EUROPEAN SOCIETY OF RADIOLOGY
European Radiology

MUSCULOSKELETAL

Ligamentum teres lesions are associated with compositional and structural hip cartilage degenerative change: region-specific cartilage degeneration

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Abstract

Objectives To investigate the association between magnetic resonance imaging (MRI)-based ligamentum teres lesions (LTL) and structural hip degeneration.

Methods Bilateral 3-T hip MRIs of participants ($n = 93$ [36 men]; mean age ($\pm$ SD) 51 years $\pm$ 15.4) recruited from the community and the orthopedic clinic of a single medical center were included. Clinical and imaging data acquired included hip disability and osteoarthritis outcome scores, semi-quantitative scoring of hip osteoarthritis on MRI (SHOMRI) scores on fluid-sensitive sequences, and cartilage $T_{1\rho}/T_2$ compositional sequences. An MRI-based LTL scoring system, incorporating continuity, thickening, and signal intensity, ranging from 0 (normal) to 4 (complete tear) was constructed. Hip morphological features associated with LTL, based on functional or anatomical relationships to LT, were defined. Relationships between MRI-LT scores and SHOMRI, global/regional cartilage $T_{1\rho}/T_2$, and proposed morphological abnormalities and LTL were explored by mixed effects linear and logistic regression models.

Results In 82 (46.1%) hips, no pain was documented; 118 (63.4%) and 68 (36.6%) hips were graded as KL-grade ≤ 1 and ≥ 2, respectively. Compared to MRI-LT score $= 0$ (normal), score $= 4$ (complete tear) revealed significantly worse subchondral bony degenerative changes for bone marrow lesions (SHOMRI-BML) and subchondral cysts (SHOMRI-sc) ($p < 0.001$, $p = 0.015$, respectively). Global acetabular $T_{1\rho}$, femoral T_2 were significantly increased for abnormal MRI-LT scores (p-range $= 0.005$–0.032). Regional analyses revealed significantly increased $T_{1\rho}/T_2$ in central acetabular/ increased T_2 in off-central femoral regions (p-range $= 0.005$–0.046). Pulvinar effusion-synovitis, shallow fovea, and foveal osteophytes were significantly associated with abnormal LT MRI findings (p-range $= < 0.001$–0.044).

Conclusion MRI abnormalities of LT are associated with worse SHOMRI-sc/BML scores, indicative of hip osteoarthritis and higher $T_{1\rho}$ and T_2 that differ by region. Pulvinar effusion-synovitis and changes in femoral head morphology are associated with LTL.

Clinical relevance statement Abnormal ligamentum teres findings identified via MRI are associated with structural degenerative changes of the hip joint and alterations in acetabular and femoral cartilage compositions show spatial differences in relation to LTL.

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Key Points

- *The clinical significance of common ligamentum teres lesions (LTL) on MRI is not well understood.*
- *LTL identified by an MRI-based scoring system is associated with worse biomarkers, indicating more advanced degenerative hip changes.*
- *Effusion-synovitis signal at pulvinar, shallow fovea capitis, and foveal osteophytes are associated with LTL on imaging.*

Keywords Ligamentum teres, Quantitative MRI, Hip, Osteoarthritis

Introduction

The prevalence of hip osteoarthritis (HOA) is rising, particularly in Europe and North America [1, 2]. The risk factors of HOA are not as well-investigated as in the knee and require more in-depth studies [1, 3]. The ligamentum teres (LT) supports the capsular ligaments of the hip, preventing femoral head subluxation at the extremes of the range of motion. Its tears are associated with hip microinstability and pain, especially in a traumatic setting or in the presence of synovitis [4–7]. The most common pathology of LT is partial degenerative tearing, constituting up to 88% of all tears [4, 8]. Complete tears are less common and are frequently associated with athletic endeavours, traumatic injuries, or hip dysplasia [5, 9]. Fibers of LT blend with the periosteum of fovea capitis, transverse acetabular ligament, and bony structures of the acetabular notch surrounding the cotyloid fossa and the pulvinar, a synovium-encased fibro-fatty tissue containing small vessels [4, 10–12]. Hip hypermobility and capsular laxity have been implicated in LT tears, especially at its femoral insertion [7, 13]. There have been numerous efforts in diagnosing and classifying LT lesions (LTL), most of which rely on surgical outcomes in symptomatic populations [10, 13–15]. Ligament injuries arising from ongoing repetitive trauma can lead to an array of abnormalities ranging from small interstitial tearing of collagen fibers to partial or complete disruptions of the ligament substance. This results in stretched and less taut or thick, but weak ligaments even after healing [16]. In the literature, the term "LT pathology" is often reserved for tears [7]. However, histological studies revealed that LT undergoes various degenerative ultrastructural changes which have overlapping findings in magnetic resonance imaging (MRI) [4, 7, 12, 14, 17]. On MRI, a normal LT is hypointense and homogeneous with a smooth contour and striated appearance with two or more bundles. Abnormal MRI findings of LT include: intrinsic signal alterations on T2-weighted (T2W) fat-saturated (FS) images, wavy appearance, hypertrophy and alterations in LT thickness, various degrees of discontinuity, and fraying [4, 12, 18, 19].

A better understanding of the biomechanics and internal structural changes within the hip joint is crucial for gaining insight into the etiology and progression of HOA, identifying causes that accelerate the disease, and ultimately planning potential interventions. Although showing structural and anatomical resemblance to the anterior cruciate ligament of the knee, unlike its counterpart in the knee, the role of LTL in HOA remains inadequately studied [4]. To date, there are only a few reports from the surgical literature suggesting an increased risk for cartilage lesions with LT tears [8, 20]. However, there are no detailed reports investigating the relationship of various LTL identified on imaging and their associations with hip degenerative changes. MRI could serve as a valuable tool for concurrently evaluating LTL and HOA by enabling direct assessment of LT and providing validated quantitative and semi-quantitative biomarkers for assessment of HOA [21–23]. Thus, the primary aim of our study was to define associations between MRI-based abnormalities of the LTL with the semi-quantitative scoring system for hip OA with MRI (SHOMRI) and femoral and acetabular cartilage compositional biomarkers of $T_{1\rho}$ and T2 relaxation. These metrics were employed in many prior studies and were shown to be reliable and sensitive to change [21–24]. Our secondary aim was to investigate secondary morphological hip findings that could be associated with LTL, based on its anatomy and proposed functions.

