences for each quantitative parameter, often with longer acquisition times and more complex reconstruction algorithms [26]. Moreover, UTE is specifically designed to capture tissues with very short T2 values, such as cortical bone or fibrocartilage, but it requires specialized hardware and expertise, limiting its widespread clinical use. In contrast, SyMRI offers a more standardized and time-efficient approach suitable for routine postoperative evaluation.

In this study, both SyMRI and conventional MRI were utilized in patients undergoing meniscus repair preoperatively, 6 months and 1 year postoperatively. Using Lysholm scores as a reference [34] to evaluate postoperative recovery status, our study aimed to explore whether the SyMRI, including qualitative and quantitative maps, could accurately evaluate the postoperative condition of patients.

Materials and methods

Patients

The study, approved by the hospital ethics committee (KY-2022-45), obtained informed consent from all

participants. Patients requiring arthroscopic surgery at the Department of Bone, Joint and Sports Medicine of the First Affiliated Hospital of Jinan University from July 2022 to November 2022 were consecutively collected. Inclusion criteria comprised individuals aged 18 to 50 years presenting with recent knee pain or discomfort, whose meniscal tears were confirmed during subsequent arthroscopic surgery. The positive indicators of knee discomfort included positive McMurray' test, Lachman test and inverse Lachman test results. Exclusion criteria included a history of knee surgery (excluding the current arthroscopic meniscal repair), inability to cooperate with MR scans, and comorbidities such as rheumatoid arthritis, gout, or ankylosing spondylitis, and patients with other intra-articular injuries. Each patient completed the Lysholm scale prior to MR scans. Additionally, to establish normative reference values, 20 healthy subjects without any history of knee pathology or trauma were recruited, and quantitative SyMRI measurements (T1, T2 relaxation time and PD value) of the medial and lateral menisci were obtained. These values were used as external controls to compare with the patient cohort and evaluate deviations related to meniscal injury and postoperative changes. Meniscal repairs were performed by experienced orthopedic surgeons using either all-inside or outside-in techniques, selected based on tear location and morphology. All-inside repairs were conducted using FAST-FIX 360 Meniscal Repair System (Smith & Nephew), while outside-in repairs were secured with non-absorbable sutures tied over the joint capsule. No inside-out techniques or hardware-based anchors were used. All patients followed a standardized rehabilitation protocol that included partial weight-bearing with brace support for 4 weeks, followed by progressive range-of-motion and strength training. Rehabilitation compliance was monitored through clinical follow-up and physiotherapist reports, although no quantitative compliance metrics were recorded.

MRI protocol

All subjects scanned with a 3.0-T MRI system (Signa Premier, GE Healthcare, Waukesha, WI) preoperatively, as well as at 6 months and 1 year postoperatively. The knee joint of each subject was centered in a 16-channel surface flexible coil. Each subject was placed in the supine position with the feet advanced and the lower limbs naturally extended, and the positioning line was placed on the lower edge of the patella.

Conventional fat-suppressed two-dimensional (2D) sagittal T1-weighted images (T1WI) were acquired using the following imaging parameters: TR, 484 ms; TE, 9.5 ms; FOV, 160 ×160 mm; image matrix, 320 ×224; slice thickness, 3.5 mm; and gap, 0.5 mm. The image acquisition time was 1 min 52 s. Conventional fat-suppressed two-dimensional (2D) sagittal PD-weighted images (PDWI-FS) were acquired using the following imaging parameters: TR, 2600 ms; TE, 30 ms; FOV, 160 ×160 mm; image matrix, 320 ×224; slice thickness, 2.5 mm; and gap, 0.5 mm. The image acquisition time was 2 min 2 s. Conventional fat-suppressed two-dimensional (2D) sagittal T2-weighted images (T2WI) were acquired using the following imaging parameters: TR, 3471 ms; TE, 68 ms; FOV, 160 ×160 mm; image matrix, 320 ×224; slice thickness, 3.5 mm; and gap, 0.5 mm. The image acquisition time was 1 min 44 s. Conventional two-dimensional (2D) coronal PDWI-FS were acquired using the following imaging parameters: TR, 2514 ms; TE, 42 ms; FOV, 160 ×160 mm; image matrix, 320 ×208; slice thickness, 2.5 mm; and gap, 0.5 mm. The image acquisition time was 1 min 46 s. A MDME sequence was performed using the following imaging parameters in a sagittal orientation for SyMRI: TR, 4000 ms; TE, 15.6 ms; FOV, 160 ×160 mm; image matrix, 200 ×200; slice thickness, 2.5 mm; and gap, 0.5 mm. The image acquisition time was 5 min 4 s.

