Original Research

Sensitivity and Specificity of MRI in Diagnosing Concomitant Meniscal Injuries With Pediatric and Adolescent Acute ACL Tears

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Background: Preoperative diagnosis of concomitant meniscal tears in pediatric and adolescent patients with acute anterior cruciate ligament (ACL) deficiency is challenging.

Purpose: To investigate the diagnostic performance of magnetic resonance imaging (MRI) in detecting meniscal injuries for pediatric and adolescent patients with acute ACL tears.

Study Design: Cohort study (diagnosis); Level of evidence, 2.

Methods: The authors retrospectively identified patients aged ≤18 years who underwent acute ACL reconstruction between 2006 and 2018 at 2 tertiary academic hospitals. The primary outcomes were arthroscopically confirmed medial, lateral, or any (defined as medial and/or lateral) meniscal tears. To control for chronically deficient knees, patients must have received their MRI study within 4 weeks of injury and must have undergone surgery no more than 8 weeks after their MRI study. Preoperative MRI reports were compared with the gold standard of arthroscopically confirmed tears to calculate sensitivity, specificity, positive predictive value, and negative predictive value. In a secondary analysis, patients were stratified by age into 2 groups (≤13 or ≥14 years), body mass index-for-age data from the Centers for Disease Control were used to classify patients as obese or nonobese, and differences between sensitivity and specificity proportions were analyzed using chi-square test for homogeneity.

Results: Overall, 406 patients with a mean age of 15.4 years (range, 10-18 years) were identified. The sensitivity, specificity, positive predictive value, and negative predictive value were as follows: for lateral meniscal (LM) tears, 51.0%, 86.5%, 78.3%, and 65.0%; for medial meniscal tears, 83.2%, 80.6%, 62.3%, and 92.5%; and for any meniscal tear, 75.0%, 72.1%, 81.5%, and 63.8%, respectively. In the stratified analysis, MRI was less specific for the following diagnoses: any meniscal tear in patients aged ≤13 years (P = .048) and LM tears in obese patients (P = .020).

Conclusion: The diagnostic ability of MRI to predict meniscal injuries present at acute ACL reconstruction was moderate. Performance was poorest at the lateral meniscus, where MRI failed to detect 97 tears that were found arthroscopically. Specificity was significantly lower in younger patients for any meniscal tear and in obese patients for LM tears.

Keywords: pediatric; adolescent; meniscus; MRI; sensitivity; specificity

Magnetic resonance imaging (MRI) is one of the most used imaging modalities in evaluating intra-articular knee injuries. In the pediatric and adolescent population, the ability to detect meniscal tears using MRI varies from poor to excellent.[2,16,27,33,35,40,42] The highest measurements of sensitivity and specificity (ranging from 87.0% to 95.0%) have been reported in studies with small samples of anterior cruciate ligament (ACL)-deficient knees, making them difficult to generalize for the growing number of young patients with ACL injuries.[2,16,27,32,33,42] Further, significant differences in diagnostic accuracy have been observed among younger, immature populations.[27,34,35,40] Limitations that we perceived from published literature were the inclusion of patients with substantial delays between MRI and surgery (in 2 studies, this approached 1 year), as well as no differentiation between acute and chronic ACL-deficient knees.[16,38] As the incidence of ACL injuries has risen in this patient population in the last 20 years, the importance of

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accurately diagnosing meniscal pathology cannot be understated as ACL injuries are highly associated with concomitant meniscal tears.[11,12,40] In clinical practice, the implications affect informed consent, operative planning, and assigning postoperative rehabilitation protocols.

The purpose of this study was to investigate the diagnostic performance of MRI in detecting meniscal injuries for pediatric and adolescent patients with acute ACL tears. A secondary stratified analysis was conducted to compare sensitivity and specificity measurements between cohorts to determine whether differences existed across age groups or among obese patients.

