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SCIENTIFIC ARTICLE

Non-traumatic anterior cruciate ligament abnormalities and their relationship to osteoarthritis using morphological grading and cartilage T2 relaxation times: data from the Osteoarthritis Initiative (OAI)

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Abstract
Objectives The aim of this work was to study anterior cruciate ligament (ACL) degeneration in relation to MRI-based morphological knee abnormalities and cartilage T_2 relaxation times in subjects with symptomatic osteoarthritis.
Methods Two radiologists screened the right knee MRI of 304 randomly selected participants in the Osteoarthritis Initiative cohort with symptomatic OA, for ACL abnormalities. Of the 52 knees with abnormalities, 28 had mucoid degeneration, 12 had partially torn ACLs, and 12 had completely torn ACLs. Fifty-three randomly selected subjects with normal ACLs served as controls. Morphological knee abnormalities were graded using the WORMS score. Cartilage was segmented and compartment-specific T_2 values were calculated.
Results Compared to normal ACL knees, those with ACL abnormalities had a greater prevalence of, and more severe, cartilage, meniscal, bone marrow, subchondral cyst, and medial collateral ligament lesions (all $p<0.05$). T_2 measurements did not significantly differ by ACL status.
Conclusions ACL abnormalities were associated with more severe degenerative changes, likely because of greater joint instability. T2 measurements may not be well suited to assess advanced cartilage degeneration.

Keywords Osteoarthritis · Anterior cruciate ligament · MRI · Knee joint · Cartilage · T2 values

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Introduction

Osteoarthritis (OA) is a leading cause of disability worldwide, with nearly 27 million individuals having clinically symptomatic OA and the knee being the most commonly affected joint. Radiographic evidence is seen in at least 70% of the population over the age of 65 years [1, 2]. Several factors contribute to the development and acceleration of OA, such as prior trauma, knee malalignment, genetics, and obesity, among others [3–5].

The anterior cruciate ligament (ACL) is an important knee joint stabilizer. A ruptured ACL leads to significant knee instability, as the ACL is the primary restraint to anterior tibial translation and internal tibial rotation [6]. Pathologies of the ACL include those induced by (1) prior trauma, which can lead to partial or complete ACL tears, and (2) degeneration, which include degenerative tears [7] and mucoid degeneration.

Mucoid degeneration, where the ligament is filled with mucoid or myxoid material [8], is considered a less common pathology. Its etiology has been the subject of much debate with possible causes ranging from senescence (entrapment of synovial tissue [9]) to chronic trauma [8]. Although ACL ruptures resulting from traumatic injuries are associated with premature knee OA [10–12], there is a paucity of data regarding the prevalence of degenerative ACL abnormalities among those with symptomatic OA and whether such abnormalities are associated with the severity of knee OA.

As magnetic resonance imaging (MRI) is the best imaging technique to non-invasively visualize articular cartilage, it is an important tool used to monitor degenerative joint disease. Furthermore, with the advent of high-field MRI, the detection and visualization of subtle cartilage lesions have dramatically improved [13, 14]. Various reliable and reproducible semi-quantitative measures have been developed to evaluate the morphological abnormalities associated with knee OA, such as the Whole-Organ MRI Score (WORMS) [15] and the Boston-Leeds OA Knees Score (BLOKS) [16]. MRI also provides a method to non-invasively detect and quantify the cartilage biochemical composition using T_2 and T_{1rho} relaxation times. As they provide information on the cartilage collagen content and architecture, water content, and concentration of glycosaminoglycans, these techniques show promise in the detection of early cartilage degeneration [17–19].

The purpose of our study was to evaluate the cross-sectional association of ACL abnormalities with knee morphological degeneration (based on WORMS scores) and cartilage T_2 measurements using knee MRIs of osteoarthritic individuals from the OA Initiative (OAI). We hypothesized that morphological cartilage and ligament abnormalities, meniscal lesions, bone marrow lesions, and subchondral cysts would be more severe in subjects with ACL abnormalities and that cartilage T_2 relaxation times would be higher in these subjects compared to osteoarthritic controls without ACL abnormalities.