Materials and methods

Study participants

Participants were prospectively recruited from the Orthopedic clinic at the University of California San Francisco and from the community via local advertisements. This study was approved by the local Institutional Review Committee. Written informed consent was obtained from all participants. The study population was comprised of healthy controls and individuals with radiographic (Kellgren Lawrence [KL] grade < 4 in both hips, joint space > 2.5 mm) or clinically symptomatic HOA. Anteroposterior radiographs of both hips were acquired at enrollment and scored for KL grades by a senior musculoskeletal radiologist (TML) with more than 25 years of experience. Participants also answered the self-administered hip disability and outcome score (HOOS)

Table 1 Magnetic resonance imaging ligamentum teres (MRI-LT) scoring system.

Description	Continuity	Signal alteration/thickening	Score
Intact LT with normal thickness and signal intensity (Entirely normal MRI appearance)	Intact	Both absent	0
Intact LT but signal alteration and/or thickening	Intact	At least one present	1
Partial LT tear *without* signal alteration or thickening	Partial tear	Both absent	2
Partial tear *with* signal alteration and/or LT thickening	Partial tear	At least one present	3
Complete tear (regardless of LT thickness or signal intensity)	Complete tear	Any	4

LT ligamentum teres, *MRI* magnetic resonance imaging

questionnaire at enrollment indicating their clinical status [25]. Exclusion criteria included previous hip surgery, knee osteoarthritis (OA), hip trauma within the last three months, intra-articular injection within the last six months, inflammatory arthropathy, hemochromatosis, hemoglobinopathies, or contraindication for MRI. Furthermore, participants were screened for exclusion if they had radiographic knee OA (KL grade ≥ 2), pain, disability, or limited range of motion in any other location except for the hip.

MRI acquisition
Using a 3.0-T scanner (GE Healthcare) and a 32-channel flexible surface coil (GE Healthcare) bilateral hip MRIs were obtained as described in detail previously [26]. MR imaging included coronal FS-T2W fast spin echo (FSE) (repetition time (TR)/echo time (TE) = 3000/60.0 ms; field of view [FOV] = 20 cm; slice thickness = 4.0 mm; spatial resolution = 4 × 0.39 × 0.39 mm), FS 3D-FSE IW (TR/TE = 1200/20 ms; FOV = 15.3 cm; slice thickness = 0.8 mm; spatial resolution = 0.8 × 0.25 × 0.25 mm) and 3D sagittal $T_{1\rho}/T_2$ magnetization-prepared angle-modulated partitioned k-space spoiled gradient echo snapshots (TSL = 0/15/30/45 ms; TE = 0, 10.4, 20.8, 41.6 ms; FOV = 14 cm; TR = 1.2 s; slice thickness = 4.0 mm; spatial resolution = 4 × 0.55 × 0.55 mm) sequences.

Assessment of direct and indirect ligamentum teres lesions on MRI
"Ligamentum teres lesion" was defined as MRI abnormalities involving LT continuity, thickness, signal intensity or combinations. Coronal FS-T2W FSE and FS-3D-FSE images with multiplanar reconstructions in three orthogonal planes were assessed by two radiologists, with eight and two years of experience (Z.A. and P.J.G.). Discordant readings were adjudicated by a musculoskeletal radiologist with > 25 years of experience (T.M.L). Ten patients were later chosen randomly after a period of > 3 months and images were re-assessed between the two observers (Z.A. and P.J.G.) for intra- and inter-reader reproducibility analysis. Each LT was assessed for its integrity, increased signal intensity, and

thickness [4, 18]. Integrity was evaluated as "intact" LT (LT appearing as continuous throughout its entire course); "partial tear" (focal discontinuity or focal/diffuse thinning of LT); and "complete tear" (complete loss of LT continuity) [19]. Focal or diffuse LT thickening and abnormal signal intensity were assessed dichotomously as present or absent. LT thickening was defined as the presence of a focal or diffuse increase in its size with a tubular shape or mass effect on the adjacent pulvinar fat pad. Particular attention was paid to the magic angle artifact near the femoral attachment of LT when assessing signal alteration [4]. Next, a compound MRI score, ranging between 0 and 4, was constructed taking various combinations of the abnormal MRI findings into account (Table 1). Figure 1 demonstrates representative case examples for each score. The rationale for this step was to be able to holistically assess different scenarios of LTL encountered in MRI, which likely point out to various types and combinations of pathologies.