METHODS

The patients in this study were incorporated retrospectively into an ACL registry that was maintained by 2 tertiary academic medical centers between 2006 and 2018. Included were patients undergoing ACL reconstruction (Current Procedural Terminology code 29888) who had no prior ipsilateral knee injury and who were aged ≤18 years at the time of surgery. To control for chronically unstable knees, patients could not have received their diagnostic MRI scan >4 weeks from their reported injury and must have undergone surgery within 8 weeks of their diagnostic MRI scan. Both cutoffs were chosen a priori, following the example of Church and Keating,[4] to limit our analyses to ACL tears without extensive chronicity. Demographic factors gathered for the registry included age, sex, and body mass index (BMI). The date of injury was reported by patients during their first encounter and collected from medical record review. Imaging and operative reports provided precise dates of MRI and surgery. The primary outcomes were any arthroscopically identified medial meniscal (MM) tears, lateral meniscal (LM) tears, and any meniscal tears (defined as a knee with a medial and/or lateral tear). Tears were recorded as positive regardless of whether they underwent any additional surgical intervention.

MRI Protocol

At tertiary hospital A, the standard MRI knee protocol over the course of the study period was proton density (PD)-weighted sequences with and without fat saturation. A T2-weighted fast-spin (FS) sequence was included as a replacement to PD in 1 plane, typically coronal. At tertiary hospital B, the standard MRI knee protocol over the course of the study period was also PD-weighted sequences with and without fat saturation. T2-weighted FS sequences were always taken in the coronal and the axial plane, and a T1-weighted FS coronal sequence was also taken. In composing the ACL registry, we determined the presence of a meniscal tear on MRI scan using the final radiology report.

Statistical Analysis

Data collected included age, sex, BMI, time interval from injury to MRI, and time interval from MRI to ACL reconstruction. For the primary outcomes, baseline characteristics were reported as a mean and SD or frequency and percentage. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated using MRI findings as a diagnostic tool and arthroscopy as the gold standard. Total true positive, true negative, false positive, and false negative results were reported separately for MM, LM, any meniscal tear, and no meniscal tear. Stratified analysis was conducted to compare sensitivity and specificity measurements at the medial, lateral, and any meniscus. Patients were age-stratified into 2 groups, those aged ≤13 years and those aged ≥14 years. BMI-for-age data from the Centers for Disease Control and Prevention were used to classify patients as obese (≥95th percentile) or nonobese.[3] Differences between sensitivity and specificity proportions were tested using the chi-square test for homogeneity. Statistical significance was set at $P < .05$. All statistics and calculations were conducted using SPSS Version 26.0 (IBM, Armonk, NY).

RESULTS

During the study period, 672 patients were identified (Figure 1). A total of 45 patients were missing a preoperative MRI study within their medical record and were excluded. While the date of MRI and surgery were reliable, occasionally patients did not remember their exact date of

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Ethical approval for this study was obtained from Geisinger Medical Center (reference No. 2018-0157).