MRI analysis

SyMRI underwent post-processing on the main scanning console, automatically generating T1WI, T2WI, PDWI, T1 mapping, T2 mapping and PD mapping. Sagittal and coronal PDWI-FS images were used to identify the optimal planes showing meniscal signal abnormalities. The region of interest (ROI) was then confirmed on the sagittal SyMRI-derived pseudo-color maps corresponding to these areas. The ROI was manually delineated on the synthetic T2 mapping, with measurements of T1, T2 relaxation time, and PD value of the abnormal meniscal signal. The principles of ROI delineation were as follows: (1) the ROI area was approximately $3mm^2$, corresponding to roughly 20–30 pixels; (2) the ROI was positioned on areas of high signal intensity on synthetic T2 mapping within the meniscus, avoiding joint fluid and interference from the transverse ligament of the knee. In cases of bucket-handle tears, ROIs were placed in the displaced but identifiable meniscal fragment, and matched postoperatively using anatomical landmarks; (3) ROI was measured 3 times and the average value was recorded (Fig. 1A). To ensure measurement consistency, all assessments were performed by the same experienced radiologist. The ROI location remained consistent preoperatively, at 6 months, and at 1 year postoperatively. To ensure consistency and reproducibility in ROI selection, all quantitative measurements were performed after the completion of all three imaging timepoints, allowing side-by-side comparison to match ROI locations across scans. To assess inter-rater reliability, two experienced

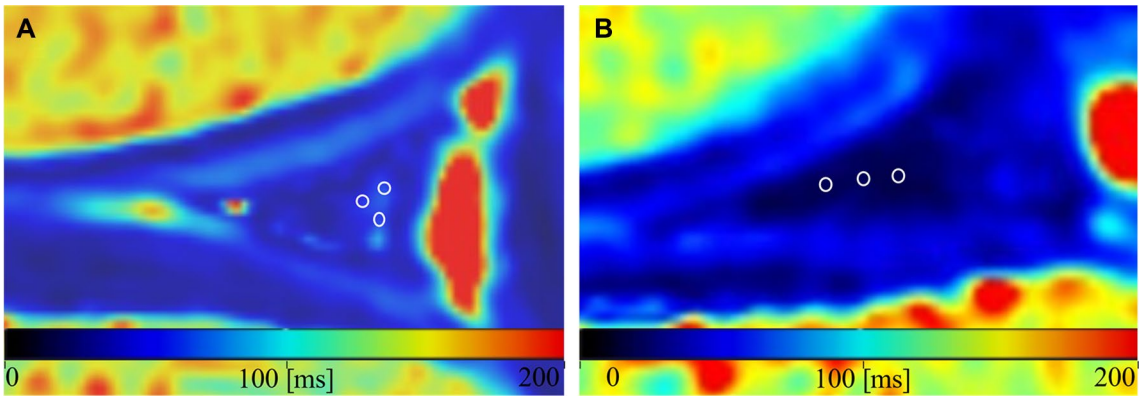

Fig. 1 **A** The location of ROIs on the patients with meniscus; **B** the location of ROIs on the normal subjects with meniscus

musculoskeletal radiologists independently performed ROI delineation on 20 randomly selected knees. T1, T2 relaxation time and PD values obtained by the two raters were compared. Each measurement was repeated three times by the same observer, and the mean value was used. In addition, ROIs were randomly placed on the four menisci of healthy subjects and averaged (Fig. 1B). At the same time, we performed Stoller grade of the meniscus on conventional MRI of all patients, and all evaluations were performed by the same experienced radiologist.

Statistics analysis

Statistical analysis was performed using SPSS 14.0 (Chicago, IL). The intraclass correlation coefficient (ICC) was calculated to assess the inter-rater reliability of the repeated measurements. The normality of quantitative data was assessed using the Shapiro–Wilk test. As all variables met the assumption of normality, results are presented as mean ± standard deviation and analyzed using one-way analysis of variance (ANOVA). For multiple comparisons of T1, T2 relaxation time and PD values, Bonferroni correction was applied to adjust the significance level. Pearson correlation analysis was conducted to evaluate the relationship between each measurement and Lysholm score. Spearman correlation analysis was conducted to evaluate the relationship between Stoller grade and Lysholm score. Statistical differences were considered significant at $P < 0.05$.

Results

The ICCs for T1, T2 relaxation time and PD values were 0.894 (95% CI 0.792–0.945), 0.918 (95% CI 0.834–0.961), and 0.903 (95% CI 0.802–0.943), respectively. Based on standard criteria, these indicate good agreement for T1 and excellent agreement for T2 and PD.

In this study, we assessed the T1, T2 relaxation time and PD values of the anterior and posterior horns of the medial and lateral menisci in 20 normal subjects. The results revealed no statistically significant differences in these parameters among the four regions ($P > 0.05$) (Table 1). The mean ± standard deviation value for T1, T2 relaxation time and PD values were 905.59 ± 282.54 (ms), 32.81 ± 2.51 (ms) and 36.04 ± 6.99 (pu).