Additional hip morphological findings (secondary predictors), which could be implicated in the abnormal MRI appearance of LT were defined based on their close anatomical or functional relationships to LT. On the acetabular side, LT has six attachments and surrounds and converges into the cotyloid fossa; on the femoral side, it attaches singly on the fovea capitis of the femoral head [11]. Due to the difficulty of investigating bony structures of a large acetabular surface on MR images, *the effusion-synovitis signal in the pulvinar fat* pad was considered as an indirect indicator that might signify LTL on non-enhanced MR images (Fig. 2a). On the femoral-side, *perifoveal osteophytes* (Fig. 2b), *subcortical bone marrow lesions* (BML) (Fig. 2c) and *fovea capitis depth* (Fig. 3a) were investigated. [11, 18, 27]. Fovea depth was measured as the distance from the deepest point of the fovea to the tangential line drawn connecting its anterior and posterior borders (Fig. 3a). Based on the functional theory of fluid distribution by LT within the joint, fluid signal surrounding femoral neck leading to distension at joint capsule and/ or joint recesses (*joint effusion*) (Fig. 2b) [28]) and *synovial plicae of the hip* (Weitbrecht's retinaculae)
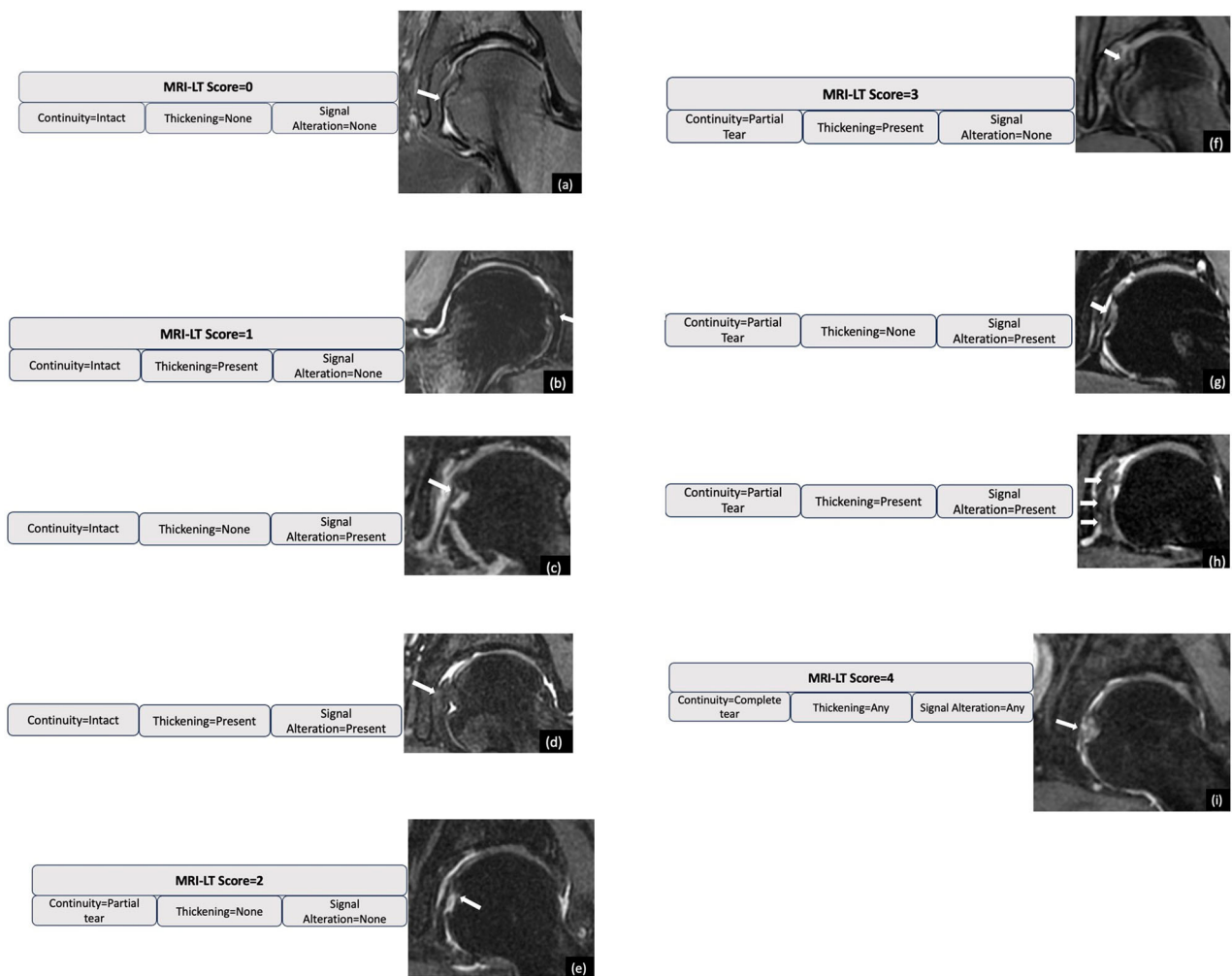
Fig. 1 Examples of MRI-LT scores. Continuous LT with uniform thickness and low signal intensity (arrow) extending between fovea capitis and transverse acetabular ligament on coronal T2-weighted fat-suppressed image (**a**) representing MRI-LT score 0. Examples for MRI-LT score 1, indicating (**b**) preserved continuity but thickening (arrow in **b**), (**c**) internal signal change (arrow in **c**) or (**d**) both (arrow in **d**). Example of MRI-LT score 2, representing partially torn LT near (arrow) without signal or thickness changes on coronal 3D-FSE image (**e**). Examples of MRI-LT score 3 (**f**–**h**) with partial tear and thickening (**f**), signal alteration (**g**), or both (**h**). Example of MRI-LT score 4 with complete discontinuity of LT from its femoral attachment with abnormal signal intensity remnants (arrow) in its expected location (**i**)

were assessed (Fig. 2d) [29]. To explore the relationships of LTL and fovea capitis morphology and capsular laxity-joint hypermobility theory, *anterior joint capsule (AJC) thickness* was measured at the level of the mid-femoral neck (Fig. 3b) [4, 13]. Both measurements were performed on axial oblique reformatted 3D-FSE images, in-plane with the long axis of the femoral neck. Other secondary MRI signs were assessed dichotomously.