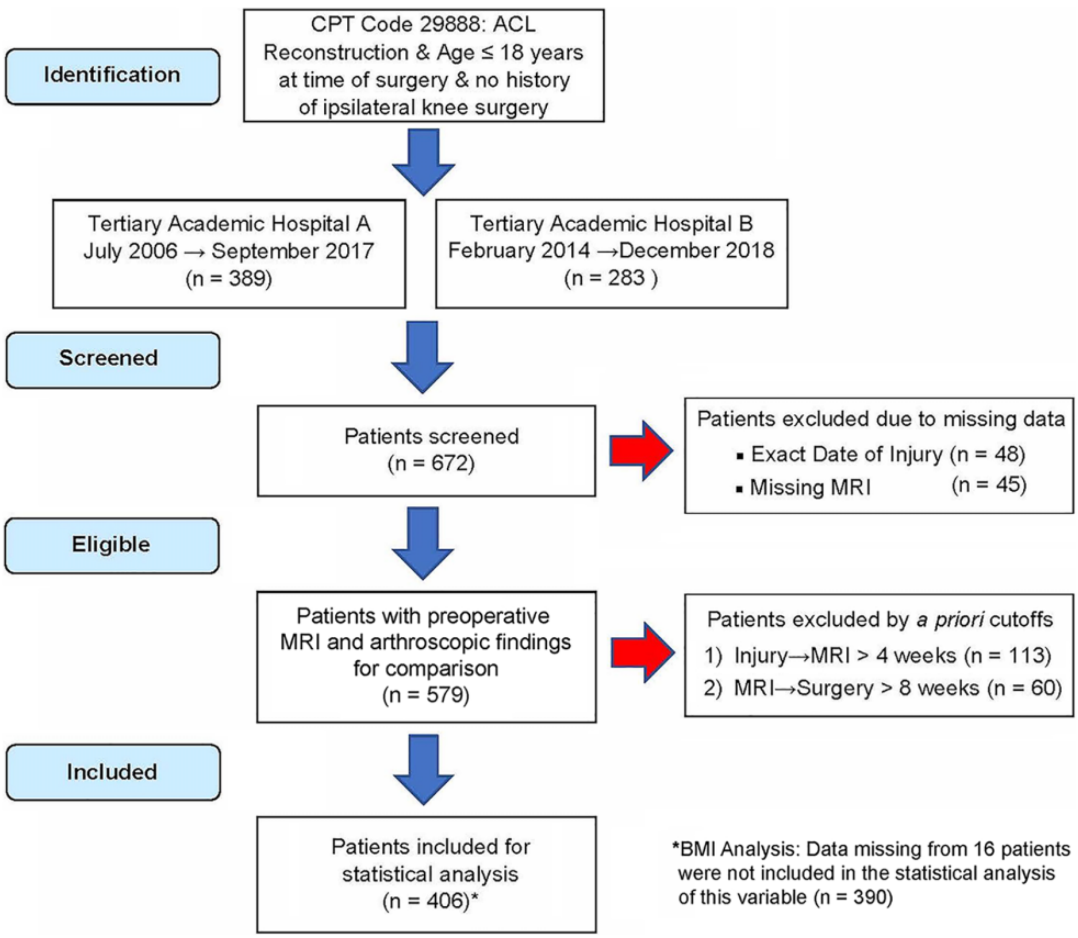

Figure 1. CONSORT (Consolidated Standards of Reporting Trials) flow diagram for patients included in the study. ACL, anterior cruciate ligament; BMI, body mass index; CPT, Current Procedural Terminology; MRI, magnetic resonance imaging.

injury. A total of 48 patients were excluded for this reason. A total of 113 patients were excluded because their delay from reported date of injury until MRI exceeded 4 weeks. In the ensuing step, 60 patients were further excluded because their delay from date of MRI until surgery exceeded 8 weeks. Of note, 16 patients were missing BMI data; when reporting statistics and analyses for this variable, we excluded these patients.

A total of 406 patients with a mean age of 15.4 ± 1.6 years (range, 10-18 years) were included. Females comprised 53.0% of patients. Of the 390 patients with BMI data, 66 (16.9%) were classified as obese. Hospital A contributed 257 (63.3%) patients, and hospital B contributed 149 (36.7%) patients. On average, patients received their MRI scan 1.3 ± 1.0 weeks after their reported injury (range, 0-4 weeks) and underwent surgery 3.8 ± 1.7 weeks after their MRI scan (range, 0-8 weeks). In total, the average time elapsed between injury and surgery for all patients was 5.0 ± 2.1 weeks (range, 0-12 weeks).

Most patients, 252 (62.1%), had at least 1 meniscal tear present at surgery. Of these tears, 198 were LM, 113 were MM, and 59 occurred bilaterally. Of the 198 LM tears, all but 6 received operative treatment, and, of the 113 MM tears, all but 1 received operative treatment. The age; frequencies of female patients and obese patients are reported for each primary outcome in Table 1. Sensitivity, specificity, PPV, and NPV are reported for each primary outcome.