Materials and methods

Subject selection

The data used to prepare this article was obtained from the Osteoarthritis Initiative (OAI) database, which is available for public access at http://www.oai.ucsf.edu/. The OAI is an ongoing multi-center, longitudinal, prospective observational cohort study, focusing primarily on knee OA. The study protocol, amendments, and informed consent documentation were reviewed and approved by the local institutional review boards. Baseline clinical and image datasets 0.C.1 and 0.E.1 obtained from the OAI coordinating center were used in this cross-sectional study. We analyzed a subset of individuals from the OAI progression cohort, which is characterized by the presence of symptomatic OA in at least one knee. Symptomatic knee OA was defined as the combination of (i) pain, aching or stiffness in or around the knee on most days for at least 1 month during the past 12 months and (ii) tibiofemoral osteophytes in the same knee with or without joint space narrowing (equivalent to Kellgren and Lawrence (KL) grade of ≥2), representing radiographic tibiofemoral OA. Exclusion criteria for the OAI included subjects with a prior traumatic injury, previous knee surgery, rheumatoid arthritis, bilateral severe knee joint space narrowing, and contraindications or inability for MRI.

Two board-certified musculoskeletal fellowship trained radiologists (7 and 24 years of experience in musculoskeletal imaging respectively) independently evaluated the right knee MRIs of 304 randomly selected progression cohort subjects for ACL abnormalities. In case of disagreement during clinical grading, a consensus reading was performed. Upon assessment, we identified 52 subjects with abnormal ACLs—28 with mucoid degeneration, 12 with a partial tear, and 12 with a complete tear (Fig. 1). From the remaining 252 subjects with normal ACLs, 53 were randomly selected to serve as controls.

Questionnaire

Physical activity levels were assessed in all OAI subjects using the Physical Activity Scale for the Elderly (PASE). This is a well-established, reliable, and validated questionnaire that has been used to measure physical activity in individuals of similar age to those investigated in the current study [20–22]. The following clinical question asked during the initial screening for the OAI was used to exclude subjects who reported a history of knee injury, which caused difficulty walking; “Have you ever injured either of your knees so badly that it was difficult for you to walk for at least one week?” The responses were recorded as either “Yes”, “No”, “Don’t know” or “refused”.

Bilateral radiographs

Bilateral standing posteroanterior (PA) “fixed flexion” knee radiographs were obtained using a Plexiglas frame (SynaFlexerTM). The knees had 20˚-30˚ of flexion and the feet had 10˚ of internal rotation. A focus-to-film distance of 72 inches was used. Baseline knee radiographs were evaluated by two radiologists in consensus and graded using the Kellgren-Lawrence (KL) grading scale [23].

MR imaging

MRI examinations were obtained with dedicated 3-T MRI systems (Trio, Siemens, Erlangen, Germany) using a quadrature transmit-receive knee coil (USA Instruments, Aurora, Ohio, USA). The following standard morphologic sequences