Image processing and analysis for semi-quantitative and quantitative MRI outcomes

Structural changes related to HOA were assessed using SHOMRI scores in cartilage, bone marrow lesions (BML), subchondral cysts (sc), and labrum domains as described

previously [22, 24]. Quantitative assessment was performed using mean femoral and acetabular cartilage $T_{1\rho}$ and T_2 relaxation times as described previously [30]. Briefly, each voxel acquired with different TSLs or echo times was mono-exponentially fit with a Levenberg-Marquardt algorithm [31]. Cartilage surfaces were automatically segmented with a single atlas-based approach and radially divided into eight subregions [21]. The segmentation masks were applied to the $T_{1\rho}/T_2$ maps to isolate the voxels of interest. Mean $T_{1\rho}$ and T_2 values were calculated across the voxels within the acetabular and femoral cartilage volumes and the eight acetabular and femoral cartilage subregions (MATLAB, The MathWorks, Inc.). Mean global and regional (five regions on femoral
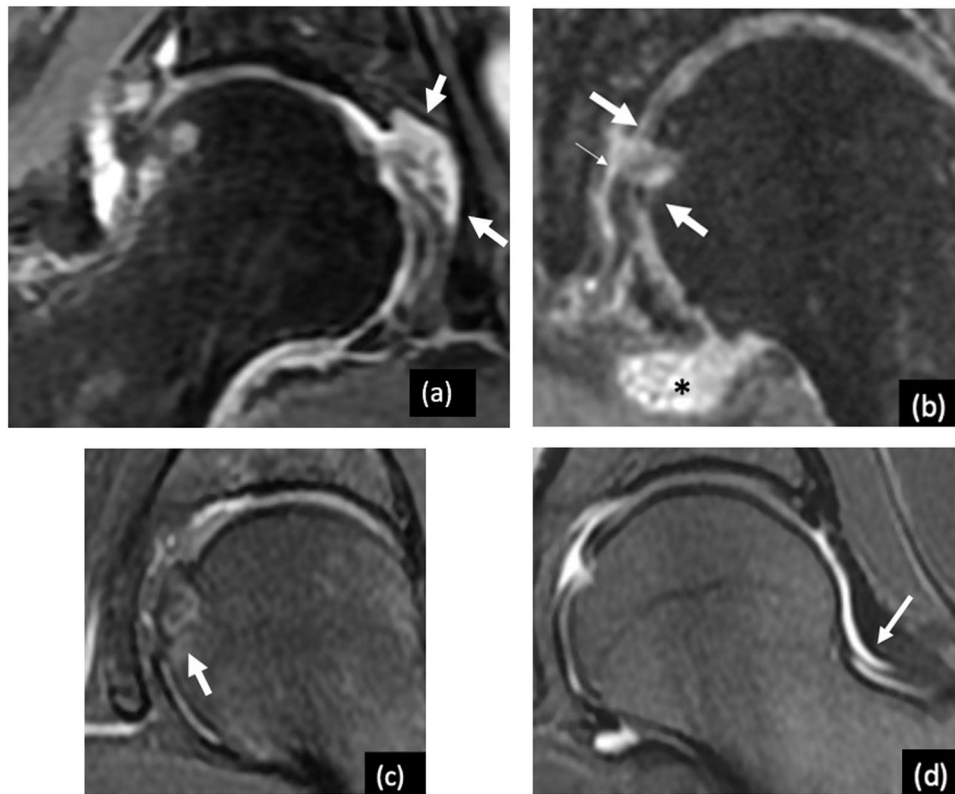
Fig. 2 Effusion-synovitis signal replacing the fat planes in pulvinar (arrows) on coronal FS-T2W image (**a**). Perifoveal osteophytes (arrows) at the upper and lower margins of fovea capitis are shown on coronal 3D-FS-FSE image (**b**). The lower osteophyte is displacing the LT. The sharp contrast in signal intensity of the proximal part of the LT at this point (thin arrow) represents a magic angle artifact. Note the joint effusion distending the capsule (asterisk). Bone marrow lesion at the inferior aspect of fovea capitis (arrow) on coronal T2W image (**c**). Superior neck plica (Weitbrecht's retinaculum) is shown (arrow) on coronal FS-T2W image (**d**)
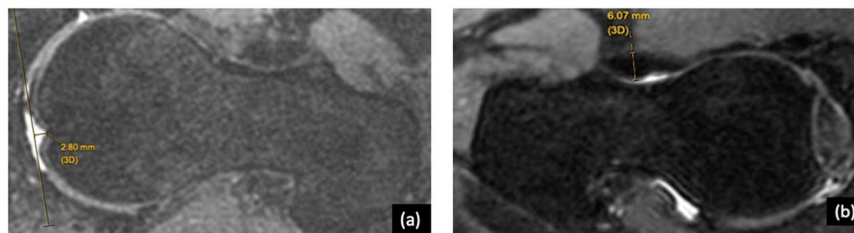
Fig. 3 Measurement of fovea capitis depth is depicted on the axial oblique reformatted 3D-FS-FSE image along the long axis of the femoral neck (**a**). Measurement of the anterior joint capsule is depicted on the same image plane and sequence in (**b**)

head, four regions on acetabular side) $T_{1\rho}/T_2$ measurements were obtained from articular surfaces covered by cartilage (Fig. 4).

Statistical analysis
Statistical analyses were performed using STATA version 18 software (StataCorp LP) with significance set to $p < 0.05$. Descriptive statistics for continuous variables were means ± standard deviation (SD) and frequencies and percentages for categorical variables. Inter- and intra-reader reproducibility were assessed by calculating weighted Cohen's Kappa and using cluster-resampled bootstrapping with 1000 repetitions to derive a 95% CI while accounting for clustered observations (two hips per person).

Outcome variables were categorized as primary and exploratory to address potential issues arising from multiple testing. For the primary aim (assessing the
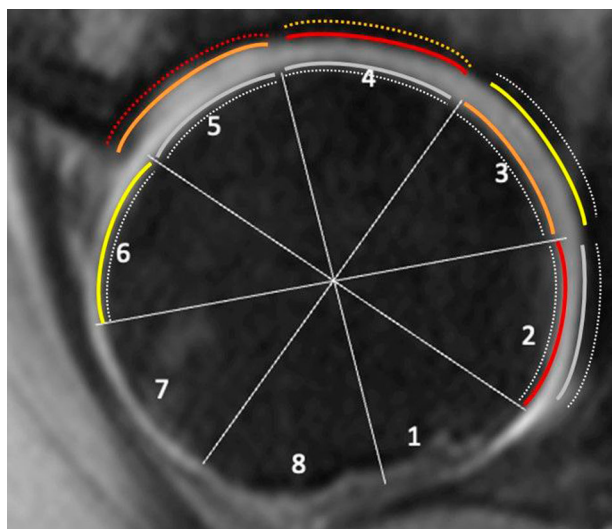
Fig. 4 Sub-regions of femoral and acetabular cartilage surfaces on sagittal-oblique reformatted FS-3D IW FSE- image. Solid arcs represent T_2 relaxation times and dashed arcs represent $T_{1\rho}$ relaxation times. Red arcs indicate that for all MRI-LT scores > 0, there were significant increases in the respective compositional cartilage outcome. Orange arcs indicate subregions where there were significant increases in compositional cartilage outcomes for more than one type of abnormal MRI-LT score (increased signal/ and or thickening [MRI-LT score = 1] or partial/ complete LT tears [MRI-LT scores = 2–3/4]. Yellow arcs indicate subregions where there were significant increases in compositional cartilage outcomes for only MRI-LT score = 2, representing partial LT tears. Gray arcs represent subregions of cartilage where no significant relationships were found between MRI-LT scores and compositional cartilage outcomes