Stratified analyses by age and obesity are presented in Table 2. Of note, 42 patients were aged ≤13 years at surgery, representing 10.3% of the study population. Obese patients comprised 16.9% of the study population (66 of 390 total patients with BMI data). Among age groups, MRI was less specific when used to detect any meniscal tear in patients aged ≤13 years relative to patients aged ≥14 years (54.5% vs 75.0%; $P = .048$). In obese patients, MRI was less specific when used to detect LM tears relative to nonobese patients (75.7% vs 89.8%; $P = .020$).

DISCUSSION

We reviewed 406 pediatric and adolescent patients undergoing ACL reconstruction to assess the diagnostic performance of MRI. Findings indicated that the sensitivity, specificity, PPV, and NPV, respectively, were as follows: for

TABLE 1
Primary Outcome Descriptive Data and MRI Diagnostic Performance[a]

	Any Meniscal Tear (n = 252)	No Meniscal Tear (n = 154)	Lateral Meniscus Tear (n = 198)	Medial Meniscal Tear (n = 113)
Age, y, mean ± SD	16.1 ± 1.5	15.7 ± 1.5	16.1 ± 1.4	16.1 ± 1.6
Female sex	117 (46.4)	98 (63.6)	82 (41.4)	64 (56.6)
Obese	41/236 (17.4)	25/154 (16.2)	29/187 (15.5)	21/104 (20.2)
Hospital A patients	113 (44.8)	144 (93.5)	95 (48.0)	33 (29.2)
Hospital B patients	139 (55.2)	10 (6.5)	103 (52.0)	80 (70.8)
MRI diagnostic performance				
True positive, n	189	—	101	94
False negative, n	63	—	97	19
False positive, n	—	43	28	57
True negative, n	—	111	180	236
Sensitivity, %	75.0	—	51.0	83.2
Specificity, %	72.1	—	86.5	80.6
PPV, %	81.5	—	78.3	62.3
NPV, %	63.8	—	65.0	92.5

[a]Data are reported as n (%) unless otherwise indicated. MRI, magnetic resonance imaging; NPV, negative predictive value; PPV, positive predictive value. Dashes indicate not applicable.

TABLE 2
Diagnostic Performance of MRI by Injury[a]

	Age			Body Mass Index		
	≤13 y	≥14 y	*P*	Obese	Nonobese	*P*
Sensitivity, %						
Any meniscal tear	80.0	74.6	.590	85.4	74.9	.149
Lateral meniscal tear	64.3	50.0	.303	62.1	53.1	.284
Medial meniscal tear	70.0	84.5	.243	85.7	84.3	.876
Specificity, %						
Any meniscal tear	54.5	75.0	**.048**	60.0	74.4	.141
Lateral meniscal tear	78.6	87.8	.184	75.7	89.8	**.020**
Medial meniscal tear	81.3	80.5	.915	82.2	80.1	.745

[a]Bolding indicates statistically significant difference between groups ($P < .05$). MRI, magnetic resonance imaging.

LM tears, 51.0%, 86.5%, 78.3%, and 65.0%; for MM tears, 83.2%, 80.6%, 62.3%, and 92.5%; and for any meniscal tear, 75.0%, 72.1%, 81.5%, and 63.8%. While this topic has been examined in previous papers, this study represents the largest cohort of pediatric and adolescent patients with acute ACL injuries and concomitant meniscal tears to date. In addition, cutoffs employed for the time elapsed from date of injury to date of MRI (4 weeks) and from date of MRI to date of surgery (8 weeks) prevented the inclusion of patients with chronic ACL deficiency. This is important because of the propensity for new meniscal tears (especially on the medial side) to occur before surgery, a trend that has been described extensively in recent literature.[1,6,21,31,37,38]

We found that the diagnostic ability of MRI to predict meniscal injuries present at ACL reconstruction was moderate. False-positive rates were higher for MM tears, while false-negative rates were higher for LM injuries. Perhaps most concerning, MRI failed to detect 97 LM tears that were later found arthroscopically. In patients aged ≤13 years, the ability of MRI to correctly detect no tear in any meniscus was significantly lower than the ability in their older counterparts. Likewise, in obese patients compared with their counterparts, the ability of MRI to correctly detect no LM tear was significantly lower.