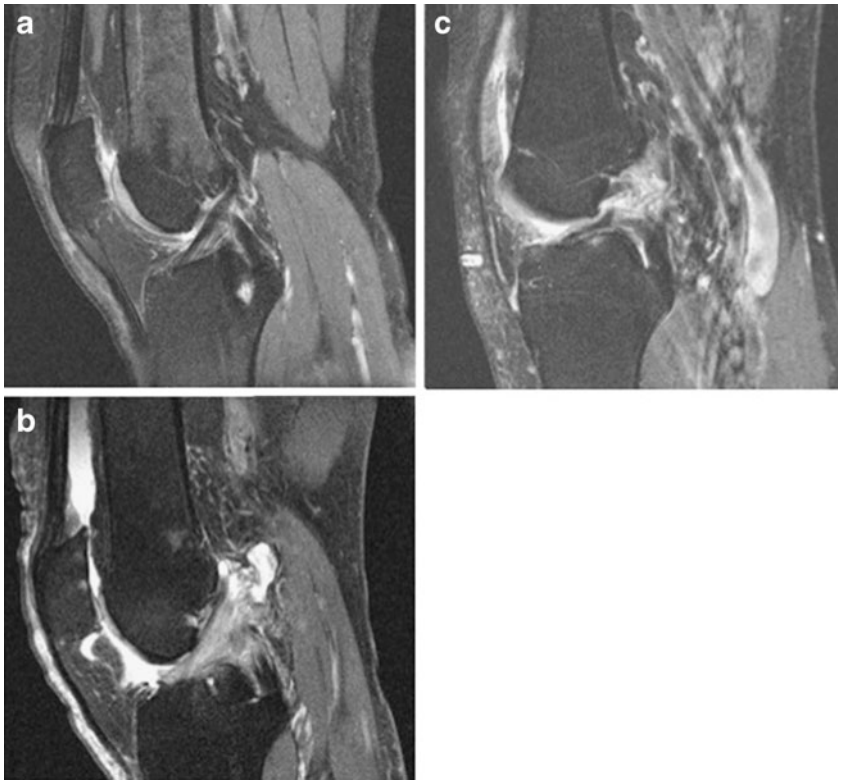

Fig. 1 Sagittal IW FS images of the knee. **a** Normal ACL - continuity of its fibers. **b** Non-complete ACL tear - increased signal intensity and a swollen appearance but fibrillary continuity of the ligament is preserved, findings are consistent with mucoid degeneration. **c** Complete tear - complete disruption of the ACL

and T_2-mapping sequences of the right osteoarthritic knee were analyzed: (i) coronal intermediate-weighted (IW) 2-D fast spin-echo (FSE) sequence (TR/TE=3700/29 ms, spatial resolution=0.365 × 0.456 mm, slice thickness=3.0 mm), (ii) sagittal 3-D dual-echo in steady state (DESS) sequence with selective water excitation (WE) with coronal and axial reformations (TR/TE=16.3/4.7, flip angle=25°, spatial resolution=0.365 × 0.456 mm, slice thickness=0.7 mm), (iii) sagittal 2-D IW FSE sequence with fat suppression (FS) (TR/TE=3,200/30 ms, spatial resolution=0.357 × 0.511 mm, slice thickness=3.0 mm) and (iv) sagittal T_2-weighted 2-D multi-echo (ME) spin-echo (SE) sequences (TR=2,700 ms, TE=10, 20, 30, 40, 50, 60, and 70 ms, spatial resolution=0.313 × 0.446 mm, slice thickness=3.0 mm, and 0.5 mm gap), as previously described in detail [24].

Image analysis

Grading of the ACL

Abnormalities of the ACL included (i) mucoid degeneration, (ii) partial tear, and (iii) complete tear. Mucoid degeneration on MRI is characterized by an ill-defined and thickened ligament with increased signal intensity on all sequences including DESS and IW FSE, which were available for interpretation during this study [25]. As previously described, there is a loss of the normal linear fibrillary pattern on the low TE images (coronal 2D IW FSE sequence), but a retention of the continuous fibers as seen on the fluid sensitive sagittal 2-D IW FSE fat-saturated sequence [26]. Though in our study the TEs are not significantly different, the sagittal fat-suppressed FSE images are still more fluid-sensitive and thus show better contrast of ACL fibers compared to surrounding high signal tissue than the non-fat-suppressed weighted FSE images in mucoid degeneration. A partially torn ACL showed a disruption of some of its fibers with the remaining ones being continuous, as previously described [27]. Some authors have reported that partial tears of the ACL and mucoid degeneration can be difficult to differentiate on MR and require arthroscopic correlation [28]. Therefore, these two abnormalities were grouped together to form a "Non-Complete Tear" group. Complete tears of either the anteromedial or posterolateral bundle were also graded as partial. ACLs with partial tears typically had a thinned cross section as opposed to ACLs with mucoid degeneration. A completely torn ACL was diagnosed when there was a complete loss of continuous fibers of the ligament, the ACL was not attaching to the femur with an abnormal orientation, and a fluid gap was visualized completely separating the proximal and distal portions in fluid-sensitive sequences [29].