This study included 49 patients with meniscus injuries and 20 healthy volunteers. Among them, 27 patients completed three MR examinations each, while the remaining 22 patients did not complete all follow-up examinations due to various reasons. The patient cohort consisted of 20 males and 7 females, with a mean age of 30.78 years (range, 18–45 years). Arthroscopic assessment revealed 12 cases of medial meniscus tears and 15 cases of lateral meniscus tears.

Regarding tear types among patients who underwent arthroscopic surgery, there were 14 cases of longitudinal tears, 8 cases of horizontal tears, 3 cases of complex tears, and 2 cases of bucket-handle tears. The T1 relaxation time and PD values measured by SyMRI at

Table 1 The T1, T2 relaxation time and PD value of normal subjects

Parameters	AH of MM	PH of MM	AH of LM	PH of LM	*F*	*P*
T1	910.53 ± 286.90	924.07 ± 231.80	855.20 ± 308.54	932.57 ± 311.21	0.295	0.829
T2	33.67 ± 1.94	32.18 ± 2.39	32.13 ± 2.66	33.25 ± 2.79	1.946	0.129
PD	37.10 ± 9.17	37.48 ± 4.39	33.86 ± 6.56	35.71 ± 6.96	1.101	0.354

MM medial meniscus, *LM* lateral meniscus, *AH* anterior horn, *PH* posterior horn, *T1* (ms), *T2* (ms), *PD* (pu), *F* the ratio of between-group mean square to within-group mean square

6 months and 1-year post-operation did not exhibit statistically significant differences compared to pre-operation values. However, the T2 relaxation time measured by SyMRI at 6 months and 1-year post-operation showed significant differences compared to pre-operative values ($P < 0.001$) (Table 2 and Fig. 2).

The injured menisci underwent suturing by orthopedic surgeons, with patients scheduled for reexamination at 6 months and 1-year post-operation. Lysholm scores demonstrated a gradual increase over time, with statistically significant differences observed ($P < 0.01$), Specifically, scores were 57.30 ± 9.58, 81.63 ± 11.61, and 90.85 ± 7.23 at the three time points, respectively. The was no significant correlation between T1 relaxation time or PD value and Lysholm scores (Fig. 3A, C). However, a statistically significant strong positive correlation was observed between T2 relaxation time of the menisci and Lysholm scores (Fig. 3B). There was also a statistically significant moderate negative correlation between Stoller grade of meniscus and Lysholm scores (Fig. 3D).

Imaging analysis

The pseudo-color map is a representation formed by employing multiple echo spin images and coding, resulting in a halftone image depicting measured values. Upon comparing with PDWI-FS and pseudo-color maps, we observed that synthetic T1 mapping and T2 mapping displayed a color spectrum ranging from green to red, indicating meniscal degeneration or tear (Fig. 4). Over time, the abnormal signal range in the T2 map gradually decreased, accompanied by a gradual reduction in signal intensity, suggesting potential meniscal recovery. Synthetic T1 mapping and synthetic T2 mapping of the normal meniscus exhibited a relatively uniform dark blue color.

Discussion

The study aimed to explore whether SyMRI can non-invasively and accurately assess postoperative status following meniscal repair. Our findings suggested that improvements in postoperative outcomes among patients undergoing meniscal repair were associated with a reduction in abnormal signal intensity at the site of meniscal injury and a gradual decrease in T2 relaxation time measured

Table 2 The T1, T2 relaxation time and PD value of 3 groups

Parameters	Pre-operation	6 months After operation	12 months After operation	*F*	*P*
T1	1134.89 ± 485.67	1054.26 ± 365.43	1191.33 ± 510.56	0.610	0.546
T2	56.56 ± 2.99	47.00 ± 2.69	39.30 ± 3.69	203.329	< 0.001
PD	42.02 ± 16.76	35.85 ± 14.23	38.07 ± 14.98	1.118	0.332

T1 (ms), *T2* (ms), *PD* (pu), *F* the ratio of between-group mean square to within-group mean square