relationship between LTL and semi-quantitative and quantitative MRI biomarkers of HOA), the predictors were MRI-LT scores; the primary outcome measures were SHOMRI scores, global mean acetabular and femoral $T_{1\rho}$ and T_2-relaxation times. For exploratory purposes, secondary outcome variables for aim 1 were regional $T_{1\rho}$ and T_2-relaxation times.

For the secondary aim (assessing associations between secondary morphological hip findings that could be associated with LTL based on its anatomy and function), the predictors were binary direct MRI findings of LT (tear, abnormal signal intensity, and thickening). Outcome variables were pulvinar effusion-synovitis, osteophytes, and BML at the fovea, joint effusion, synovial plicae count, AJC thickness, and fovea depth.

Mixed effects models with continuous predictors (MRI-LT scores) and continuous outcomes were employed to test for trends. Mixed effects linear and logistic models with a random effect for participant (accounting for two hips per person) were used to assess the relationships between predictors and continuous outcomes (i.e., global mean $T_{1\rho}/T_2$-relaxation times) and binary outcomes (i.e., pulvinar effusion-synovitis) respectively. Adjusted mean

values and beta (B)-coefficients were reported. Unstandardized beta (B) coefficients represent the magnitude and direction of the difference in a continuous outcome variable (i.e., SHOMRI scores, T1ρ/T2 measurements) for each one-unit increase in the predictor variable. The odds ratios (OR) indicate the odds that an outcome will occur given the presence of the predictor variable, compared to the odds of it occurring given its absence. All models were adjusted for age, body mass index (BMI), and sex.

Results

The cohort included 93 individuals (36 men) with a mean age and BMI of 51 ± 15.4 years (range = 23–79) and $24.3 \pm 3.6 \text{ kg/m}^2$. A total of 118 hips (63.4%) were graded as KL grade ≤ 1 and 68 hips (36.6%) as KL grade ≥ 2. According to the HOOS pain questionnaire, 82 hips (46.1%) scored 100 out of 100, indicating no pain.

Upon MR image review, one participant was diagnosed with bilateral congenital absence of the LT and excluded from analyses related to MRI-LT scores. Table 2 summarizes the descriptive statistics of direct MRI findings of LTL, hip morphological findings proposed to be secondarily implicated in LTL, MRI-LT scores, and clinical and radiological hip findings.

There were no significant associations between age, sex or BMI, and MRI-LT scores ($p = 0.130$, $p = 0.362$ and $p = 0.074$, respectively). Women had significantly thicker AJC ($\beta = 0.49$, [95% CI = 0.07, 0.91], $p = 0.022$). Joint effusion showed positive (OR = 0.087 [95% CI = 0.76, 0.98], $p = 0.026$) and synovial plicae count showed inverse relationships with BMI ($\beta = -0.03$, [95% CI = -0.07, -0.002], $p = 0.037$).

Weighted kappa for inter-rater agreement was 0.48 ($p = 0.003$ [95% CI = 16–79.9]). The intra-rater reliability of the composite scores revealed kappa values of 0.52 ($p < 0.001$ [95% CI = 21.1–83.3]) for observer 1 and of 0.54 ($p < 0.001$ [95% CI = 30.3–77.4]) for observer 2.

Results for primary aim: relationships between MRI-LT scores and quantitative and semiquantitative MRI outcomes

The trend analysis showed that higher MRI-LT scores were associated with greater SHOMRI scores ($\beta = 0.89$ [0.17, 1.60], $p = 0.016$) and higher femoral T_2 values ($\beta = 0.61$ [0.13, 1.09], $p = 0.013$).

Mixed effects models revealed significant results for SHOMRI-BML and sc scores for MRI-LT score 4 ($p < 0.001$ and $p = 0.015$, respectively) compared to MRI-LT score 0. Mean global acetabular $T_{1\rho}$ values were significantly greater for all MRI-LT scores > 0. Scores indicating partial tears (2 and 3) showed significant positive associations with greater mean global femoral T_2 (Table 3).

Table 2 Distribution of MR-based imaging findings involving LT and other radiological and clinical findings, stratified by Kellgren-Lawrence grades