Semi-quantitative morphological analyses

MR images of the right knee were analyzed on picture archiving communication system (PACS) workstations (Agfa, Ridgefield Park, NJ, USA). A whole-organ magnetic resonance imaging score (WORMS) [15] was used to

evaluate the images for OA-related abnormalities of the knee, as previously described [21]. The following anatomical compartments were analyzed separately: (i) patella, (ii) trochlea, (iii) medial femur, (iv) medial tibia, (v) lateral femur, and (vi) lateral tibia. Using the semi-quantitative scoring system, the following joint structures were separately evaluated: (i) cartilage, (ii) menisci, (iii) bone marrow lesions, (iv) subchondral cysts, and (v) medial collateral ligament, as previously described in detail [21]. The mean of cartilage WORMS scores for all subregions in a knee as well as the percentage of knees with mean cartilage scores >3, which indicate more diffuse degeneration, were used to assess cartilage degeneration. WORMS scores summed over all subregions were used to assess bone marrow lesions, subchondral cysts, medial meniscus, and lateral meniscus. Additionally, global joint WORMS scores were calculated for the medial tibiofemoral joint (MTFJ), lateral tibiofemoral joint (LTFJ), patellofemoral joint (PFJ), and total joint so that the severity of degeneration could be assessed for each region. This was done by adding together the cartilage, ligament, subchondral cyst, and bone marrow lesion WORMS scores for each compartment.

Two board-certified radiologists with 24 and 7 years of experience in musculoskeletal imaging separately graded the images. If WORMS scores were not identical, consensus readings were performed. During the reading session, ambient light was reduced. Radiologists had access to all of the acquired sequences, and no time constraints were used.

Quantitative measurements

T2 relaxation time

The T_2 relaxation time was approximated by fitting an exponential function to the signal intensity at different echo times as follows: $SI(TE) \sim \exp(-TE/T_2)$, where SI(TE) is the signal intensity as a function of echo time and T_2 is the transverse relaxation time. A monoexponential decay model was used [21].

Images were transferred to a remote SUN/SPARC workstation (Sun Microsystems, Mountain View, CA, USA) and analyzed with software developed at our institution using an Interactive Display Language (IDL) (Research Systems, Boulder, CO, USA) environment. Manual segmentation of the cartilage in the patella, medial femoral condyle (MFC), medial tibia (MT), lateral femoral condyle (LFC), and lateral tibia (LT) was performed on the T_2 maps from the sagittal 2-D ME SE sequences of the right knee, as previously described in detail [30]. Rarely, the cartilage was absent or significantly thinned, making segmentation not possible; these individual compartments were not segmented and accounted for as missing data during the statistical analysis. The whole compartment of each region was segmented on all slices with well-visualized artifact-free cartilage. The trochlea was not segmented because of the interfering flow artifacts from the popliteal artery. An IDL routine was used to simplify the manual drawing of splines delineating cartilage areas. The mean T_2 values from the regions of interest created in the T_2 maps were subsequently calculated.

Reproducibility measurements

Thirteen subjects were randomly selected out of the 105 subjects (with and without ACL abnormalities) enrolled in the study. Grading of the ACL was performed in these 13 subjects twice by two radiologists and reproducibility was determined with Cohen's kappa values. There was an interval of 4 weeks between the two reproducibility readings. Reproducibility for the semi-quantitative WORMS score was demonstrated to be good in a prior study, with the Cohen's kappa values equal to 0.76 and 0.72 for the inter-observer and intra-observer agreement, respectively [21]. Reproducibility of the quantitative T_2 measurements was evaluated with two repeated segmentations done for each of ten randomly selected subjects with an interval of 3 weeks between the two segmentations. Inter-observer and intra-observer agreement was determined using global intraclass correlation coefficients.