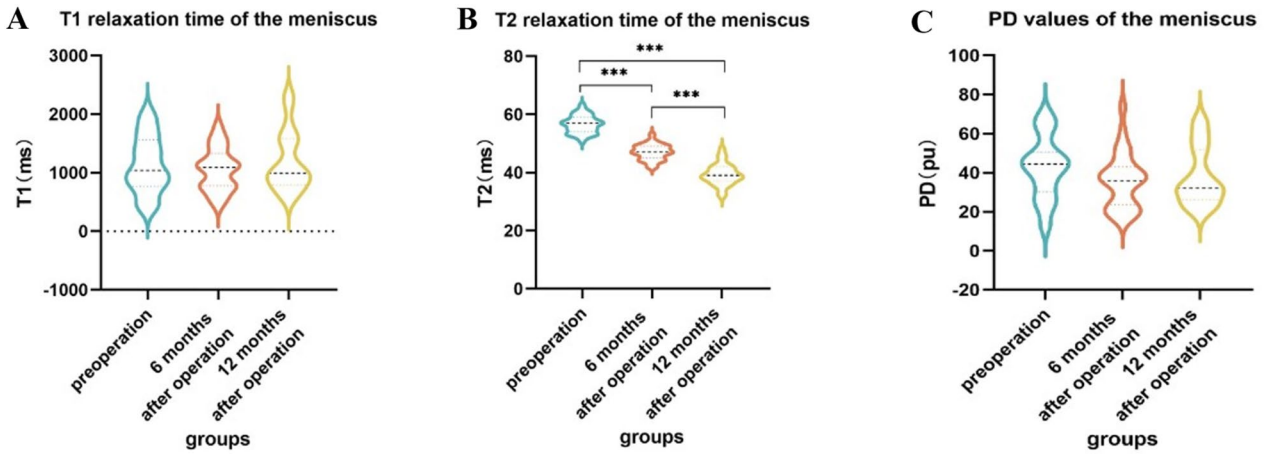

Fig. 2 The T1, T2 relaxation time and PD values among the preoperative group, 6 months postoperative group and 12 months postoperative group were analyzed. **A** There was no significant difference in T1 relaxation time measured by SyMRI among the 3 groups ($P = 0.546$). **B** The difference in T2 relaxation time was statistically significant ($P < 0.001$). **C** There was no significant difference in PD values measured by SyMRI among the 3 groups ($P = 0.332$)