MRI is an essential noninvasive test to assess intra-articular knee pathology.[14,41,47] In the pediatric and adolescent population, MRI is extremely reliable at assessing ACL injuries among patients with suspected intra-articular pathology.[27,33,42] Similar encouraging literature has been published documenting the ability of MRI to detect MM and LM injuries.[2,16,27,32-34,42] However, MRI is seemingly more reliable in detecting meniscal tears when these are in isolation than when associated with an ACL injury.[8,9,35,40] A 2014 study by Nam et al[36] examined traumatic meniscal lesions in adults and adolescents who had either an acute ACL tear or an intact ACL. The sensitivity for detecting LM and MM tears via MRI was significantly lower in the cohort with an acute ACL tear (70.2% MM, 71.4% LM) relative to patients without an acute ACL tear (94.0% MM, 82.1% LM).[36] In 2014, Gans et al[16] examined 178 pediatric and adolescent patients with various knee conditions. Likewise, in patients with >1 intra-articular lesion, meniscal tears were less likely to be diagnosed correctly using MRI.[16] Table 3 presents a comparison of study design parameters and diagnostic measurements across peer-reviewed literature. Studies are sorted in descending order based on the sample size of patients with ACL deficiency.

Multiple hypotheses have been presented as to why visualizing concomitant meniscal tears in patients with acute ACL injury on MRI scans still poses a diagnostic challenge. The subject of many previous studies has been

TABLE 3
Comparison of Similar Intra-Articular Diagnostic MRI Studies[a]

Lead Author (Year)	Sample Size[b]	Concomitant ACL Tear, n (%)[b]	Age, y[c]	Time From Injury to MRI, wk[c]	Time From MRI to Surgery, wk[c]	Diagnostic Performance of MRI: Any Meniscal Tear	Medial Meniscal Tear	Lateral Meniscal Tear
Present study	406	406 (100)	15.9 (10-18)	1.3 (0.0-4.0)	3.8 (0.1-8.0)	Sn: 75.0% Sp: 72.1%	Sn: 83.2% Sp: 80.6%	Sn: 51.0% Sp: 86.5%
Munger (2019)[35]	107	107 (100)	15 (7-18)	2.4 (0.1-74.6)	5.4 (0.4-12.4)	Sn: 62.3% Sp: 68.4%	NR	NR
Samora (2011)[40]	69	69 (100)	14.1 (12.7-16.1)	NR[d]	NR[d]	Sn: 58.7% Sp: 91.3%	NR	NR
Gans (2014)[16]	178	54 (30.3)	13.9	NR	6.4 (0-46.3)	NR	Sn: 87.5% Sp: 91.1%	Sn: 67.5% Sp: 94.9%
Schub (2012)[42]	119	47 (39.5)	16 (10-19)	NR	6.6 (0.1-52.3)	NR	Sn: 81.0% Sp: 90.9%	Sn: 68.8% Sp: 93.0%
Luhmann (2005)[32]	96	39 (40.6)	14.6 (7.3-18.7)	13 (2 wk-5 y)	NR	NR	Sn: 94.4% Sp: 91.0%	Sn: 88.9% Sp: 87.0%
Kocher (2001)[27]	118	32 (27.1)	12.6	NR	NR	NR	Sn: 79.3% Sp: 92.0%	Sn: 66.7% Sp: 82.8%
Major (2003)[33]	59	25 (42.4)	15 (11-17)	NR	NR	NR	Sn: 92.0% Sp: 87.0%	Sn: 93.0% Sp: 95.0%
Bouju (2011)[2]	69	21 (30.4)	13.3 (9-16)	33	8.3	Sn: 70.0% Sp: 81.0%	Sn: 75.0% Sp: 77.0%	Sn: 78.0% Sp: 69.0%