Statistical analysis

Statistical analysis was performed with JMP software, version 7 (SAS Institute, Cary, NC). Multiple linear and logistic regression models were used to determine significant differences in WORMS scores and T_2 values between knees with a normal and abnormal ACL. The knees in the "non-complete tear" group and those with complete tears were compared to each other and they were assessed together as one group and separately against the normal ACL subjects. All WORMS analyses were adjusted for age, sex, and BMI, and T_2 analyses were also adjusted for KL grades. WORMS analyses were not controlled for KL grades because we expect WORMS scores to increase as KL grades increase. Statistical significance was defined for all calculations as $p < 0.05$.

Results

Of the 304 subjects with symptomatic knee OA, 52 (17.1%) had abnormal ACLs, 28 (9.2%) with mucoid degeneration, 12 (3.9%) with a partial tear, and 12 (3.9%) with a complete tear. As outlined previously, differentiation between mucoid degeneration and partial tear is limited. We therefore combined the partial tear and mucoid degeneration groups and defined them as non-complete tear group (n=40, 13.1%). Subject characteristics are displayed in Table 1. The WORMS scores

Table 1 Subject characteristics[a]

	Normal ACL (n=53)	Abnormal ACL (n=52)	p value t test
Gender	11 males, 42 females	23 males, 29 females	0.010*
Age (years)	64.5±9.6	65.7±8.7	0.497
BMI (kg/m^2)	27.9±4.7	28.1±4.3	0.846
PASE	138.5±71.4	148.8±73.2	0.470
Anterior tibial translation (cm)	–0.02±0.29	0.20±0.44	0.004*
KL Grade 1	n=0	n=0	
KL Grade 2	n=17	n=3	
KL Grade 3	n=36	n=46	
KL Grade 4	n=0	n=3	

[a]Values are expressed as mean ± SD unless otherwise noted

*Significantly different if p<0.05

of males and females did not significantly differ in either the normal or abnormal ACL groups; thus, they were evaluated together in all analyses. Higher KL grades (KL>2) were more frequent in the abnormal ACL group.

ACL abnormalities in relation to WORMS

When evaluating cartilage lesions (Table 2), the abnormal ACL knees had significantly higher mean cartilage WORMS scores than the normal ACL group in all compartments ($p\leq0.05$) except the patella, which was trending toward significance. The individual ACL abnormalities (non-complete tear and complete tear groups) also displayed significantly higher WORMS scores in all compartments of the knee except for the patella in the complete tear group, when compared to the normal ACL group ($p<0.05$). Similar results were found when evaluating the percentage of subjects with more advanced cartilage degenerative disease (WORMS scores >3, Table 2).

When evaluating the other joint structures except the MCL, the abnormal ACL group displayed significantly greater WORMS scores than the normal group in all structures (Table 2). Compared to the normal ACL group, WORMS scores were significantly higher in the medial meniscus of the complete tear group ($p\leq0.0001$) and the non-complete tear group ($p=0.0059$). The non-complete tear group also had significantly higher WORMS scores than the normal knees for all other structures of the joint ($p<0.05$). The complete tear ACL group had significantly higher WORMS scores for subchondral cysts and bone marrow lesions, than the control group ($p\leq0.05$), but no difference in other structures, which may have been related in part to the smaller number of subjects in this group.

When global joint WORMS scores were assessed, the abnormal ACL group displayed significantly higher WORMS scores than the normal ACL group in all regions, but to a greater degree in the MTFJ and total joint (Table 2). Comparing the individual ACL pathologies to the control group, they had significantly higher WORMS scores in all regions ($p<0.05$), except for the LTFJ and the PFJ of completely torn ACL subjects.

Differences between the individual ACL abnormality groups

Comparing the WORMS scores of the non-complete and complete tear group revealed few differences (Table 2). However, it should be noted that the completely torn ACL group had significantly higher medial meniscal WORMS scores than the non-complete tear group ($p=0.035$).