	Description		KL-0, n = 44 (23.9%)	KL-1, n = 72 (39.1%)	KL-2, n = 38 (20.7%)	KL-3, n = 30 (16.3%)	Total, n = 184 (100%)
Direct MRI Findings of LT	Intact LT		28 (11.5)	30 (16.3)	15 (8.2)	15 (8.2)	88 (47.8)
	Partial tear		11 (6)	28 (15.2)	17 (9.2)	10 (5.4)	37 (20.1)
	Complete tear		5 (2.7)	14 (7.6)	6 (3.3)	5 (2.7)	29 (15.8)
	Thickened LT		29 (15.8)	30 (16.3)	24 (13)	9 (4.9)	92 (50)
	Signal increase		26 (14.1)	44 (23.9)	27 (14.7)	17 (9.2)	114 (62)
Proposed Hip	Pulvinar effusion-synovitis (%)		26 (14.1)	44 (23.9)	29 (15.8)	16 (8.7)	115 (62.5)
Morphological Findings	Foveal BML		2 (1.1)	5 (2.7)	5 (2.7)	6 (3.3)	18 (9.8)
Secondarily implicated in	Perifoveal osteophytes		6 (3.3)	22 (12)	17 (9.2)	14 (7.6)	59 (32.1)
LTL	Fovea depth* (mm) (SD)		2.89 (0.95)	2.74 (0.89)	2.97 (1.52)	3.30 (1.77)	2.91 (1.23)
	Anterior Joint capsule thickness* (mm) (SD)		5.96 (0.98)	5.86 (1.15)	5.78 (1.37)	5.77 (1.39)	5.86 (1.19)
	Joint effusion		29 (15.8)	37 (20.1)	21 (11.4)	16 (8.7)	103 (56)
	Number of synovial plicae per hip	1 plica	15 (8.2)	20 (10.9)	19 (10.3)	10 (5.4)	64 (34.8)
		2 plicae	4 (2.2)	9 (4.9)	5 (2.7)	1 (0.5)	19 (10.3)
		3 plicae	0 (0)	0 (0)	0 (0)	1 (0.5)	1 (0.5)
MRI-LT Scores	Entirely normal MRI appearance	0	6 (3.3)	12 (6.6)	1 (0.5)	6 (3.3)	25 (13.6)
	Intact LT with thickening and /or signal alteration	1	22 (12)	18 (9.9)	14 (7.6)	9 (4.9)	63 (34.2)
	Partially torn LT without thickening or signal alteration	2	2 (1.1)	4 (2.2)	2 (1.1)	1 (0.5)	9 (4.9)
	Partially torn LT with thickening and/or signal alteration	3	9 (4.9)	24 (13)	15 (8.2)	9 (4.9)	57 (31)
	Complete tear of LT irrespective of thickening or signal alteration	4	5 (2.7)	14 (7.6)	6 (3.3)	5 (2.7)	30 (16.3)
Radiological and Clinical Hip Findings	Mean SHOMRI scores (SD) — Cartilage (range: 0–20)		0.77 (1)	1.88 (2.1)	2.97 (2.26)	5.29 (3.53)	2.37 (2.65)
	Labrum (range: 0–20)		4.86 (3.1)	6.37 (4.2)	7.11 (4.9)	8.2 (5.6)	6.44 (4.5)
	BML (range: 0–30)		0.05 (0.21)	0.45 (0.9)	0.6 (1.3)	1 (1.8)	0.47 (1.13)
	Subchondral cysts (range: 0–20)		0.09 (0.36)	0.52 (1.27)	0.25 (0.5)	1 (1.59)	0.43 (1.1)
	Mean $T_{1\rho}$ (SD) (msec)* — Femoral		36.1 (2.91)	36.3 (2.81)	37.6 (4.17)	35.8 (3.82)	36.5 (3.36)
	Acetabular		35.5 (3.28)	36.2 (3.62)	38.4 (4.00)	35.5 (3.67)	36.4 (3.76)
	Mean T_2 (SD) (msec)* — Femoral		32.4 (4.67)	32.6 (4.41)	34.6 (4.70)	31.6 (4.85)	32.8 (4.67)
	Acetabular		31.9 (4.84)	31.9 (4.63)	34.9 (4.14)	34.5 (8.25)	33.0 (5.48)
	Mean HOOS pain (SD)		91.1 (14.9)	91.4 (13.9)	87.5 (15.9)	82.8 (18.9)	89.1 (15.7)

Unless otherwise specified, data are numbers of patients with percentages in parentheses

The composite MRI-LT Scores, ranging between 0 (normal MRI appearance) and 4 (complete tear of LT) are indicated in bold

MRI-LT score magnetic resonance imaging ligamentum teres score, *KL* Kellgren-Lawrence, *HOOS* hip disability and osteoarthritis outcome score, *SD* standard deviation, *BML* bone marrow lesions

SHOMRI scoring hip osteoarthritis with MRI, *mm* millimeters, *msec* milliseconds

* Values are means ±standard deviations

Results from post-estimation analysis for regional differences on femoral and acetabular cartilage surfaces revealed that femoral T_2 was significantly greater in the posterior-inferior aspect (region 2) for MRI-LT scores > 0 (*p*-range: [< 0.001–0.028]). Compared to MRI-LT score = 0 (normal MRI findings), for MRI-LT scores > 0, mean acetabular T_2 and $T_{1\rho}$ were significantly greater in the anterior-central (region 4) (*p*-range: [0.001–0.021]) and central (region 5) (*p*-range: [0.016–0.040]) regions, respectively (Fig. 4). Results for exploratory analyses are presented in the Supplementary Table.

Results for secondary aim: relationships between hip morphological findings and MRI-abnormalities of LT

The OR of having pulvinar effusion-synovitis was significantly higher with all LTL (Table 4). The OR of having foveal osteophytes was 5.5 times higher with LT tears (95% CI = 1.8, 16.3, *p* = 0.002). Fovea capitis depth was greater in the presence of LT thickening by 0.40 mm (95% CI = 0.01, 0.79, *p* = 0.044) and in the presence of LT signal abnormality by 0.45 mm (95% CI = 0.09, 0.82, *p* = 0.014). It was diminished by 0.46 mm (95% CI = −0.81, −0.10, *p* = 0.011) with LT tear.

Discussion

Using a composite scoring system that assesses the cardinal MRI features of LT, continuity, altered thickness and signal intensity, we observed that complete tears of LT are associated with worse SHOMRI-BML and SHOMRI-sc scores, indicating later stages of HOA whereas, milder forms of LTL, including various combinations of signal or thickness alterations or partial tears were linked to significantly higher mean acetabular $T_{1\rho}$ and mean femoral T_2 relaxation times, which might reflect earlier changes in the joint cartilage surfaces before full-scale cartilage loss is evidenced. The lack of significant associations for SHOMRI-cartilage and labrum scores might be due to our relatively healthy study population. Moreover, we identified that effusion-synovitis signal at the pulvinar, foveal osteophytes and altered depth of fovea capitis were associated with abnormal LT imaging findings.