[a]ACL, anterior cruciate ligament; MRI, magnetic resonance imaging; NR, not reported; Sn, sensitivity; Sp, specificity.
[b]Presented in descending order by number of patients in study with concomitant ACL tear.
[c]Mean and range (if reported).
[d]Inclusion criteria were patients undergoing surgery within 3 months of injury.

the LM tear, where false-negative rates are consistently highest.[13,27,34,42] Tear locations, such as the posterior horn of the lateral meniscus, and oblique tear orientation have been the most difficult for imaging planes to visualize adequately.[7-9,23,30] However, no specific clinical characteristics such as patient age, injury mechanism, delay from injury to imaging, delay from imaging to surgery, or magnetic resonance sequence type are significantly associated with lowering false-negative rates at the lateral meniscus.[9,24,30]

Imaging pediatric and adolescent patients also present distinctive challenges, both in capturing and interpreting images. Motion artifact, patient pain tolerance, developmental maturity, and other underlying conditions have been presented as challenges with image acquisition.[20,39,45] In interpreting studies, training background and experience have correlated with higher interpreting reliability among radiologists in 1 study yet yielded no significant difference in another.[25,46] One of the elements cited most often as influencing study interpretation is the underlying anatomical variations among pediatric and adolescent patients. Specifically, the increased vascularity in the preadolescent meniscus and its effect on imaging has been thoroughly described.[5,15,16,26,27,32,41,47] Furthermore, a high signal in the meniscus has been observed in both atraumatic and asymptomatic children and adolescents in additional studies.[28,29,44] Conceivably, higher false-positive rates among patients aged ≤13 years can be a manifestation of falsely interpreting high signal in the menisci as a positive study. However, this conjecture and others presented in literature are mostly speculative.

In the present study, the patients analyzed came from the same geographical area but differed in rural versus metropolitan setting. The patients in hospital A were younger and had a higher proportion of females compared with those in hospital B. In addition, data from 1 institution spanned 11 years, while data from the other spanned 4 years. However, because they represent 2 distinct and diverse patient populations, the study results are more likely to be generalizable.

The strengths of the present study include the largest population of pediatric and adolescent patients presented in literature to date, in addition to meticulous detail as to the timing of interventions, with strict time interval cutoffs. In examining the peer-reviewed literature, we found this practice to be inconsistent. By strictly including only patients with time from MRI to surgery of ≤8 weeks, the current study reduced the risk of false-negative MRI results by minimizing the time in which a new injury could be sustained.

A shorter time interval is also an important consideration for this population in controlling for the inverse outcome (ie, false-positive MRI results representing true tears that healed before surgery). This phenomenon has been the topic of multiple previous studies.[10,19,22,24] Notably, a 2014 investigation by Kijowski et al[24] reported 17 of 18 tears located at the medial meniscus outer rim had healed before surgery. Mean time from MRI to surgery for all patients in this study was 48 days (range, 12-98 days). In another study of 7 longitudinal tears of the posterior horn of the medial meniscus treated conservatively, at repeat arthroscopy 3 months later, 6 of 7 tears were healed.[19]

We observed that, in the existing literature, it was common to use longer time intervals to increase the size of the study cohort size.[16,32,35,42] To that end, imposing a strict time frame as we have done between the diagnostic MRI and its confirmatory arthroscopy aimed to control for confounding variables that would overestimate both false-negative and false-positive rates.