Cartilage T_2 relaxation times in relation to ACL abnormalities

T_2 values of abnormal ACL subjects were trending toward being lower than normal ACL subjects in the MFC ($p=0.091$) and MT ($p=0.078$), but no significant differences were found (Table 3). When assessing the individual ACL pathologies, the only significant relationship was that the completely torn ACL group had lower T_2 values than the control group in the MT (36.9 ms vs. 38.1, $p=0.022$).

Reproducibility

The reproducibility for grading of the ACL into the *different* categories was excellent with the Cohen's kappa values equal to 0.850 and 0.925 for the inter-observer and intra-observer agreements, respectively. Using the global intra-class correlation coefficient, the T_2 measurement inter-observer and intra-observer agreements were found to be 0.990 and 0.994, respectively.

Discussion

The results of our study suggest that ACL abnormalities are fairly prevalent in subjects with symptomatic knee OA (17%) who do not have a self-reported history of a knee

Table 2 Comparison of normal and abnormal ACL knees using WORMS. Comparison of individual ACL abnormalities using WORMS[a,d]

WORMS	Abnormal vs. normal ACL			Differences in individual ACL abnormalities	
	Normal ACL (n=53)	Abnormal ACL (n=52)	p value (normal vs. abnormal ACL)	Non-complete tear group (n=40)	Complete tear group(n=12)
Cartilage					
MFC	1.83±1.57	3.54±1.57	<0.0001*	3.50±1.61	3.67±1.92
MT	0.80±1.43	2.61±2.21	<0.0001*	2.48±2.19	3.00±2.34
LFC	1.45±1.58	2.94±1.95	<0.0001*	2.93±2.02	3.00±1.81
LT	1.47±1.85	2.87±2.06	0.0002*	2.96±2.15	2.54±1.78
Patella	3.11±1.47	3.63±1.48	0.074	3.70±1.51	3.42±1.43
Trochlea	1.69±1.66	2.92±1.83	0.002*	2.93±1.86	2.92±1.83
MFC >3[b]	5 (9%)	31 (60%)	<0.0001*	24 (58%)	8 (67%)
MT >3[b]	4 (8%)	23 (44%)	0.0001*	17 (40%)	7 (58%)
LFC >3[b]	4 (8%)	22 (42%)	<0.0001*	18 (43%)	5 (42%)
LT >3[b]	8 (15%)	21 (40%)	0.002*	19 (45%)	3 (25%)
Patella >3[b]	19 (36%)	27 (52%)	0.050*	25 (60%)	3 (25%)
Trochlea >3[b]	6 (11%)	18 (35%)	0.005*	16 (38%)	3 (25%)
Medial meniscus[e]	1.87±2.03	3.92±2.28	<0.0001*	3.57±2.34	5.08±1.72^
Lateral meniscus[e]	1.70±2.07	2.88±2.49	0.016*	3.10±2.50	2.17±2.48
Bone marrow lesions [e]	1.83±2.06	4.35±3.03	<0.0001*	4.40±3.22	4.17±2.44
Subchondral cysts[e]	0.30±0.72	1.21±1.46	0.0001*	1.18±1.31	1.33±1.97
MCL tear present[c]	2 (4%)	8 (15%)	0.073	7 (15%)	2 (17%)
Global					
MTFJ[e]	5.0±4.6	12.0±7.0	<0.0001*	11.2±6.8	14.7±7.6
LTFJ[e]	5.0±5.7	10.0±7.3	0.0002*	10.6±7.7	8.1±6.0
PFJ[e]	5.9±3.5	8.3±4.6	0.010*	8.4±4.7	8.0±5.0
Total [e]	15.9±8.6	30.3±9.8	<0.0001*	21.8±8.3	30.8±9.4

[a] Values are the mean ± SD unless otherwise noted; all analyses adjusted for age, sex, and BMI

[b] Mean cartilage WORMS >3 expressed in number of subjects (%)

[c] Number of subjects (%)

[d] Logistic regression analysis unless otherwise noted

[e] Multiple linear regression analysis

* WORMS of abnormal ACL group > normal ACL group (p<0.05)