LT assessment has historically been focused on its tears [19, 32, 33]. However, histological studies confirmed overlapping abnormal MRI findings for ultrastructural changes such as hemorrhage, mucoid or fibromatous degeneration, chronic inflammatory infiltrates, osteo/chondroid metaplasia within LT [12, 17]. Thus, an intact LT may not always be entirely normal. In fact, the thickness of LT depends on its degeneration pattern [12]. In this study, in addition to LT integrity, we investigated the significance of LT thickening, which may represent hypertrophy and/ or degeneration, and increased signal, which may represent partial tear, degeneration, or synovitis. The simple and clinically adaptable composite scoring system, enables assessment of the LT holistically as it incorporates these three MRI findings, potentially bridging the gap between macroscopic findings and confounding signal changes due to microscopic alterations within the ligament ultrastructure.

Tightening of LT causes femoral head to be pulled inside the acetabulum [7, 11]. Its resection results in increased hip adduction, revealing biomechanical alterations with loss of LT functionality [34]. Perumal et al have reported a greater rate of total hip arthroplasty for patients with LT lesions compared to those without [35]. Our results imply a temporal relationship as part of a spectrum of internal derangements, where MRI-LTL scores indicative of milder LTL (MRI-LT scores 2–3) are associated with earlier HOA changes, represented by cartilage compositional alterations, whereas MRI-LTL score of 4 (complete tear), is associated with more advanced HOA, evidenced by structural subchondral bony changes. Thus, gradually diminished functionality of LT, characterized by MRI abnormalities could lead to altered biomechanics of the femoral head within the acetabular fossa.

Additionally, our results suggest that there could also be spatial differences, evidenced by regional differences in $T_{1\rho}$ and T_2 measurements of femoral and acetabular cartilage, in various scenarios of LTL. Reports from surgical literature indicate a spatially selective distribution for cartilage lesions in patients with and without LT tears. To the best of our knowledge, there are only two prior studies investigating the regional cartilage alterations in patients with LT tears and both were carried out exclusively on patients with femoroacetabular impingement (FAI). Of these studies, Chahla et al reported higher incidences of chondral defects on femoral head at perifoveal and weight-bearing regions compared to peripheral zones [8] and Kaya et al reported cartilage lesions at anterior superior zone of acetabulum and lateral zones of femur, attributing their results to be FAI-specific [20]. Our results from a cohort more representative of the general population, support surgical literature in differential involvement of acetabular and femoral cartilage regions.

Domb et al emphasized the significance of acetabular morphology in LT tears [36]. Furthermore, in a previous cadaveric study, LT thickness was found to be associated with larger fovea depth and width and with inferior bony proliferations at the foveal margin [12]. Our results support that foveal morphology is significant in relation to LTL. We observed that fovea capitis is smaller with LT tears, which could either be an adaptive secondary remodeling or the underlying cause of LTL. In addition,

Table 3 Results for associations between MRI-LT scores and semi-quantitative scores of hip osteoarthritis and quantitative MR measurements on global femoral and acetabular quantitative cartilage outcomes

Semi-quantitative MRI Outcomes

MRI-LT Score	SHOMRI-Cartilage			SHOMRI- Subchondral Cysts			SHOMRI-Bone Marrow Lesions			SHOMRI-Labrum		
	Adj. Mean	95% CI	p	Adj. Mean	95% CI	p	Adj. Mean	95% CI	p	Adj. Mean	95% CI	p
0	2.51	Reference		0.20	Reference		0.70	Reference		5.27	Reference	
1	2.25	−1.35 0.84	0.645	0.21	−0.46 0.47	0.987	0.16	−0.40 0.58	0.722	6.42	−0.72 3.02	0.229
2	2.21	−2.12 1.52	0.746	0.03	−0.95 0.61	0.670	0.78	−0.10 1.53	0.086	7.27	−1.06 5.05	0.200
3	2.44	−1.23 1.09	0.909	0.62	−0.09 0.91	0.105	0.59	−0.00 1.04	0.050	6.52	−0.76 3.26	0.222
4	2.40	−1.45 1.21	0.862	**0.91**	**0.13 1.28**	**0.015**	**1.18**	**0.52 1.71**	**< 0.001**	6.98	−0.64 4.04	0.154

Quantitative MRI Outcomes

MRI-LT Score	Global Femoral Mean $T_{1\rho}$			Global Femoral Mean T_2			Global Acetabular Mean $T_{1\rho}$			Global Acetabular Mean T_2		
	Adj. Mean (msec)	95% CI	p	Adj. Mean (msec)	95% CI	p	Adj. Mean (msec)	95% CI	p	Adj. Mean (msec)	95% CI	p
0	36.0	Reference		31.4	Reference		34.5	Reference		33.6	Reference	
1	36.1	−1.30 1.60	0.839	31.9	−1.54 2.51	0.638	**36.5**	**0.53 3.52**	**0.008**	33.0	−3.08 1.89	0.639
2	37.5	−0.95 3.95	0.231	**35.9**	**0.97 7.87**	**0.012**	**37.4**	**0.41 5.40**	**0.023**	34.5	−3.20 5.09	0.656
3	36.9	−0.59 2.42	0.233	**33.7**	**0.20 4.41**	**0.032**	**36.8**	**0.68 3.81**	**0.005**	33.0	−3.18 1.98	0.651
4	36.4	−1.29 2.07	0.651	33.3	−0.44 4.25	0.112	**36.5**	**0.21 3.74**	**0.028**	32.0	−4.43 1.36	0.299

Models are adjusted for age, sex, body mass index. Bold numbers indicate statistically significant results ($p < 0.05$). Beta-coefficients represent change in SHOMRI scores or $T_{1\rho}/T_2$ values for each MRI-LT score compared to MRI-LT score $= 0$ (reference score), which indicates normal MRI appearance of LT

LT ligamentum teres, *SHOMRI* scoring of hip osteoarthritis on MRI, *Adj. Mean* adjusted mean value, *msec* milliseconds

osteophytes at fovea were also significantly associated with LT tears. However, we did not observe significant relationships between foveal BML and LTL, confirming previous MRA studies [19].