We recognize the intrinsic limitations of this study. It was retrospective and thus prone to selection bias as well as differences in institutional record keeping. One flaw was the reliance of radiologist reports rather than independent review with intra- and interrater reliability. Furthermore, multiple radiologists and multiple surgeons provided data. During the 11-year study period, 3.0-T magnets were adopted. Data detailing which MRI studies were gathered using 1.5-T magnets and which were gathered using 3.0-T magnets was not available to the researchers. Nevertheless, since their introduction into clinical practice, the question of whether new scanners, capable of generating twice the magnetic field strength, are indeed more diagnostically accurate has been thoroughly investigated.[17,18,42,43] Specifically, as it pertains to diagnosing meniscal tears, data from multiple studies have shown comparable accuracy but no significant diagnostic superiority in favor of 3.0-T machines. A 2021 study by Hancock et al[18] examined 330 pediatric and adolescent patients (mean age, 13.5 years) with any intra-articular knee pathology, with 125 patients receiving MRI with 3.0-T magnet strength and 205 receiving 1.5-T MRI. Mean time between MRI scan and surgery was 120 days. No significant difference in accuracy (sensitivity or specificity) was reported for any knee pathology (ACL rupture, meniscal tear, osteochondral defects, or chondral lesions)[18] Furthermore, a 2016 meta-analysis by Smith et al[43] examined the efficacy of 3.0-T machines and compared diagnostic measures to a previous meta-analysis with 1.5-T machines.

This study included pediatric, adolescent, and adult patients, with a mean age of 41.9 years. Mean time between MRI and surgery was 47.4 days. At the medial meniscus, no significant difference in sensitivity or specificity was found. At the lateral meniscus, there was no significant difference in sensitivity, but there was a significantly greater specificity for detecting LM tears in favor of the 1.5-T machines (95.7% vs 87.0%).[43]

Differences in specialty training (pediatric vs adult specialized and sports fellowship training) were known to exist at each institution. In addition, the use of birth age as a proxy measurement for maturity was used as opposed to bone age or physeal patency. This method has previously been used in published literature.[27,34,35] In agreement, we believe that a study that analyzes MRI as a screening test for the pediatric and adolescent population is justified in using a general measurement such as birth age for a cutoff. Often, surgeons examining a patient at an initial visit after an ACL injury will not have an accurate bone age or physeal patency to reference. Birth age, however, will be a known constant regardless and, thus, an acceptable proxy measurement to gauge potential accuracy of the screening MRI study.

The results of this study suggest that MRI is better at screening patients for MM tears than LM tears. In patients aged $\geq$14 years, MRI is more specific for any meniscal tear and, in nonobese patients, more specific for the LM tears. MRI also appears to positively predict LM tears more effectively than MM tears. It is worth noting that our study redemonstrates that LM tears are more common than MM tears in patients with acute ACL deficiency, in agreement with previous literature.[1,31,37] The implications of this are worth highlighting, as the prevalence of a disease directly influences pretest probability. In this study, the roughly 2-fold likelihood that a patient would have a true LM tear instead of a MM tear influenced both PPV and NPV. Hence, because LM tears are more prevalent with acute ACL injuries, the PPV of an MRI study was expected to be greater (LM PPV, 78.3% vs MM PPV, 62.3%). Likewise, because MM tears are less common in acute ACL injuries, the NPV was expected to be greater (MM NPV, 92.5% vs LM NPV, 65.0%). We observed both trends in this study.

We recommend that preoperative discussions, including consent, with patients and their guardians should cover the possibility of finding undiagnosed meniscal tears at arthroscopy. Operative planning and postoperative rehabilitation protocols should also include these contingencies. Above all, clinicians should use sound judgment to correlate each patient's ACL injury chronicity, mechanism, and other clinical factors when anticipating concomitant meniscal pathology in surgery from a positive or negative MRI study.

CONCLUSION

The diagnostic ability of MRI to predict meniscal injuries present at ACL reconstruction was moderate. Performance was poorest at the lateral meniscus, where MRI failed to detect 97 tears that were found arthroscopically. Among all patients, false-positive rates were higher for MM tears, while false-negative rates were higher for LM injuries. The specificity of MRI as a diagnostic tool for detecting any meniscal tear was significantly lower for patients aged $\leq$13 years as well as for detecting LM tears for obese patients.

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