^ WORMS of complete tear > non-complete tear group (p=0.035)

MFC medial femoral condyle, *MT* medial tibia, *LFC* lateral femoral condyle, *LT* lateral tibia, MCL medial collateral ligament

MTFJ medial tibiofemoral joint, *LTFJ* lateral tibiofemoral joint, *PFJ* patellofemoral joint

Table 3 Cartilage T2 values of normal ACL knees compared to abnormal ACL knees in all five compartments

T2 values	Normal ACL (n=53)	Abnormal ACL (n=52)	p value
Patella	42.4±4.5	42.2±4.1	0.689
Medial femoral condyle	54.1±3.7	53.0±4.1	0.089
Medial tibia	38.1±3.9	37.3±3.7	0.077
Lateral femoral condyle	49.9±2.9	48.6±4.4	0.137
Lateral tibia	39.2±5.2	39.2±4.7	0.409

[a] Values are the mean ± SD. T2 values are in ms

[b] Multiple linear regression analysis adjusted for age, sex, BMI, and KL grades

* Signficantly different (p<0.05)

injury that caused difficulty walking. We found significantly more severe degenerative changes in subjects with abnormal ACLs compared to normal ACL subjects, as evidenced by higher WORMS scores in all joint structures (cartilage, menisci, bone marrow lesions, subchondral cysts, and MCL) and in all compartments of the knee, though particularly in the medial compartment. Surprisingly, the severity of degeneration in the knee joint did not differ between the complete and non-complete ACL groups, except in the medial meniscus. Contrary to our hypothesis, cartilage T_2 relaxation times were not associated with ACL abnormalities; this may be due to the severe cartilage degeneration in our subjects with established OA, as it substantially limits segmentation and T_2 analysis.

We found that 17.1% of knees in our study with mostly mild and moderate OA (94% of knees with ACL abnormalities had a KL grade of 2 or 3 at baseline) had abnormalities of their ACLs, a finding that has been reported to be as high as 64% in knees with more advanced OA [31]. Although mucoid degeneration has been regarded as a rare pathology [26], we found its presence in 9.2% of our subjects. Although ACL tears [31] and mucoid degeneration [26] have been described in osteoarthritic knees, the exact cause of such ACL changes is not completely understood, particularly because many (and all of the subjects in the present study) do not recall a prior knee injury. It has been suggested that intercondylar notch stenosis caused by osteophytes produces a shear force during flexion and extension, which eventually damages the ACL [32]. Cushner and colleagues harvested 19 ACLs from patients undergoing total knee arthroplasty and found loose, fibrous tissue and myxoid and cystic occurrences to be common forms of degeneration [33]. Additionally, McIntyre [25] observed that one out of ten of his subjects with mucoid degeneration developed a non-traumatic ACL tear within a year. This perhaps lends credence that these ACL changes are part of a continuum of senescence and degeneration.

Our data suggests that in individuals with symptomatic OA, ACL abnormalities are associated with more severe knee degeneration, based on WORMS scores. It has been speculated that the antero-posterior and rotatory instability of ACL-deficient knees increases the shear force to the cartilage, contributing to accelerated OA [34]. Additionally, external adduction moments are elevated in ACL-deficient knees, increasing medial loads and thus the risk for medial degeneration [34, 35]. In fact, we found that the cartilage WORMS scores did not differ significantly between the types of ACL pathology. Compared to the osteoarthritic subjects with normal ACLs, the subjects in the two abnormal ACL groups had greater cartilage degeneration (based on mean WORMS scores and percentage of subjects with WORMS scores greater than 3) in all compartments except the patella, though the medial compartments displayed the greatest significance. The patellar WORMS scores did not significantly differ from the controls likely because the controls had relatively severe patellar degeneration.