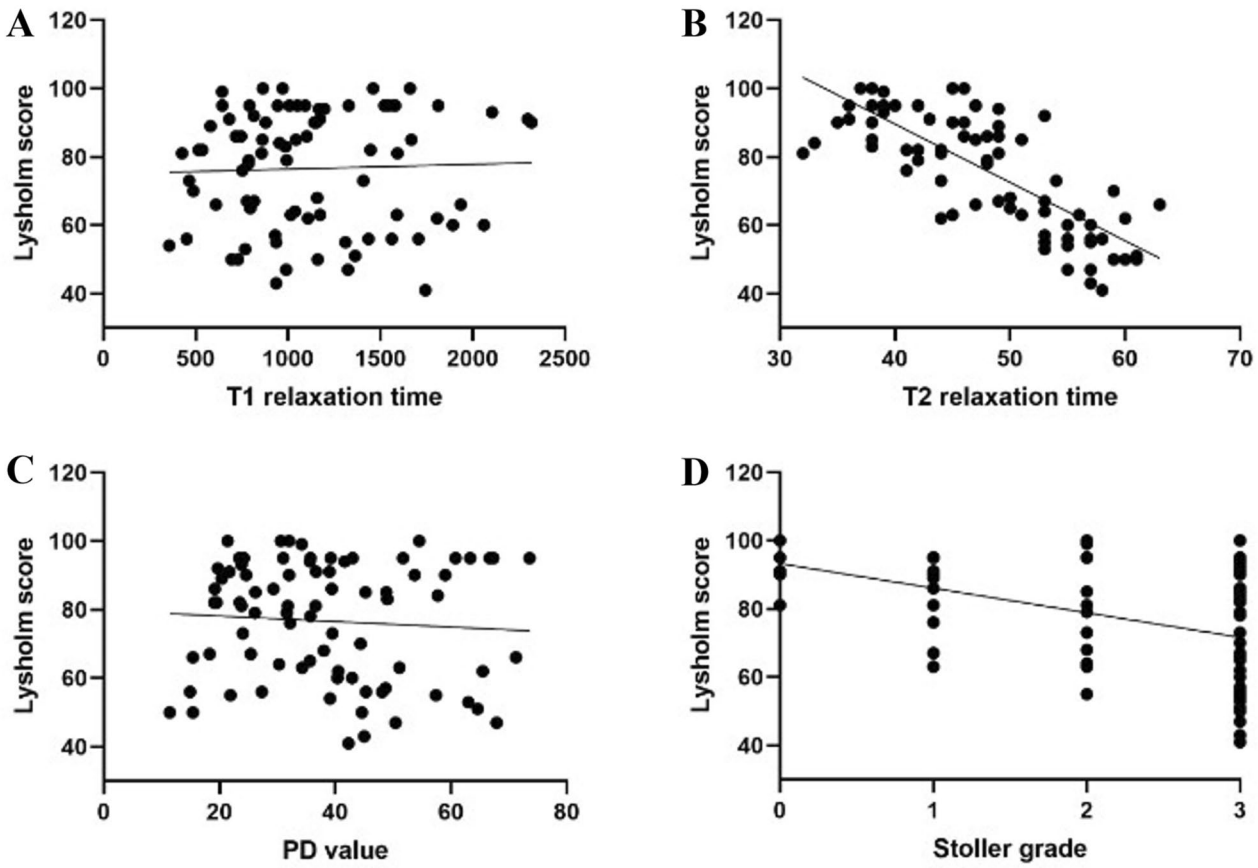

Fig. 3 The correlation between Lysholm scores and T1, T2 relaxation time, PD values or Stoller grade, respectively. **A** There is no correlation between T1 relaxation time of meniscus and Lysholm scores ($P = 0.739$). **B** The correlation between T2 relaxation time of meniscus and Lysholm scores was statistically significant strong positive ($r = -0.772$, $P < 0.001$). **C** There is no correlation between PD values of meniscus and Lysholm scores ($P = 0.522$). **D** The correlation between Stoller grade of meniscus and Lysholm scores was statistically significant moderate negative ($r = -0.409$, $P < 0.001$)

by SyMRI. These results indicated that T2 relaxation time of SyMRI could accurately reflect meniscal changes and correlated well with clinical manifestations.

The assessment of postoperative meniscal condition, whether through resection or repair, is a prominent area of research. Current methods for analyzing postoperative meniscal status include clinical evaluation, MRI, MR arthrography and second-look arthroscopy [12]. Clinical evaluation typically involves medical history and physical examination, often utilizing scoring systems such as the Lysholm score, IKDC score, KOSS score, Tegner score, among others [34]. However, these methods are relatively subjective. While second-look arthroscopy is considered the gold standard for postoperative meniscal assessment [12], it is invasive and carries the risk of patient injury. SyMRI has the potential to be integrated into standard knee imaging protocols, primarily due to its ability to generate multiple quantitative maps and synthetic contrast-weighted images from a single acquisition. This capability can significantly streamline the imaging workflow by reducing the number of sequences required. The total acquisition time for SyMRI is approximately 5–6 min, which is shorter or comparable to conventional protocols that require multiple separate scans for quantitative assessment. Moreover, the automated post-processing of SyMRI is relatively efficient, which may further improve clinical workflow. From a cost perspective, although initial implementation may require investment in software and training, the reduction in scan time and increased data yield per session could offset these costs over time. Thus, SyMRI offers a promising alternative for quantitative assessment of postoperative knees, especially in settings prioritizing efficiency and comprehensive tissue evaluation.

Patients who underwent meniscus repair were followed up at 6 months and 1 year, with a total of 27 patients returning to our hospital for follow-up. The clinicians observed significant improvement in