We found that the pulvinar effusion-synovitis, near acetabular-sided attachment of LT, is implicated in all forms of LT abnormalities (thickening, altered signal, and tear), which is a novel, complementary imaging indicator of LTL. Animal models showed that ligament failure occurs by an initial peel-off from the acetabular side, followed by avulsion from the femoral head [37]. Using MRA, Chang et al reported a large pulvinar and/or ligamentum plica in about 18%, and highlighted the significance of non-fat-suppressed images to distinguish tears of LT from ligament plicae but effusion-synovitis signal within the pulvinar in relations to LTL was not reported previously [19]. In this study, we did not see any associations for the number of plicae and LTL but there was an inverse relationship between synovial plicae number and BMI which needs further investigation. On the other hand, joint effusion was more common in patients with higher BMI which is in line with previous quantitative reports on hip effusion [38].

Hips with tears of LT have almost four times higher likelihood of being diagnosed with capsular laxity at arthroscopy [39]. Female predominance in LT tears was previously attributed to the higher frequency of joint laxity in women [8, 39]. In this study, using AJC thickness as a potential surrogate for hip hypermobility we tried to investigate these relationships. Our results indicate a thicker AJC in females by about 0.5 mm, but no significant relationships between AJC and LTL. This may result from differences in study populations where the current study is not restricted to surgical patients or it may merely reflect the limitation of AJC thickness to indicate joint laxity.

As opposed to arthroscopy-based studies, one of the strengths of this study was bilateral assessment of hips which better allowed us to study the spectrum of LT changes in a population with a wide age range. However, the lack of surgical validation of the proposed MRI-LT scoring system or histological verification of LTL constitutes a significant limitation of this study and requires further research for validation. Furthermore, reproducibility tests revealed only moderate inter-/intra-rater agreement, which emphasizes the challenge of assessing LT on MRI. In addition, we did not

Table 4 Relationships between direct and indirect MRI findings of LT lesions

Binary LT Predictors	AJC[a] Thickness (mm)		Depth of Fovea[a] Capitis (mm)		Number of hip plicae[a]		BML at Fovea (yes/no)[b]		Osteophytes (yes/no)[b]		Pulvinar Effusion/ Synovitis (yes/no)[b]		Joint Effusion (yes/no)[b]	
	B (95% CI)	p	B (95% CI)	p	B (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p
Tear (yes/no)	0.09 (−0.25, 0.43)	0.614	**−0.46 (−0.81, −0.10)**	**0.011**	−0.07 (−0.28, 0.13)	0.486	2.81 (0.93, 8.52)	0.068	**5.48 (1.84, 16.29)**	**0.002**	**5.10 (1.95, 13.41)**	**0.001**	1.52 (0.65, 3.62)	0.334
Thickening (yes/no)	0.17 (−0.21, 0.54)	0.376	**0.40 (0.01, 0.79)**	**0.044**	−0.13 (−0.35, 0.10)	0.270	1.42 (0.48, 4.25)	0.526	1.47 (0.45, 4.84)	0.528	**9.3 (2.86, 30.38)**	**<0.001**	1.74 (0.73, 4.15)	0.214
Signal Alteration (yes/no)	0.26 (−0.08, 0.60)	0.133	**0.45 (0.09, 0.82)**	**0.014**	−0.10 (−0.31, 0.11)	0.343	NA*	NA*	2.31 (0.70, 7.68)	0.169	**6.49 (2.18, 19.28)**	**0.001**	0.98 (0.42, 2.29)	0.958

Results from mixed effects multilevel regression tests ([a]) for continuous outcomes and mixed effects logistic regression tests ([b]) for binary outcomes that vary by hip side, respectively. The beta coefficients (B) represent the magnitude of change in a continuous outcome variable for each 1 mm increase in the predictor variable. The odds ratios (OR) indicate the odds that an outcome will occur given the presence of the predictor variable, compared to the odds of it occurring given its absence. Models are adjusted for age, sex, and BMI. Bold numbers indicate statistically significant results

* Among the cases with normal LT signal, there were no cases with BML at fovea

AJC anterior joint capsule, *BML* bone marrow lesions, *OR* odds ratio, *mm* millimeters

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evaluate acetabular morphology since this was beyond the score of this study. Also, it is not possible to infer causal relationships in the cross-sectional design, thus, it is still unclear whether degenerative LT tears are the cause or the outcome of HOA. Furthermore, we might have underscored the number of plicae due to inadequate joint distension on routine MRI. Last, as this is the first study systematically investigating the significance of LTL and is thus hypothesis-forming in nature, we refrained from applying statistical adjustments for multiple comparisons, we acknowledge that our findings will require subsequent validation.

In conclusion, this proof-of-concept study indicates that increasing abnormal LT changes are associated with progressive acetabular and cartilage compositional changes, while complete LT tears are associated with sub-chondral changes such as bone marrow lesions and subchondral cysts in the later stages of OA assessed by SHOMRI. While these results serve to generate hypotheses and require further validation, they underscore the significance of MRI in assessing LT in HOA. Secondary MRI findings, particularly pulvinar effusion-synovitis, shallow fovea capitis, and perifoveal osteophytes are also associated with LT MRI abnormalities, which could be helpful diagnostic clues.

Abbreviations

AJC	Anterior joint capsule
BMI	Body mass index
FS	Fat-saturated
FSE	Fast spin echo
HOA	Hip osteoarthritis
LT	Ligamentum teres
LTL	Ligamentum teres lesions
MRI	Magnetic resonance imaging
OA	Osteoarthritis
SHOMRI	Scoring of hip osteoarthritis on MRI
T2W	T2-weighted

Supplementary information

Compliance with ethical standards

Guarantor

The scientific guarantor of this publication is T.M.L.

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