Our data is in agreement with two previous studies [7, 36] that evaluated subjects with symptomatic OA and complete ACL tears. Amin and colleagues [36] found through a 30-month longitudinal study that ACL-deficient knees had accelerated cartilage degeneration, based on WORMS, in the medial tibiofemoral joint and there was a trend in the lateral tibiofemoral joint, but no association was found in the patellofemoral joint. Furthermore, Hill et al. [7] found ACL-deficient knees to have more severe medial radiographic OA. Roughly half of the subjects in each of these studies recalled a previous knee injury; we excluded these subjects because prior injury is a known risk factor for OA. Additionally, we evaluated individuals with mucoid degeneration and partial tears rather than only those with complete ACL tears.

The medial meniscus was the only structure that differed between the two ACL pathologies. The completely torn ACL group had greater medial meniscal degeneration than the other group. Despite the marginal p value for this difference, it is supported by prior research. It is well documented that chronically ACL-deficient knees have increased incidence of medial meniscal tears [36–38]. It is postulated that the posterior horn acts as a buttress by wedging against the posterior aspect of the MFC to prevent posterior femoral translation (and concurrent anterior tibial translation). In an ACL-deficient knee, the demand on the medial meniscus to resist anterior tibial translation significantly increases, which could explain the increased incidence of meniscal tears [39].

Despite the known predisposition for medial compartment degeneration, an association was also seen within the rest of the joint in those with an abnormal ACL, as evidenced by the global WORMS scores. This global joint degeneration is likely the result of intermediate to long-term sequelae of the degenerated ACL.

Cartilage T_2 values have been utilized to detect the early biochemical changes that precede morphological deterioration [21]. These changes are primarily related to the cartilage water content, macromolecular composition, and organization of the collagen fibers [17]. The only significant difference we found in T_2 values was that the completely torn ACL group had lower MT T_2 values than the normal ACL group, which was not expected as more degenerated cartilage should have higher T_2 measurements. However, T_2 measurements may be better suited to detect early OA rather than assess advanced OA; David-Vaudey et al. [40] showed an increase followed by a decrease in cartilage T_2 relaxation times with a histological grading of 1 and 2 (simplified Mankin's criteria), respectively. This was postulated to be related to the anisotropy of collagen fibrils, causing an

increase in T_2 values in grade 1 histological changes before sufficient loss of water content results in decreased T_2 values in grade 2 histological changes. It is possible that the cartilage of our subjects was beginning to undergo grade 2 histological changes.

A limitation of the study is that arthroscopic correlation with the MR diagnosed ACL abnormalities was not possible. Another limitation is the evaluation of ACL without longer TE T2 images, which can make it difficult to differentiate between the types of ACL abnormalities. The diagnostic accuracy of 3-T MRI for ACL abnormalities varies in literature; Dyke et. al found an accuracy of 97% for complete ACL tears and 95% for partial tears upon correlation with arthroscopy [41]. We acknowledge the difficulty in segmenting the cartilage of subjects with established OA, as only visible remnant cartilage is targeted. Areas of denuded full-thickness cartilage loss, contributing to a WORMS grade of 5 or 6, have no segmentable cartilage. Changes in cartilage of severe OA knees would hence not be fully represented by the T_2 values and require quantification using the WORMS morphological score. This further suggests that T_2 quantification is better suited to detect early OA prior to morphological deterioration.

Another limitation was a relatively small sample of subjects ACL *abnormalities*. This may have affected our ability to detect significant differences in these groups. Future studies with a larger number of subjects and a longitudinal follow-up are needed to elucidate the relationship between ACL abnormality and progression of OA. A longitudinal follow-up may also determine the impact of worsening OA on the ACL.

Conclusions

In summary, when evaluating symptomatic osteoarthritic subjects, we found that an abnormal degenerated ACL was associated with more severe pathology of knee OA in multiple joint structures assessed by MRI, particularly in the medial compartment. The severity of degeneration between the two abnormal ACL groups (the non-complete tear and complete tear groups) did not differ in any structure except for the medial meniscus, which was more degenerated in the completely torn ACL group. Cartilage T_2 relaxation times did not show significant differences between normal and abnormal ACL groups with established OA, suggesting that cartilage T_2 values may be less suited to assess more advanced cartilage degeneration.

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