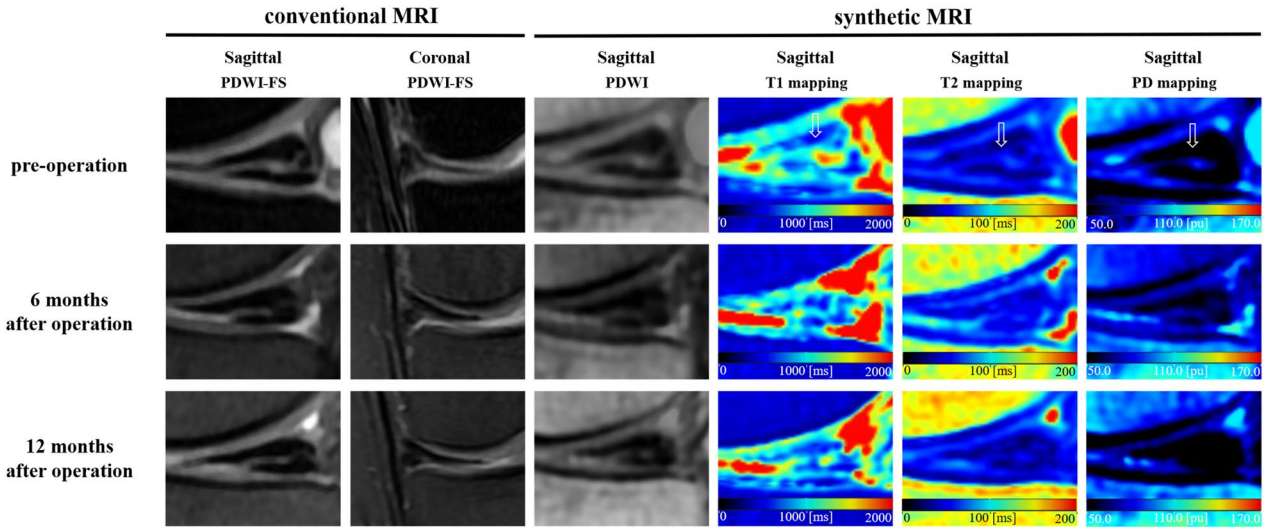

Fig. 4 A 30-year-old male subject with posterior horn of the medial meniscus of left knee joint. Lysholm scores at the three time points, respectively, were 47, 65 and 94. The highest signal intensity of the meniscus was slightly reduced but not significantly different on conventional MRI, which did not correspond to changes in Lysholm scores. The T2 relaxation time of the meniscus, respectively, at the three time points were 57, 50 and 39 (ms) and they shortened significantly, indicating the meniscus was gradually recovering, which was consistent with changes in Lysholm scores. An oval T2WI high-signal cyst is seen posterior to the posterior horn of the medial meniscus

postoperative clinical symptoms compared to pre-surgery. In our study, Lysholm scores showed a gradual increase at the three time points, with statistically significant differences, indicating that Lysholm scores accurately reflected the postoperative condition of the patients.

MRI plays a crucial role in diagnosing meniscal injuries. It could also document surgical complications, reinjury, and other sources of symptoms, as well as evaluate recurrent or residual symptoms post-operation [35–37]. Various MRI findings, such as linear fluid intensity signals extending to the articular surface on PDWI or abnormal meniscus morphology inconsistent with the postoperative state, may indicate poor healing or re-tear of the meniscus [18]. However, studies have shown that post-meniscus repair, increased signal intensity at the contact articular surface, may be due to fibrovascular or granulation tissue [38, 39]. Consequently, high signal intensity at the meniscus repair site in conventional MRI may not accurately distinguish between meniscal healing and re-tear. Quantitative MRI can objectively quantify tissue relaxation time, offering insights into water content, composition, and collagen fiber anisotropy [40–43]. For instance, T2 relaxation time derived from T2 mapping could quantify changes in water content and collagen fiber composition [40]. T1ρ and T2 values can non-invasively assess the extracellular matrix of articular cartilage, with T1ρ value being more sensitive to proteoglycan content and T2 value reflecting collagen orientation and water content [41]. dGEMRIC effectively quantifies GAG distribution, enabling early detection of cartilage degeneration in osteoarthritis [43].

One-way ANOVA was employed to analyze the T1, T2 relaxation time and PD value of the same meniscal injury site at three time points. Significant differences were observed in T2 relaxation time ($P < 0.001$), indicating postoperative meniscal shortening, suggestive of reduced water content, increased proteoglycan concentration, and restoration of collagen content and network integrity, thus indicating a gradual attenuation of the inflammatory response [44–46]. As depicted in Fig. 4, preoperative conventional MRI revealed a linear high signal intensity on PDWI-FS extending to the articular surface in the posterior horn of the lateral meniscus, indicating a meniscus tear. After surgical suture, high signal intensity on PDWI persisted at the injury site, potentially leading to radiologist interpretation of recurrent tear or nonunion. Persistence of meniscal abnormal signals on synthetic PDWI was also observed. Synthetic T2 mapping demonstrated a wider range of high signal intensity at 6 months post-operation, but the T2 relaxation time was lower compared to pre-surgery. Subsequent to 12 months post-surgery, the high signal intensity on synthetic T2 mapping significantly diminished, with further reduction in T2 relaxation time. Additionally, changes in T2 relaxation time were consistent with Lysholm scores, suggesting that T2 relaxation time accurately reflected meniscal repair in patients recovering postoperatively. Several previous studies have explored the use

of quantitative MRI for evaluating meniscal injury and repair, particularly using T2 mapping and T1 mapping. Yamasaki et al. [24] reported T2 relaxation times of 31.7 ± 3.4 ms in healed menisci, 32.8 ± 3.8 ms in incompletely or unhealed menisci, and 26.9 ± 2.2 ms in healthy controls following meniscal repair. In our study, the T2 values observed in injured menisci were slightly higher than those reported by Yamasaki, which may be due to differences in MR field strength, imaging protocols, postoperative time points, and sample characteristics. Similarly, studies such as those by Kajabi et al. [23] and Einarsson et al. [25] have demonstrated that quantitative T2* and T1 mapping techniques are also capable of detecting subclinical or early degenerative changes in the meniscus. Although T1 relaxation time can reflect interstitial water content [47] and is sometimes used in conjunction with other techniques like dGEMRIC and T2 mapping, it is not yet established as a primary biomarker for early cartilage degeneration [42, 48]. In Li et al. [49] study, the lack of significant T1 differences between groups may highlight its limited sensitivity for detecting subtle cartilage changes. Similarly, PD values, which represent free water content [50], may have limited utility in this context, but it always seems to be meaningless in terms of the musculoskeletal system.

The presence of high signal intensity on conventional T2WI helps in diagnosing meniscal changes; however, increased signal intensity on postoperative T2WI lacks specificity in diagnosing recurrent meniscal tears. This is attributed to potential meniscus scarring within 1 year postoperatively, leading to false-positive diagnoses [51]. In addition, short TE signal extending to the articular surface of the meniscus after surgery could also be considered as normal findings. Nevertheless, as meniscus recovery progresses, abnormal signal intensity gradually diminishes in depth, length, and scope, with some young patients even returning to a normal state [52]. Because of only a 1-year follow-up period, T2 relaxation times in some postoperative patients with partial meniscus repair did not revert to normal levels. This finding is consistent with previous studies, which have reported that even clinically healed menisci can exhibit persistently elevated T2 values at 1 year, suggesting incomplete biochemical recovery (Fig. 5). For example, Yamasaki et al. found higher T2 values in repaired menisci compared to normal controls at 1-year follow-up despite arthroscopic healing [24], and Schwach et al. similarly observed MRI signal abnormalities in some patients at 1-year post-repair [53]. However, in patients exhibiting good meniscal recovery, T2 relaxation time returned to normal levels, consistent with our findings. Although the abnormal signal intensity range may widen, a corresponding reduction in T2 relaxation time on synthetic T2 mapping diagrams indicated ongoing meniscal recovery. Although Stoller grading correlated with Lysholm scores, the correlation was weak ($r = -0.409$) and lower than the correlation between T2 relaxation time and Lysholm ($r = -0.772$). This suggests that the assessment efficiency of SyMRI in postoperative meniscal states may surpass that of conventional MRI. Interestingly, although changes in SyMRI-derived T2 values were observed postoperatively, corresponding improvements in Lysholm scores were not

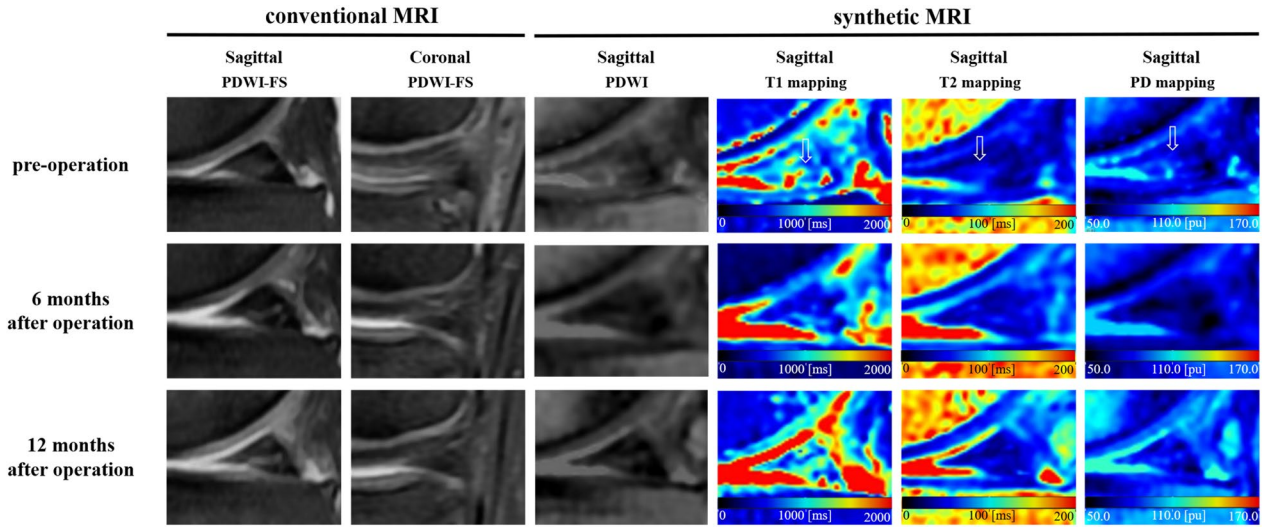

Fig. 5 A 32-year-old male subject with posterior horn of the medial meniscus of right knee joint. Lysholm scores at the three time points, respectively, were 52, 76 and 63. The highest signal intensity of the meniscus was not significant change on conventional MRI, which did not correspond to changes in Lysholm scores. The T2 relaxation time of the meniscus, respectively, at the three time points were 51, 47 and 54 (ms), indicating the meniscus was poor healing, which was consistent with changes in Lysholm scores

always statistically significant. This may indicate a potential temporal lag between biological or structural healing detectable by quantitative MRI and symptom resolution perceived by the patient. Previous imaging studies have similarly suggested that tissue-level recovery may outpace functional or symptomatic recovery in musculoskeletal injuries [54]. This underscores the potential of SyMRI as a sensitive tool for detecting subclinical healing and monitoring tissue changes before symptom improvement becomes evident. Further prospective research is needed to validate the timing and clinical implications of such imaging changes. Additionally, we acknowledge that meniscal healing outcomes may be influenced by variability in surgical technique and postoperative rehabilitation adherence. Although we employed standardized repair methods and rehabilitation protocols, individual differences in technique application and patient compliance could have impacted both clinical (Lysholm scores) and imaging outcomes.

This study had several limitations. Firstly, although this study recorded the types of meniscal tears and the duration of symptoms prior to surgery, subgroup analysis based on tear morphology or chronicity was not performed due to the limited sample size. However, variations in tear type or chronicity may influence quantitative MRI parameters. Future studies with larger cohorts are warranted to explore these potential associations and better understand the relationship between tear characteristics and tissue composition on SyMRI. Although the use of healthy subjects provided standardized reference values, internal controls such as the contralateral or unaffected meniscal regions could potentially offer more individualized baselines. However, in our cohort, some patients exhibited bilateral or diffuse meniscal degeneration, limiting the reliability of such comparisons. This is a recognized limitation, and future studies with more selective patient inclusion criteria may allow for internal control analysis. Secondly, it was a single-center study, lacking data from other medical centers. Additionally, postoperative meniscal states and Lysholm scores may vary among patients with different conditions. Moreover, injuries to other tissues such as ligaments and cartilage may influence Lysholm scores. Variations in surgical techniques could also impact postoperative meniscal signal intensity. Furthermore, the study had a short follow-up period, potentially obscuring postoperative meniscal changes in some patients. Another limitation is that although all patients underwent standardized postoperative care, including routine physical therapy, detailed data on individualized rehabilitation plans or additional interventions during the follow-up period were not collected. Additionally, our correlation analysis between preoperative and postoperative meniscal T2 relaxation time and Lysholm scores lacked validation through second-look arthroscopy. This study utilized small, localized ROIs focused on regions of high signal intensity to minimize the influence of adjacent anatomical structures and partial volume effects. However, assessing the meniscus more globally—including regions without overt tearing—may provide insights into more subtle, diffuse tissue changes. Future studies may consider applying whole-meniscus segmentation or volumetric analysis to explore these broader alterations. In addition, SyMRI itself had limitations. Firstly, SyMRI is only scanned once, so it has high requirements for scan quality. Being a single-scan technique, it demands high-quality scans and is susceptible to motion artifacts, especially in elderly patients. This highlights the need for future studies to assess motion correction techniques or the development of faster acquisition strategies to mitigate these limitations. Secondly, synthetic STIR diagrams in SyMRI knee scans may exhibit local low signal-to-noise ratio and blood vessel pulsation artifacts, potentially affecting observations. Although Stoller grading in this study was performed using conventional MRI sequences, future studies could explore the diagnostic consistency between conventional and SyMRI-derived morphological images. Such analysis may help determine whether SyMRI-calculated sequences are interchangeable with conventional images in grading meniscal pathology, and whether any discrepancies influence the correlation with clinical outcomes.

Conclusion

In summary, this study suggests that SyMRI-derived T2 relaxation time may serve as a quantitative biomarker for evaluating postoperative meniscal healing. SyMRI enables the acquisition of multiple MRI in a single, time-efficient scan, offering a noninvasive tool for postoperative assessment. Such insights may provide valuable information and guidance for clinicians in identifying patients with postoperative meniscal conditions.

Abbreviations

ECM	Extracellular matrix
MRI	Magnetic resonance imaging
MR	Magnetic resonance
SyMRI	Synthetic magnetic resonance imaging
MDME	Multiple dynamic multiple echo
T1WI	T1-weighted image
PDWI-FS	Fat-suppressed sagittal PD-weighted image
TR	Repetition time
TE	Echo time
FOV	Field of view
T2WI	T2-weighted image
ROI	Region of interest

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Author contributions
Lingtao Zhang: data curation, formal analysis, investigation, project administration, software, visualization, writing—original draft, writing—review & editing. Yun Su: data curation, investigation, software, writing—review & editing. Wenfeng Mai: investigation, project administration, writing—review & editing. Xukai Mo: investigation, writing—review & editing. Xiubao Song: data curation, funding acquisition, writing—review & editing. Changzheng Shi: conceptualization, funding acquisition, methodology, writing—review & editing. All authors reviewed the manuscript.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The trial was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the ethics committee of the First Affiliated Hospital of Jinan University (KY-2022-45) and informed consent was taken from all individual participants.

Consent for publication
All authors approved the manuscript for publication.

Competing interests
The authors declare no competing interests.

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